PHYSICAL PROCESSES AND SEDIMENT FLUX THROUGH REEF-LAGOON SYSTEMS

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Abstract

Studies of physical processes in reef-lagoon systems continue to emphasize the importance of waves and wave-induced currents at the reef crest as agents of sediment transport to backreef environments. These across-the-reef currents are also largely responsible for driving backreef lagoon circulation. Rapid energy transformations associated with the process of wave breaking at the reef crest are responsible for strong reef-normal surge currents. Estimates of energy loss, as determined by wave height changes caused by wave breaking, can be as high as 70-80% for discontinuous reefs and >90% for continuous examples. The amount of energy loss is related to depth of water over the reef crest, a function of reef topography and tidal regime. Low-tide conditions promote the greatest incident wave modification and attenuation as a result of increased breaking-wave intensity. Under trade-wind conditions found in the Caribbean, surge currents of 50-80 cm/sec for durations of 2-6 sec are common in a low to moderate wave-energy setting (4-6 sec input waves, 40-50 cm average heights). Sediments through the sand sizes up to pebbles are easily transported lagoonward by these periodic bursts of energy.

Flow in shallow backreef lagoons (generally <3 km wide) is driven largely by across-the-reef currents resulting from breaking waves. Long, unbroken reefs tend to induce axial currents in the backreef lagoon which flow roughly parallel to the reef trend. Side-scan sonographs indicate that large bedforms define a region of bottom sediment migration related to strong currents down the lagoon axis, presumably activated during periods of abnormal wave activity on the reef.

Localized and discontinuous shallow reefs tend to store coarse sediments in the backreef in sand bodies oriented at high angles to the reef trend. Combined effects of wave refraction and tidal exchange around the flanks of these localized reef masses give rise to tombolo-like sediment accumulations in the shallow backreef area. Backreef sand bodies

associated with continuous linear reefs tend to be oriented parallel to the reef trend.

Lagoonal sediments are transported through tidal passes to the forereef shelf, where sediment sinks commonly develop behind actively growing shelf-margin reefs. Side-scan sonar and high-resolution subbottom data confirm both sediment sinks and preferential offshelf transport routes on narrow, rough-bottomed forereef shelves. In trade-wind-island systems (e.g., Crand Cayman and St. Croix) sediments are stored in large quantities on the forereef shelf at the downwind flanks of the islands. Forereef shelf morphology indicates that at these same locations routes for offshelf sediment transport are optimized.

Introduction

Investigations of process-response interactions in coral reef and reef-associated environments (Munk and Sargent, 1954; Inman et al., 1963; Roberts, 1974; Roberts et al., 1975; Davies, 1977; Roberts et al, 1977; Suhayda and Roberts, 1977; and others) hsve demonstrated close relationships between physical processes, reef geometry, and sediment distribution. Sediment transport routes and sinks in lagoon and shelf environments display considerable variability, depending largely on linearity of the reef, closeness of the reef to the shoreline, lagoon geometry, and local physical process setting.

Recent studies conducted on the Caribbean islands of Crand Cayman, Great Corn (Nicaragua), and St. Croix have provided a framework for better interpreting sediment flux through lagoon-reef-shelf systems by integrating results of wave-current investigations with side-scan-sonar surveys and high-resolution seismic profiles. Results of these studies regarding the magnitude and variability of physical processes and the resultant effects on sediment transport are summarized in this paper for continuous linear reefs with narrow backreef lagoons (Grand Cayman and St. Croix) and a discontinuous reef example (Creat Corn Island, Nicaragua).

Direct field measurements of waves and wave-driven currents were replicated in contrasting reef geometries and under a variety of tide and incident wave conditions typical of the trade-wind-dominated and microtidal Caribbean region. The data acquisition system for studies near the reef crest consisted of an array of absolute pressure transducers and low-inertia ducted current meters (Fig. 1). Data were cabled back to a central collection center and recorded in an analog format. In situ recording bottom-mounted current meters (Marine Advisers Q-16) and drogue studies were used to determine the characteristics of lagoon and shelf circulation. A Klein 100-kHz side-scan-sonar system equipped with a 3.5-kHz subbottom profiler was used for mapping lagoon and shelf bottom features. Accurate navigational control was provided by a Decca Del Norte locating system.

Reef-Crest Wave/Current Interactions

Shallow linear and quasilinear reefs that are situated close to a land mass generally have profiles similar to the one shown in Figure 1.

