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(10) Joseph N. Suhayda, Harry H. Roberts
and Stephen P. Murray

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NEARSHORE PROCESSES ON A FRINGING REEF

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ABSTRACT

A field experiment was conducted on Grand Cayman Island during 1972 and on Barbados during 1973 to determine the characteristics of wave-dominated nearshore processes in a fringing reef. Results from these field experiments indicate that nearshore processes on reefs occur in a distinctly different pattern from that on sandy coasts.

Deepwater wave characteristics are significantly modified by reef morphology before the waves reach the shoreline. Shelf morphologic features produce a significant reduction in wave height (~20%), owing to the combined effects of friction, scattering, and reflection, at a rate significantly greater than that occurring on sandy coasts. At the fringing reef crest energy loss resulting from breaking produces a substantial reduction in wave height which is accompanied by an extreme modification to the wave spectrum, including the introduction of multiple low-frequency peaks. Wave-induced currents cross the fringing reef crest and interact with lagoon geometry to produce a circulation pattern in the back-reef lagoon characterized by velocities which increase toward the main lagoon outlet. Sediment thickness within the lagoon decreases toward the lagoon opening and increases toward the shoreline. This pattern is in qualitative agreement with the generally predicted lagoon current movement.

INTRODUCTION

The presence of coral reefs along a shoreline produces an interesting and distinctive coastal environment. Coral reefs are composed of networks of complex feedback systems involving biological, chemical, and physical processes. Although many aspects of reef systems are not well understood, there is ample evidence that in coral reefs the intensity of the process interactions is greater than that in any other coastal environment. Thus reefs hold the promise of providing natural laboratories for uncovering fundamental knowledge about coastal systems. This knowledge could help form a rational basis for the desirable development of all coastal environments.

Coral reefs have been estimated to occur extensively along 22,000 km of shoreline throughout the world (Inman and Nordstrom, 1971), primarily island shorelines. They also occur along the eastern coasts of Africa and South America, the eastern coast of Central America, around the Middle East, and along the northern and eastern shores of Australia (Stoddart, 1969). The global distribution of reefs is confined to latitudes less than about 25°, and within this range they account for about 10% of the world's shorelines. Reefs occur in a variety of structural patterns characterized by gross morphology, size, relationship to non-limestone rocks, and in some cases by depth of surrounding water. The largest type of reef structures are barrier reefs, fringing reefs, and atolls. Although barrier reefs are the largest reef structures, atolls and fringing reefs are more common and occur in numerous examples throughout the reef belt of the globe. Reefs are being exploited at an accelerated pace (e.g., Palmer, 1971; Grigg et al., 1973) and therefore greater demands will be placed on our understanding of reef processes in order to manage these valuable natural resources rationally.

Recent studies of reef systematics have indicated that physical processes and their interaction with biological and chemical elements of the system are the least known of reef processes (e.g., MacIntyre et al., 1974). These physical processes involve primarily oceanographic factors of waves, tides, currents, and water mass properties and their interaction with reef morphology. In very shallow water, one set of processes is particularly intense and dominates. These nearshore processes include the action of waves in shallow water and wave-induced circulation and sediment transport. Understanding of nearshore processes has been a prime factor in development of coastal environments and will play a key role in the successful development of reefal coasts.

Nearshore processes in reefal areas have always been a part of reef studies in general because of the realization that there is close involvement of biological, geologic, and physical processes. Therefore, references to general aspects of nearshore processes on reefs can be found scattered throughout the reef literature. Reviews of reef literature can be used as sources of information about reports containing substantial information, or key observations, about nearshore physical processes on reefs. General reviews can be found in Shepard (1963), Stoddart (1969), Jones and Endean (1973), and DiSalvo and Odum (1974). Specific research on nearshore processes on reefs has been conducted more recently by Inman et al. (1963), Storr (1964), Leont'yev (1969), and Roberts et al. (1975). These studies have indicated that a zonation exists in nearshore processes which is primarily determined by the geometry of the reef complex. Quantitative documentation of these zones has generally been scarce.

In order to provide additional data on the physical processes occurring on reefs, a series of projects has been conducted by the Coastal Studies Institute, Louisiana State University, U.S.A., in reefal environments. Although these studies have been intensive investigations of specific sites, careful selection of the sites and a desire to elucidate the fundamental interactions underlying the physical processes will, it is hoped, provide results which are of general interest. Results have been reported concerning reef sediments (Roberts, 1971a, b), reef morphology (Roberts, 1974; Hernandez and Roberts, 1974), and reefal currents (Roberts et al., 1975). Reports now underway concern inshore currents (Murray et al., 1975) and bottom currents (Roberts, 1975). This paper will report the results from these studies concerning nearshore processes on fringing reefs.