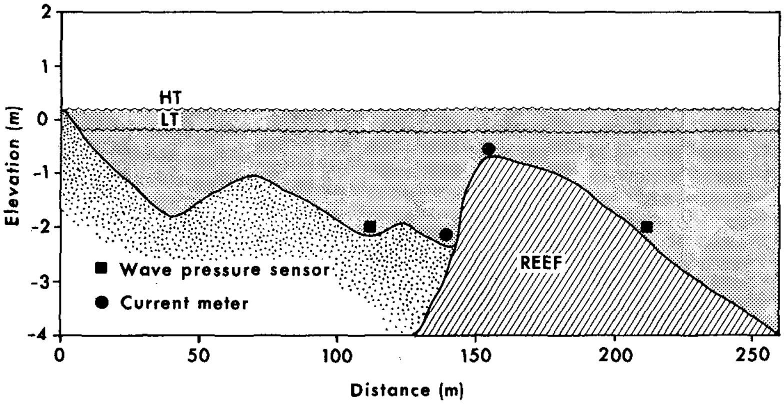

Figure 1. Instrument array for a study of wave/current interaction at the reef crest, Great Corn Island, Nicaragua. A similar instrument array was used for a reef crest study in St. Croix, U.S. Virgin Islands.

In the Caribbean region these reefs tend to be narrow and are commonly associated with a backreef lagoon with water depths generally less than 10 m. Although the shallow zone of living reef is very narrow compared to most backreef lagoons, it functions as a renewable source of abundant sediments to backreef areas. Both biological and mechanical degradation of skeletal components of the reef produces sediments that are available for transport to other environments. The apex or crest of this linear reef is a critical zone for intense wave-related processes. Shallow water depths (commonly about 1 m) induce extreme modification of incoming waves, usually resulting in wave breaking. Because water depth over the crest can strongly influence the intensity of wave-reef interactions, even small tidal variations such as those found in the Caribbean region become important. Waves may break continually as they transit the reef crest, or they may propagate unbroken until secondary wave crests are formed. The degree of wave transformation is highly dependent on water depth at the reef crest and incident wave characteristics.

Reef crest experiments were conducted on a rather discontinuous linear reef approximately 150 m from the northwest shoreline of Great Corn Island, Nicaragua. Wave sensors placed at the same depth (2 m) in the water column seaward and lagoonward of the reef crest (Fig. 1) were used to evaluate wave modification and energy loss as incident waves intersected the reef and propagated across it to the backreef lagoon. Forereef and backreef wave spectra (Fig. 2) derived from 20-min wave records collected at high tide describe a 68% energy loss as a result of wave breaking at the crest. Although the breaking process is not explained well by hydrodynamic theory, the reduction of wave height across the reef crest induced by breaking and wave reformation can be empirically described. Suhayda and Roberts (1977) show that data from Nakamura et al. (1966), as well as the Nicaragua experiments, can be used to establish an

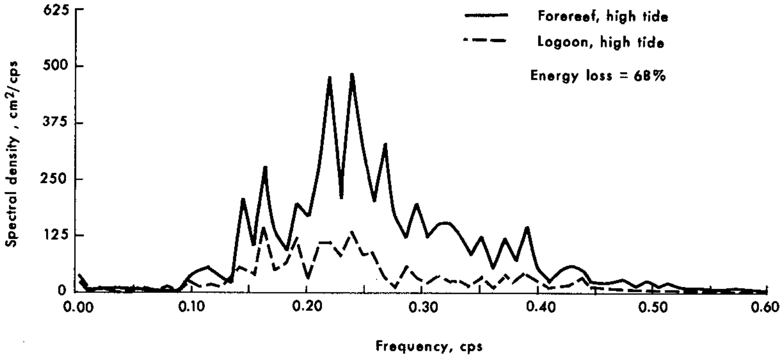

Figure 2. Comparison of forereef and backreef wave spectra derived from data collected at high tide. Interaction between incoming waves and the reef crest results in an energy loss of 68%.

expression for wave height H at the point of reforming. This expression is given by:

$$H = H_o \, (1-0.8^{e^{-0.6 \, d/H_o}}), \; H_o > 0$$

where H_o is the wave height near the breakpoint and d is the mean water depth at the reef crest. The range of water depths for which the formula is valid is d/H_o from zero to about 5. This expression indicates that when $d/H_o = 0$ wave heights in the lagoon will be about 20% of the wave heights outside the reef. Actual field measurements show that the heights of lagoon waves are closer to 30% of waves outside the reef. These estimates assume a narrow reef crest, which is generally the case in Caribbean settings.

As water depth over the reef crest declines during falling tide, the process of wave breaking becomes more intense. Energy loss associated with these conditions is accelerated. Forereef and backreef wave spectra derived from low-tide data sets indicate that approximately 10% more energy is lost through reef-crest/wave interactions at low tide than at high tide (Fig. 3). These values, derived from a discontinuous reef, are conservative compared with similar data sets collected from a continuous linear system (St. Croix), where a 92% energy loss was recorded during high tide and 97% at low tide (Fig. 4). Although a 77% energy loss is indicated in the Nicaragua low-tide data, the dominant incoming wave period (about 6 sec) is present as the highest energy peak of the backreef spectrum. Leakage of energy around the flanks of the discontinuous reef may be partially responsible for this relationship, in which case the estimate of energy loss resulting from wave breaking is conservative. In both the continuous and the discontinuous reef-crest data sets, only the

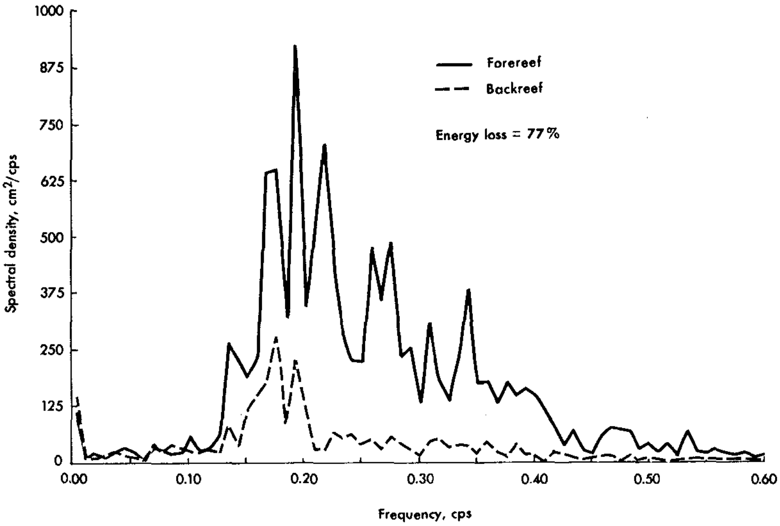

Figure 3. Comparison of forereef and backreef wave spectra derived from data collected at low tide. A 77% energy loss is described due to interaction between the reef crest and incoming waves.

low-frequency peaks of the forereef spectra persist in the backreef records. Shape of the backreef wave spectrum is important because wave steepness (wave height/wavelength) has an important effect on sediment transport and shoreline beach stability (Hayami, 1958). It therefore follows that reef-crest morphology exerts a critical influence on the characteristics of waves impacting the backreef shoreline.

Surprisingly strong but short-lived across-the-reef currents are associated with breaking waves. As waves break on the reef crest, water is driven into the backreef by surge currents. Under typical 4-6-sec input waves with heights of approximately 45 cm, shoreward-directed crest-normal currents displayed average velocities of between 10 and 20 cm/sec. Intensity of energy transformation associated with the wave-breaking process and current velocities that result varies with tide, as can be clearly seen in the wave spectra of Figures 2, 3, and 4 and the averaged reef-crest currents shown in Figure 5. The current data show that variations about the mean speed of up to 50% can occur on time scales of 1-2 min. Although the averaged reef-crest currents seem quite low, actual instantaneous measurements show that the effect of each wave transiting the reef crest produces surge currents with maximum measured speeds as high as 80 cm/sec. These periodic and short-lived currents have durations of only a few seconds (Fig. 6). During times when wave breaking at the reef crest is most intense (low tide), surge currents display the highest range of velocities. This trend was also true of reef-parallel currents monitored in the

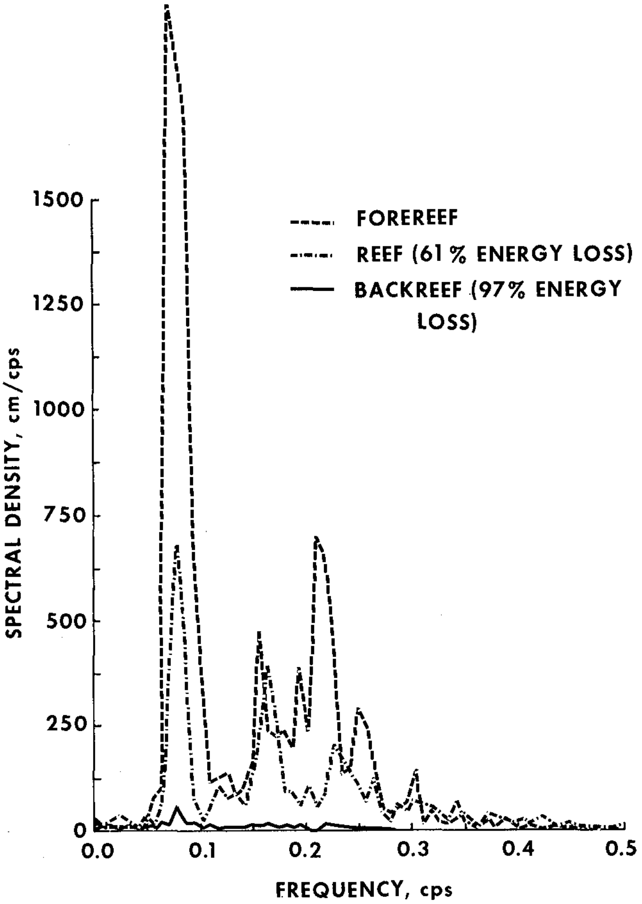

Figure 4. Comparison of forereef, reef crest, and backreef spectra derived from wave data collected at low tide from a continuous linear reef separating Great Pond Bay, along the south coast of St. Croix, from the forereef shelf. The reef crest spectrum is uncorrected for sensor depth and thereby represents a very conservative estimate of the energy loss.