AREAS OF STUDY AND FIELD OPERATIONS

A field experiment was conducted on Grand Cayman Island, B.W.I. (Fig. 1), during November 1972, and subsequent studies were made on Barbados, W.I., during 1973. Figure 2 shows the array of instruments deployed during the Grand Cayman experiment superimposed on a schematic profile of the fore-reef shelf and adjacent lagoon. Similar instrumentation was deployed around Barbados. The study area on Grand Cayman consisted of a linear fringing reef, a shallow back-reef lagoon, and a narrow fore-reef shelf, a configuration which is typical of many reef systems in the Caribbean-Atlantic reef province. Fringing reefs nearly encircle the island; the exceptions are the leeward western coast and a few areas where sea cliffs have developed. Seaward of the shallow, alongshore-trending reefs lies a narrow, stepped fore-reef shelf. An abrupt break in slope at approximately 8 meters marks the seaward margin of a shallow terrace. A deeper terrace slopes seaward from a depth of approximately 13 meters (base of the shallow terrace) to the margin of the shelf, which commonly occurs at depths near 20 meters. At its seaward margin the fore-reef shelf is intersected by a steeply sloping, seaward-facing surface (ranging from approximately 40° to nearly vertical) which descends several hundred meters to a point at which the island slope is encountered. The shallow and deep fore-reef terraces contained spurs and sediment-floored grooves (Roberts et al., 1975), which create a texture of roughness on the shelf that is unique to reef environments.

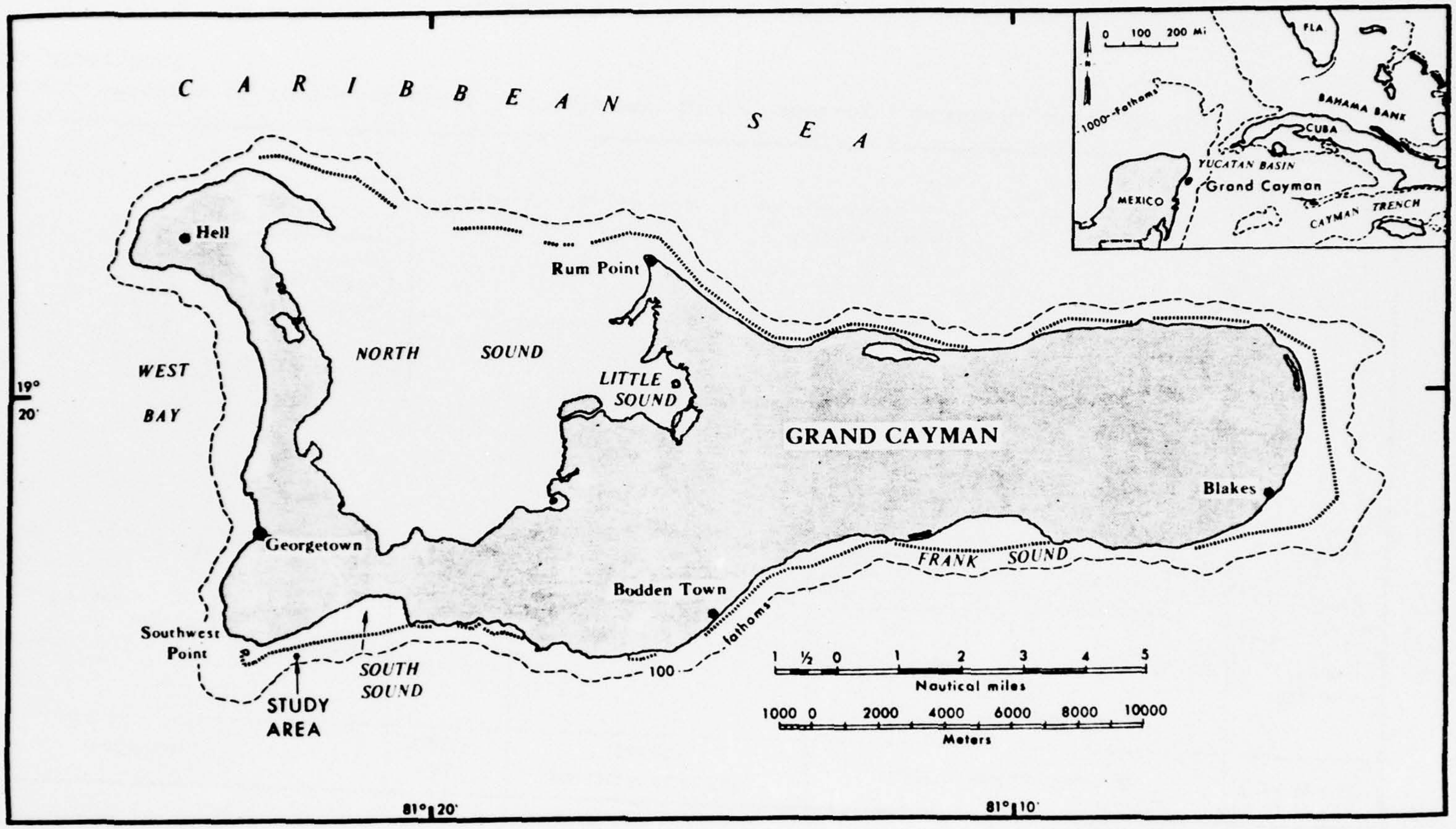

Figure 1. Location map of Grand Cayman Island and the study site.