immediate backreef (Fig. 1). Although backreef current speeds averaged 30-40% less than simultaneous reef-crest values, speeds at high tide were about 30% lower than low-tide values in the discontinuous reef example. As

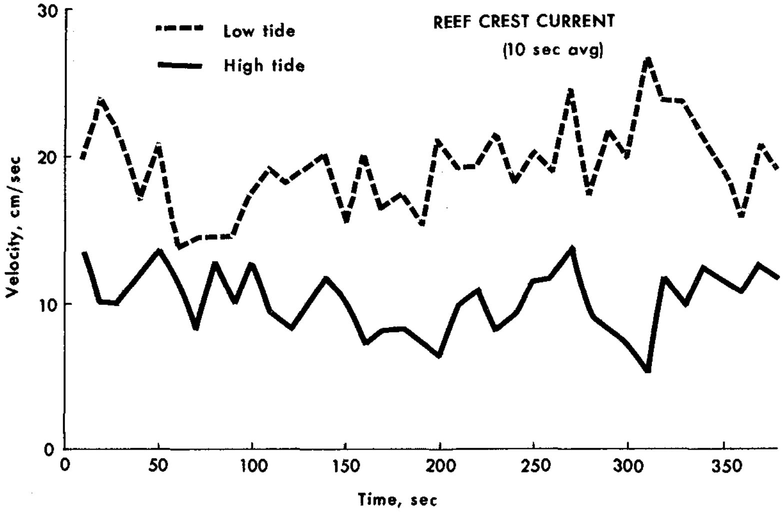

Figure 5. Shoreward-directed reef crest current at high tide and low tide. Current velocities represent values derived from 10-sec averages.

average velocity changed, currents directly behind the reef changed direction. These currents generally described lagoon filling during rising tide and draining of the lagoon as the tide fell.

Lagoon Processes

Shallow backreef lagoons that are fronted by a continuous linear reef are generally very homogeneous water bodies with regard to both density and current structure. Currents near the reef are primarily the results of mass transport of water associated with the previously described process of wave breaking at the reef crest. General lagoon circulation is commonly forced by a combination of momentum provided by the wind and mass transport across the reef. Water input may be associated with the combined effects of waves and tide, but field studies suggest that wave input is the dominant process (von Arx, 1954; Inman et al., 1963; Storr, 1964; Roberts et al., 1975; Suhayda and Roberts, 1977). However, Kjerfve (personal communication) reports that water in the backreef lagoon at Carrie Bow Cay (British Honduras) is primarily wind driven and does not have an obvious tidal signature.

Drifting-drogue studies, current-meter profiles, and in situ recording-current-meter data from Great Pond Bay, along the south coast of St. Croix, suggest that mean flow velocities under typical trade-wind conditions (5-7 m/sec) are in the range of 10-25 cm/sec (Roberts et al., 1980). The Great Pond Bay system is similar in size and shape to other backreef lagoons in the Caribbean reef province, as well as other carbonate

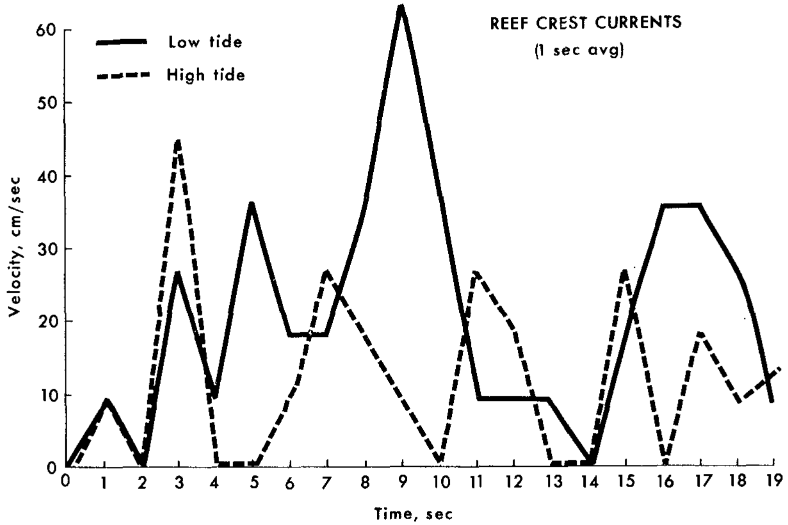

Figure 6. Crest-normal surge currents associated with waves transiting the reef crest. Current velocities represent values derived from 1-sec averages.