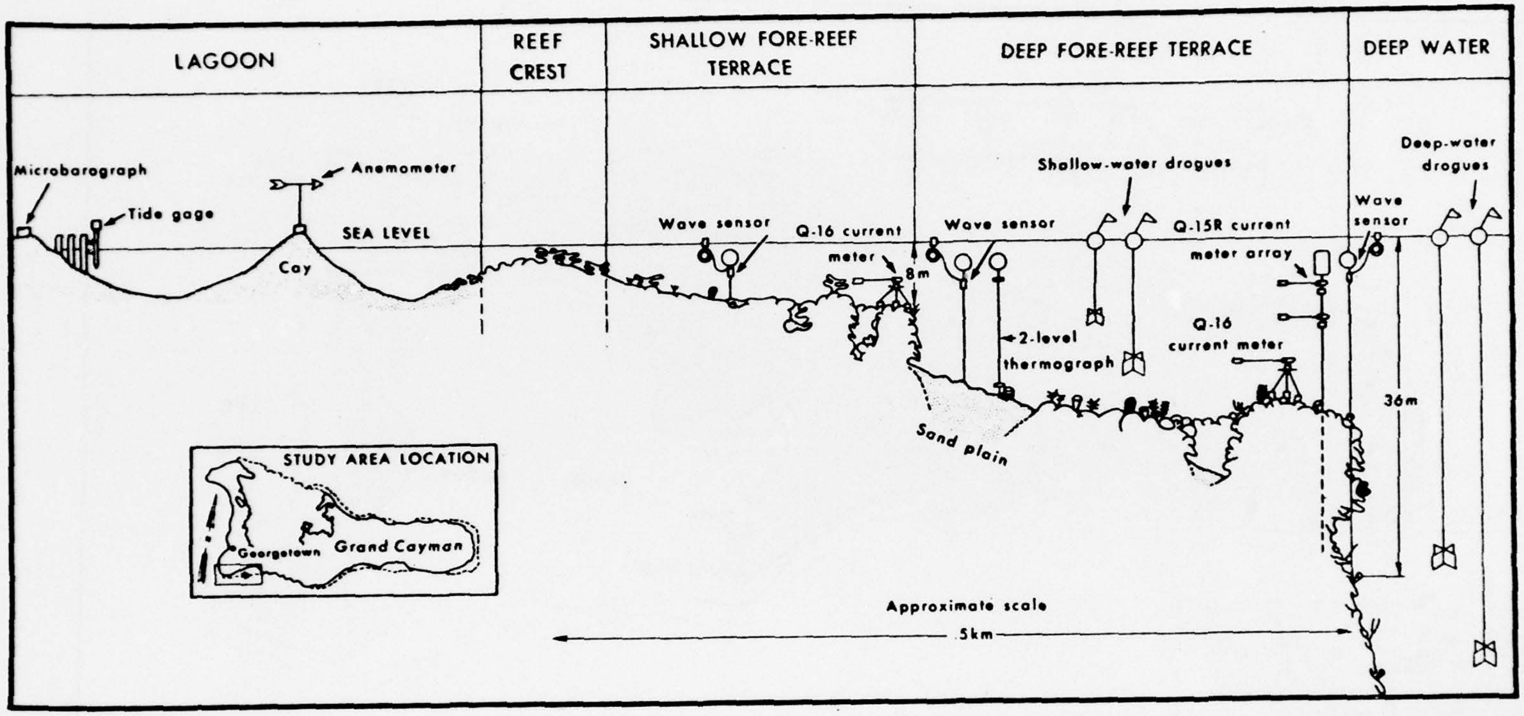

Figure 2. Profile of fore-reef shelf and adjacent lagoon showing instrument array during the Grand Cayman experiment.

The instruments used in the study, as illustrated in Figure 2, were deployed in a north-south transect across the lagoon-reef-shelf complex at South Sound, near the southwestern extremity of the island.

Tide fluctuations were measured on a specially designed capacitance tide gage which was installed, along with an air-sea thermograph, near the shoreline of the shallow back-reef lagoon. Barometric pressure was monitored by a Weathermeasure Corporation microbarograph at a land-based station as background data to help identify possible effects of large-scale storm systems on coastal processes. A recording Climet anemometer was mounted on a small sand cay adjacent to the fringing reef. This instrument provided a continuous record of wind speed and direction during the experiment.

Data for defining the wave spectra on the shelf were collected from three buoyed absolute pressure sensors. Signals were corrected to give surface wave measurements. Wave-induced pressure changes were measured and recorded at each station on a boat-based analog recorder. Sensor depth was read before each measurement by employing a low-pass filter.

WINDS AND WAVES ON THE FORE-REEF SHELF

Table 1 shows a long-term summary of surface wind speeds and directions for November in the ocean area surrounding Grand Cayman. Northeasterly trades are dominant and display typical speeds of 5-6 m/sec; 73% of the winds have an easterly component.

Table 1
Oceanic Surface Winds for November, Grand Cayman Region

Speed (m/sec)	NW	N	NE	E	SE	Total %
2-5	2	8	17	12	3	42
5-8	1	8	15	11	1	36
8-13	1	6	9	4		19
≥13			1			1
Total %	3	22	42	27	4	

Reference: Oceanographic Atlas of the North Atlantic, Section IV: Sea and Swell (1963). U.S. Naval Oceanographic Office, Publ. No. 700, Washington, D.C., 227 p.

Local winds were measured on an offshore cay in the study area at the southwestern extremity of Grand Cayman over a period of several weeks. Although the frequencies of occurrence of the observed winds are somewhat different from the long-term averages, the general trends were similar. The expected northeasterly trades produced the modal direction (26.5%), but winds varied considerably in both speed and direction. The variability is attributed to the influence of local topography and storms. Easterly components (65%) clearly dominated the direction field, but the wind speeds were considerably reduced. This frictional attenuation of wind speed across an island was documented in the 1973 Barbados study, in which a 2-3 m/sec velocity differential on the downwind coast was observed (Conlon, 1974). Garstang et al. (1970), in an earlier study, noted the same effect. Observations of easterly and southeasterly winds with speeds greater than approximately 5 m/sec were associated with intermittent southeasterly storms.