coasts of the world. Drogue tracks in Figure 7 illustrate that flow through the lagoon is directed slightly toward the northwest. Near the coast continuity of flow forces currents to become more parallel to the shoreline. As water is forced through the tidal pass at the west end of the lagoon, velocities increase. Water involved in this flow enters Great Pond Bay through a small tidal pass at the east end of the lagoon as well as across the continuous reef that separates the lagoon from the open shelf. During the Great Pond Bay studies it was observed in both the drogue and the current-meter data that the passage of squalls greatly increased flow toward and through the tidal passes, as wave state in the lagoon increased significantly. These events induced greater variability in current velocities than tidal fluctuations. Brief but frequent squalls may be very important in transporting sediment through these shallow environments.

Studies conducted on Grand Cayman Island (Roberts et al., 1975; Suhayda and Roberts, 1977; M. E. C. Giglioli, personal communication) indicate that the long-term lagoon circulation pattern is reflected in sediment thickness and facies relationships. Figure 8 illustrates that the eastern region of the lagoon, which is characterized by low current velocities, collects a thick sequence of relatively fine grained sediments. As current velocities increase to the west, toward the opening to the open shelf, sediments tend to coarsen and accumulations become thinner. In the tidal channel throat strong currents remove sediments, leaving

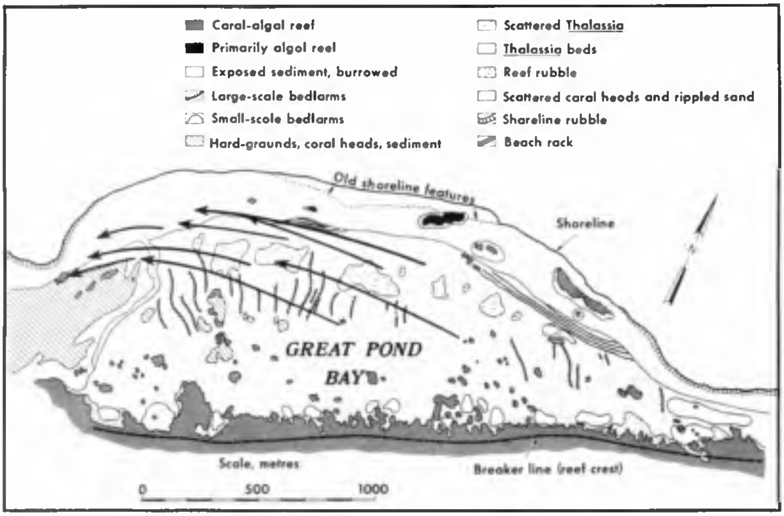

Figure 7. Lagoon circulation under typical easterly wind conditions as determined by drogue tracks (Great Pond Bay, St. Croix). Tracks are superimposed on bottom features. Bottom feature map interpreted from side-scan-sonar data, bottom samples, and diving. Arrows indicate the basic circulation pattern and areas of water input to the system.

the limestone floor of the lagoon exposed. Only beach-related sediments near the coast and coarse sand and rubble directly behind the reef are preserved at the western end of the lagoon.

The geometry of Great Pond Bay (St. Croix) is similar to that of South Sound (Grand Cayman), with the exception of an opening at the upwind end connecting it with an adjacent lagoon. Both systems are characterized by a continuous linear reef which separates a shallow lagoon from the open shelf. Side-scan sonar coverage of Great Pond Bay permitted a detailed bottom-features map to be prepared (Fig. 7). As in the case of South Sound (Grand Gayman), sediments have been generally scoured from the downwind opening tidal pass between the lagoon and the shelf. Because of the connection with an adjacent lagoon, coarse sediments are transported to Great Pond Bay and a well-defined carbonate mud facies, which is commonly present at the upwind end of the system, does not develop. Small-scale bedform distribution indicates active exchange between the adjacent lagoons, as well as preferential sites along the linear reef, where waves and wave-induced currents transit the reef crest to interact actively with lagoon sediments. These areas are obviously key pathways for input of shelf water and sediment into the relatively low energy setting of the backreef. They are also areas where these relatively coarse sediments derived from degradation of the reef are transported toward the lagoon

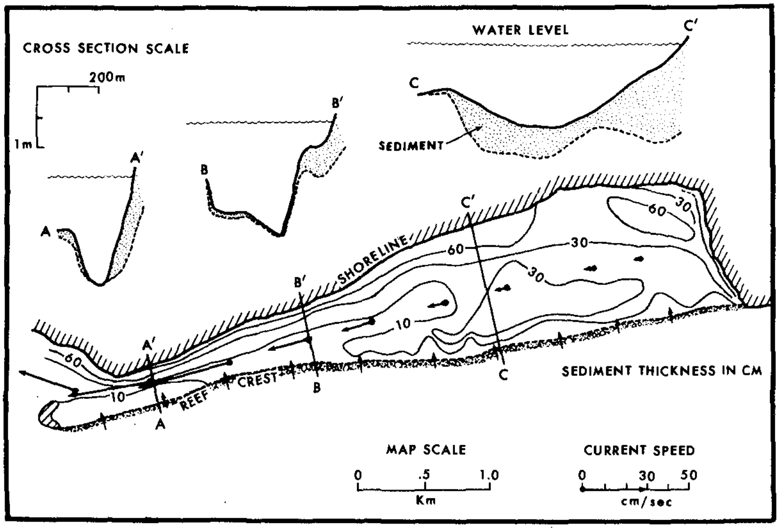

Figure 8. Sediment thickness and facies relationships in South Sound along the southwestern coast of Grand Cayman Island, West Indies. Arrows indicate the direction and relative velocities of the lagoon axis current as determined by Roberts et al. (1972). Note the correspondence of thick sediment accumulation with regions of low speed and sediment-free lagoon floor, where currents are maximized.

interior. Larger, low-amplitude and long-wavelength bedforms were found roughly down the axis of the lagoon (Fig. 7). Since these features were obviously inactive during average conditions, they probably represent remnant bedforms generated by a hurricane that passed near the island several weeks prior to collection of the side-scan data. The presence of such bedforms confirms active sediment transport from east to west nearly down the lagoon axis. Although bioturbation had destroyed much of the bedform morphology, the averaging effect of side-scan sonar data permitted discrimination of these features over higher frequency bottom-roughness elements.

Sediment Transport Routes and Sinks

Sediment storage sites and transport routes for two types of reef-lagoon systems are being considered in this study. One type is composed of linear but discontinuous reef elements (Nicaragua example), while the other has a continuous linear reef between the backreef lagoon and the open shelf (Grand Cayman and St. Croix examples). In both cases the reef functions as a major source of sediments for the backreef lagoon and a low-pass filter for incident waves from the open shelf.

In the discontinuous example numerous large breaks between reef elements allow the transfer of open shelf waves through the lagoon to the backreef shoreline. Refraction and diffraction effects under these conditions generally result in a highly irregular backreef shoreline consisting of numerous cuspate coastal features with dimensions related primarily to the width of the lagoon and spacings of openings in the reef trend. Breaks in the general reef trend also function as sites for tidal exchange of lagoon and shelf water. However, mass transport across the reefs, associated with wave breaking, is important as a sediment transport process as well as a source of water to drive backreef circulation. As schematically shown in Figure 9, sand bodies associated with the dis-

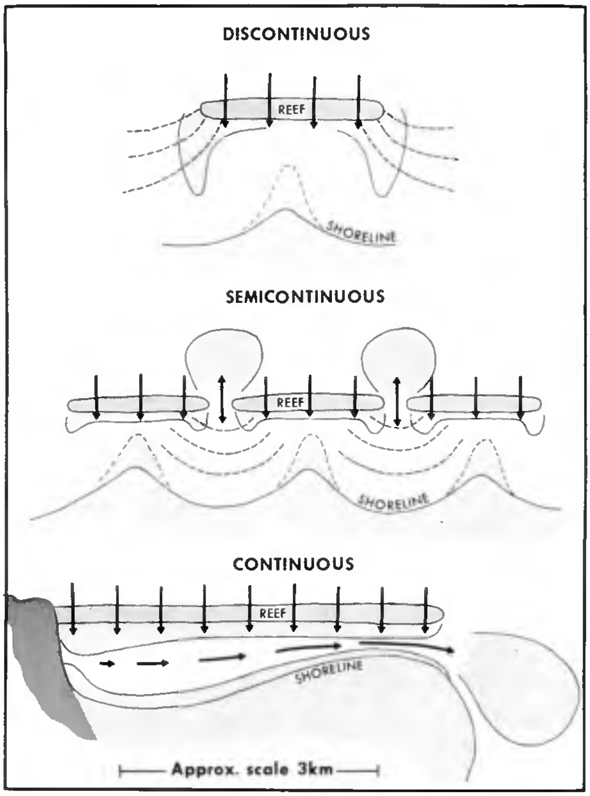

Figure 9. Schematic representation of sediment sinks and transport routes in discontinuous, semicontinuous, and continuous reef-lagoon systems.

continuous reef elements are generally oriented at high angles to the reef trend and tend to form horns attached to the ends of the reef at the tidal channel margins. The combined effects of tidal exchange and wave refraction/diffraction are responsible for shaping these sediment bodies. Sediments are also commonly stored in backreef shoreline cusps, which arise from energy gradients along the coast set up by wave refraction through the major breaks between reef elements. Sediments accumulate in cuspate shoreline features, which prograde toward the offshore reef elements. If the distance between reef elements and the shoreline is not great, cusps may prograde toward the reef until attached. Such depositional features commonly form in response to manmade offshore breakwaters.