Wave measurements on the fore-reef shelf and in the fringing reef lagoon indicate that deepwater wave characteristics are significantly modified by reef morphology. An example of the spectral changes occurring between the shelf edge and the seaward margin of the shallow terrace, a distance of about 0.4 km, is shown in Figure 3. Comparison of the spectra shows a general decrease in energy density of about 20%, but the general shape of the spectrum and the frequency of the spectral peak remain the same. Changes in wave height on the fore-reef shelf are due to the combined effects of a number of processes, e.g., shoaling, refraction, reflection and scattering, and frictional attenuation. The complexity of the fore-reef shelf morphology makes the contribution of each process difficult to evaluate; however, general estimates of the importance of certain processes can be made. Wave frictional attenuation and scattering depend in part upon the bottom roughness. For a bottom roughness and amplitude averaging 2 meters, wave scattering (Long, 1973) and the bottom friction coefficient (Kajiura, 1968) would be about 10 times that found on a sandy shelf. Wave reflection from the scarp between the deep and the shallow terraces could be significant. On the South Sound shelf the coefficient at the scarp (Kajiura, 1963) is about 0.1 or 10% for terrace depths of 8 meters and 13 meters. Wave refraction and shoaling across the shelf also result in wave height changes, which for the example given in Figure 3 would have decreased the wave height about 10%; however, the roughness of the fore-reef shelf may cause slight changes in the wave phase speed. These fore-reef shelf wave processes cannot all be estimated quantitatively at this time because the energy loss associated with percolation and movement of water within the reef matrix and around small-scale roughness elements is unknown. Because wave processes on the shelf are strongly coupled to bottom roughness, variability in reef morphology implies a corresponding high variability in the rate of these processes.

The data shown in Figure 3 are typical of wave conditions on the shelf; however, in one respect they are atypical of the experiment. In general, as shown in Table 1, on a seasonal basis the Caribbean trade winds blow from the northeast at about 5-7 m/sec and typically create waves having a significant height of 1 meter and a period of 6 seconds (Garstang et al., 1970). As discussed previously, wind speeds and directions during the experiment were considerably variable. During the period of observation of the data shown in Figure 3, wind direction was toward 270° (approximately from the east), yet the waves at South Sound were observed in deep water to be arriving from the ESE, or about 45° to the trade wind direction. Owing to the narrowness of the shelf, these waves could not have resulted from refraction around the headland to the east. This observation can, however, be explained by the fact that trade wind waves do not all have directions parallel to the wind direction. This variability in the direction of wind waves, illustrated in Figure 4, has been shown (Arthur, 1949) to have an important effect on wave conditions on the shelf along shorelines that are irregular in their orientation, such as on islands. Observations of wave directional properties (Longuet-Higgins, 1962) have shown that wave height decreases off the wind direction but that waves are generated up to 90° to the wind direction. Generally, the height of the waves generated at an angle θ to the wind direction is given by $H_o \cos^2 \theta$, where H_o is the height of the waves in the wind direction ($\theta = 0$). This spread of trade wind waves is shown in Figure 4 by the wave rose, where the length of the vectors is proportional to the wave height at the angle of the vector. Trade wind waves traveling at 45° to the wind directions have direct access to the shelf at South Sound from the southeast (Fig. 4). At 45° to the wind direction, these waves would have a height of approximately one-half the downwind wave height. If the downwind wave spectrum is assumed to be given by the empirical Pierson-Moscowitz relation (Pierson and Moscowitz, 1964), then the spectrum measured at the deep shelf edge should be comparable with the empirically determined PM spectrum. The PM spectrum shown in Figure 3 is for a wind speed (10 m/sec) which matches the observed spectral peak; the energy density levels are one-quarter as large and represent the spectrum occurring at 45° to the wind direction. Although there are noticeable differences between the observed spectrum and the PM spectrum, especially at low frequency and in the sharpness of the peak, reasonable agreement can be seen to exist. The observed significant wave height of 85 cm agrees well with the height of 106 cm predicted from the PM spectra.

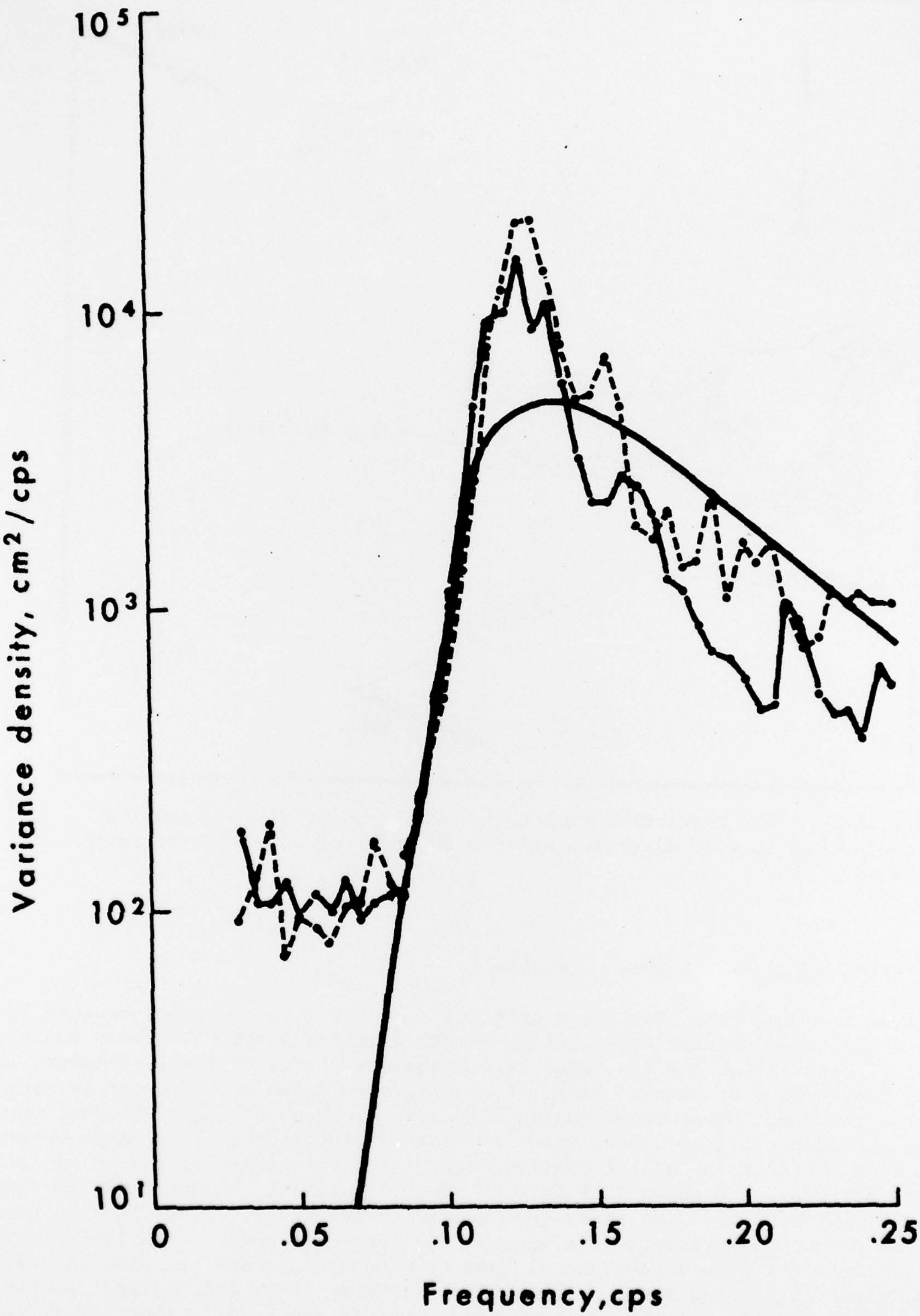

Figure 3. Wave spectra (variance density) from wave measurements on the shelf edge (dashed line) and near reef crest (dotted solid line). Also shown for comparison is the Pierson-Moscowitz empirical wave spectrum for wind speed of 10 m/sec at 45° to the wind direction (solid line).