Continuous reef systems store sand in the backreef lagoon in sediment bodies that tend to parallel the reef trend (Fig. 9). These coarse sediments are composed of debris which originates from the reef and is transported to the lee of this structure by across-the-reef currents previously described. Constituent particles decrease in grain size in a lagoonward direction, but there is generally a very distinct transition between the coarse reef-derived material and the finer lagoonal facies. Lagoon interiors commonly are floored with abundant sediment-producing calcareous green algae. The disintegration products of many members of the algal community are 2-4-micron needles of aragonite, which accumulate to form a carbonate mud. Frequently it is only at the backreef shoreline that there is enough energy to hydraulically sort the sediments so that coarse particles are concentrated. Under these conditions a narrow sandy beach develops. The beach is commonly oriented roughly parallel to the continuous reef trend that separates the lagoon from open-shelf conditions.

As discussed with regard to lagoon circulation, strong currents can develop in the downwave ends of these systems (Fig. 8). Such flow is driven by both the wind and constant input of water to the lagoon by wave overwash at the reef crest. These currents provide the driving force for exporting reef-derived and lagoonal sediments to the adjacent forereef shelf. Actual sediment budgets for systems of this description have never been established. However, geomorphic and sedimentologic evidence suggests that large volumes of sediment are transported from reef-lagoon systems to deeper sedimentary environments on the shelf. Side-scan sonar data from St. Croix (Fig. 7) suggest that during intense storms large-scale bedform migration can be an active form of sediment transport. During average conditions the intense burrowing activity of shrimp and polychaete worms may be important to the sediment transport process. Sediment mounding, which is typical of the two groups of organisms, requires that both coarse and fine sediments be expelled from a burrow into the water column. These particles may be transported downcurrent by the mean drift in the lagoon. The intensity of burrowing in these backreef environments suggests that significant quantities of sediment can be moved by this mechanism.

Processes responsible for transporting sediments from the lagoon to the open shelf and beyond have not been studied in detail. However, sedimentological evidence (Moore et al., 1976; Land and Moore, 1977; James, 1978) shows that sediments generated in shallow backreef environments are transported to the forereef shelf. A significant proportion of these sediments are conducted across the shelf to adjacent deepwater slope and basinal settings. Figure 10 shows the sediment transport paths and sinks in a lagoon-reef-shelf complex along the southwestern flank of Grand Cayman Island. Both physical process measurements and geological data from several field projects were integrated to produce the sediment transport model described in this figure. Although most sediment produced by the shallow reef is either trapped in the reef matrix or transported toward the lagoon, some sediments produced on the reef front are transported seaward to deeper parts of the shelf. It is common that a sediment sink develops on the lower forereef shelf behind an actively growing shelf-margin reef. As shown by Roberts et al. (1975), the dramatic break in slope at the seaward edge of many reef-dominated shelves is a focal point for strong tidal exchange. Shelf-margin reefs respond to the energy expenditure at this point along the shelf profile by developing into flourishing sill-like structures that impound sediment in their lee. This deep-shelf sediment sink is represented in Figure 10 by a tabular sand body paralleling the shelf edge. High-resolution seismic data suggest that maximum thicknesses of Holocene sediments may be on the order of 20 m in the Grand Cayman example.

Side-scan sonar data indicate that shelf-margin reef morphology is a key to interpreting significant offshelf sediment transport routes. In regions of the shelf where the shelf-margin reef has coalesced to form a coherent ridge, sediments impounded in the lee of this structure can be transported off the shelf only through narrow grooves (Fig. 11A). These grooves are active transport routes (Meaney, 1973), but only limited amounts of sediment can be fluxed to the slope and possibly the adjacent basin by this means. However, around islands there are preferential sites