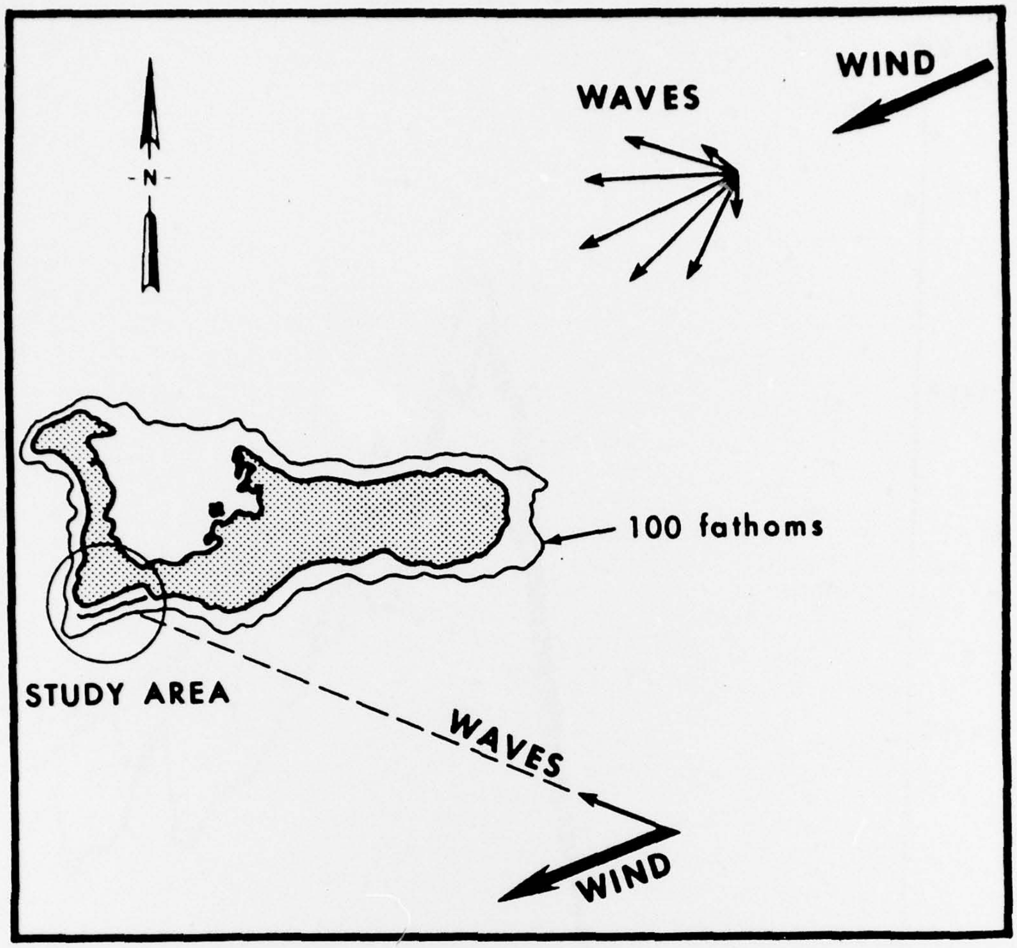

Figure 4. The characteristics of a trade-wind-driven sea showing the spread in wave direction and the approach of waves toward South Sound.

SHALLOW-WATER WAVES AND LAGOONAL CIRCULATION

The shallow fringing reef crest is a critical zone for wave processes because interactions there cause extreme modification of the incoming waves. The main feature of the reef crest affecting the waves is its shallow depth, typically 1 meter, which normally causes wave breaking. Tide, of course, causes the actual depth to vary throughout the day. Waves break continually as they transect the reef crest until reaching the deeper lagoon water, where reformation into nonbreaking waves occurs. Observations at the point of reformation, taken in a fringing-reef-formed windward lagoon on Barbados, are shown in Figure 5. For comparison, the deepwater PM spectrum for a typical trade wind speed (6 m/sec; Garstang et al., 1970) is also shown because no actual measurements were made on the fore-reef shelf. Two features are obvious: There has been a substantial loss of wave energy, and the wave spectrum has significantly changed shape. The estimated energy loss, calculated from the change in wave height, for the observed conditions is about 75%. This result is in rough agreement with laboratory measurements of wave transformation over a submerged shoal (Nakamura et al., 1966). This energy loss has not been uniform because the observed spectrum shows that considerable energy remains at low frequencies. Thus breaking has flattened the spectrum peak and perhaps transferred energy to low

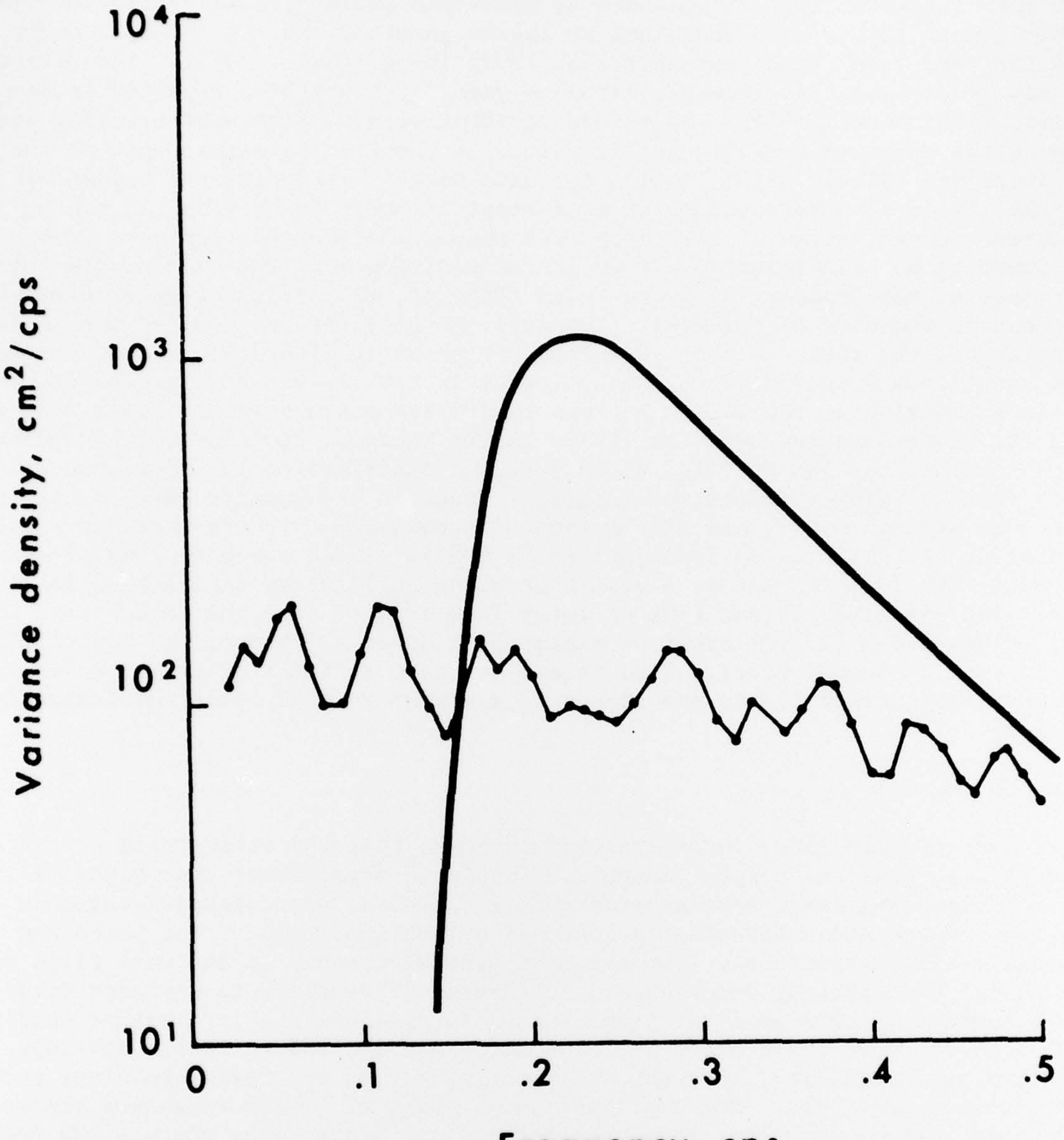

Figure 5. Wave spectra from a measurement inside the reef crest (dotted line) compared to Pierson-Moscowitz input spectrum (solid line) inferred from 6 m/sec trade wind, illustrating the extreme modification due to wave breaking.

frequency. The exact amount of energy loss and the spectral change induced depend upon the depth of water over the reef crest and the input wave conditions. The reef crest did not contain surge channels, which have been observed in Pacific reefs (Munk and Sargent, 1954) to significantly modify the incoming waves. This final form of the spectrum in the lagoon is important because the wave steepness (wave height/wavelength) has been shown to have a significant effect on sediment movement and shoreline beach stability (Hayami, 1958). These results suggest that reef crest morphology will have a critical effect on controlling the magnitude of waves reaching the shoreline behind the reef.

It has been suggested that circulation of water and sediment distribution within a fringing reef lagoon are determined by lagoon geometry and the input of water across the reef crest (Kohn and Helfrich, 1957; Inman et al., 1963). The inflow of water may be wave or tide induced, although wave input has been reported to dominate (von Arx, 1954; Storr, 1964). Wave-induced input results from wave breaking and set-up on the reef crest (Tait, 1972), which are enhanced as water depth on the reef crest decreases (Sibul, 1955). Using the wave data taken during the Cayman experiment, the influx of water across the reef crest at South Sound (Fig. 1) can be calculated. Conservation of this mass flux allows the average transport within South Sound to be calculated as a function of position down the axis of the lagoon. As a result of the geometry of South Sound (Fig. 6), the influx of water over the reef crest is funneled to the west. Currents in the lagoon calculated for an input current across the reef crest of 10 cm/sec are shown in Figure 6. Lagoon current speeds range from 2 to 45 cm/sec, being lowest in the eastern part of the lagoon and abruptly increasing as the lagoon narrows toward its western part. These velocities are in the range measured by Storr (1964) in the Bahamas. Examination of sediment thickness within the lagoon (Fig. 6) indicates a distribution in accordance with the current field. Thick sediment accumulations occur in the eastern part of the lagoon (see section C-C'), and as the lagoon narrows and currents increase sediment thickness decreases abruptly (sections A-A', B-B'). Thick accumulations of sediments occur along the island coast as a result of beach building by wave action in the lagoon. For the given volume flux of water (400 m^3/sec) over the reef crest, the lagoon volume (3.3×10^6 m^3) could be replaced in about 2.5 hours; the implication is rapid renewal of lagoon water. Thus it appears that sediment distribution and near-shore wave and current fields are linked in a system to reef crest and lagoonal morphology.

CONCLUDING REMARKS

Initial results from these investigations indicate that the interaction of currents and waves with reef and coastal morphology are more significant than might be expected, producing large spatial gradients in physical processes and sediment distribution. Waves are substantially affected by configuration of the shelf and its organically built structures. The greatest spatial changes in the wave field result from coastal orientation, which determines degree of exposure to dominant directions of wave approach. This gradient is maximized for islands set in a rather unidirectional wind and wave field where definite high- and low-energy coasts develop. Within any given locality, however, shelf configuration and reef morphology become important wave modifiers. The amplitude and spacing of bottom roughness elements, for example, affect wave frictional attenuation and scattering, whereas the occurrence of a shallow fringing reef structure can completely modify the spectral characteristics of shelf waves moving into a back-reef lagoon. Wave-driven currents occur in definite patterns; they have strong gradients over the reef crest and along the length of lagoons toward openings in the reef. Sediment is driven by waves and currents across the reef crest into the lagoon, where it may be deposited on the bottom or in shoreline beaches under normal conditions. Extreme wave action and associated currents scour the lagoon and carry sediments offshore through reef channels into deep water. An important practical implication from these process interactions is that individual processes (waves and currents) and the reef are linked in a system. This association suggests that modification of one major component may induce changes throughout the entire system. For example, cutting a channel through the shallow fringing reef may result in realignment of the back-reef shoreline, redistribution of sediment within the lagoon, and possibly deposition of sedimentary materials over living reefs of the fore-reef shelf. Although changes in reef structure resulting from environmental alterations are likely associated with time lags measured in years, sediments and biological components of the reef may undergo more rapid transformations on a time scale of months, comparable to erosional and depositional changes along sandy coasts. These relationships are important to man's

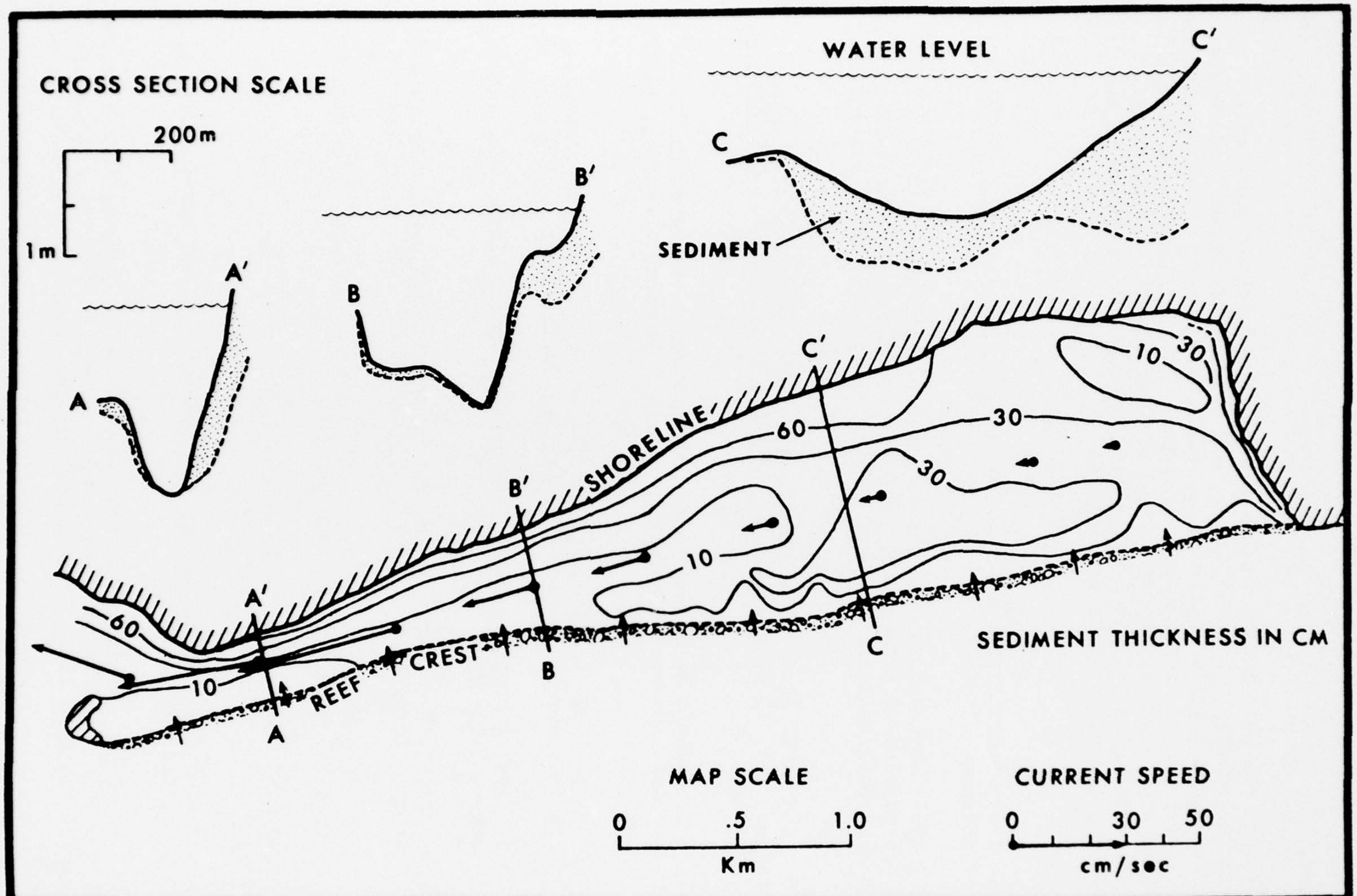

Figure 6. Sediment thickness distribution in South Sound shown in plan view and cross section, and the lagoon axis current speed (shown by arrows). Note the correspondence of the thick sediment accumulations and low speed, and thin sediment accumulations and high speed.

proper usage of reef systems, which will invariably involve, and has already involved, modification of the environment.

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CUTLINES

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13. ABSTRACT

A field experiment was conducted on Grand Cayman Island during 1972 and on Barbados during 1973 to determine the characteristics of wave-dominated nearshore processes in a fringing reef. Results from these field experiments indicate that nearshore processes on reefs occur in a distinctly different pattern from that on sandy coasts.

Deepwater wave characteristics are significantly modified by reef morphology before the waves reach the shoreline. Shelf morphologic features produce a significant reduction in wave height (~20%), owing to the combined effects of friction, scattering, and reflection, at a rate significantly greater than that occurring on sandy coasts. At the fringing reef crest energy loss resulting from breaking produces a substantial reduction in wave height which is accompanied by an extreme modification to the wave spectrum, including the introduction of multiple low-frequency peaks. Wave-induced currents cross the fringing reef crest and interact with lagoon geometry to produce a circulation pattern in the back-reef lagoon characterized by velocities which increase toward the main lagoon outlet. Sediment thickness within the lagoon decreases toward the lagoon opening and increases toward the shoreline. This pattern is in qualitative agreement with the generally predicted lagoon current movement.

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