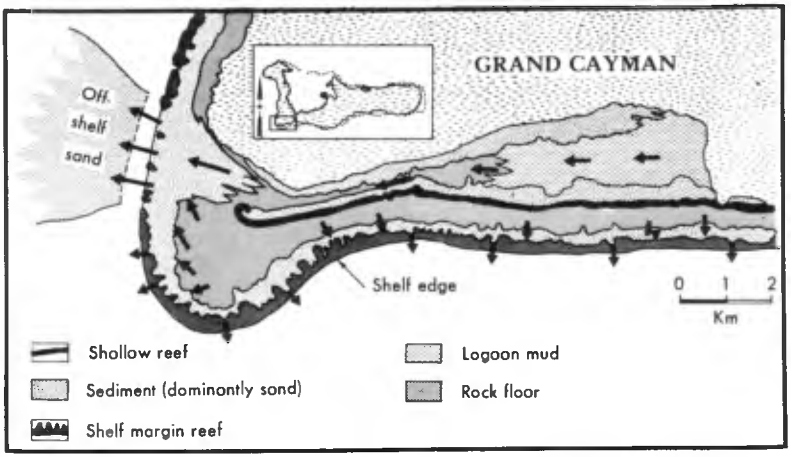

Figure 10. Sediment transport routes and sinks associated with South Sound and the adjacent shelf, Grand Cayman Island. Arrows indicate sediment transport directions.

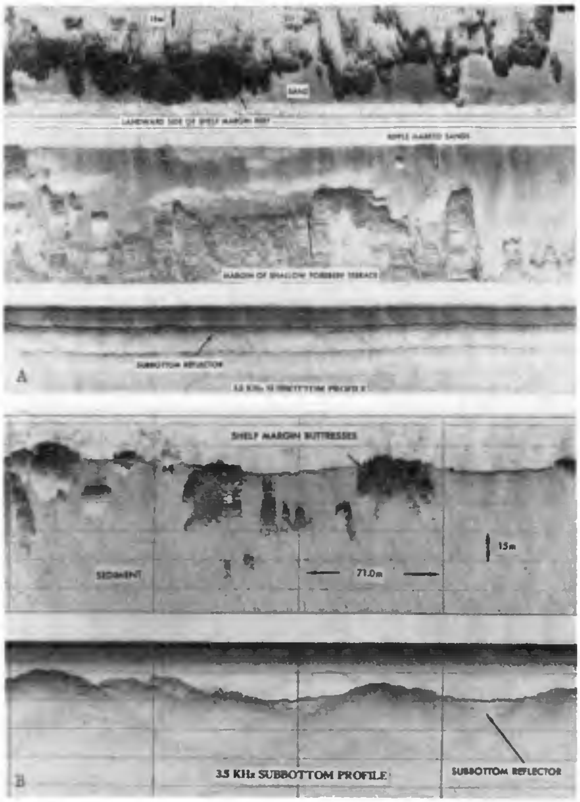

Figure 11. A, side-scan sonograph of lower forereef shelf, Grand Cayman Island, illustrating a well-developed shelf margin reef with only narrow grooves through it for off-shelf sediment transport. The shelf margin reef has relief of 3-4 m above the adjacent sediment plain. Seismic profile shows a reflection of the sediment plain at a depth of 5 m.

B, side-scan sonograph (only one channel) showing broken shelf-margin reef morphology with wide channels for offshelf transport of sediments. This broad area of sediment accumulation is opposite the downcurrent opening to South Sound (see Fig. 10).

for sediments to accumulate on the shelf (Murray et al., 1977). In the Grand Cayman example, an island in a strong unidirectional drift and trade-wind setting, the major sediment accumulation zones are at the southwest and northwest flanks. The site at the southwest flank, as shown in Figure 10, is also opposite the downcurrent end of the South Sound reef-lagoon system. Shelf-margin reef morphology at this location (Fig. 11B) describes a broken reef trend with wide channels for the offshelf movement of sediments. This type of reef morphology implies that sediments have been supplied in abundance to this site for a long period of time; that is, the substrate for shelf-edge reef building has been partially eliminated by the unstable movement of sediments over the shelf edge to the slope and basin environments. Once sediments reach depositional sites on the lower forereef shelf, they are nonrenewable to the coast.

Conclusions

Field studies conducted on the Caribbean islands of Crand Cayman, Great Corn (Nicaragua), and St. Croix have provided a data base from which the magnitudes and variations of physical processes as well as the flux of sediment through lagoon-reef-shelf systems can be better interpreted. The following conclusions can be made from these studies.

1. Wave breaking on the reef crest creates strong reef-normal surge currents, 50-80 cm/sec, with durations of 2-6 sec under normal trade-wind wave conditions. Sediments larger than the sand sizes are easily transported lagoonward by these periodic current bursts.

2. Estimates of forereef to backreef wave energy loss from the breaking process were in the range of 70-80% for discontinuous reefs and up to 97% for continuous examples. Intensity of the breaking process varied with tide. Wave energy loss between the forereef and backreef was greatest at low tide. Surge current velocities were maximized at this time. Across-the-reef currents were always directed lagoonward and did not change direction with tide.

3. Flow in shallow backreef lagoons is driven largely by water introduced to the system by across-the-reef currents. Long, unbroken (continuous) reefs tend to develop near axial currents that roughly parallel the reef trend.

4. Migratory bedforms in the lagoon environment, as determined by side-scan sonar, indicate sediment transport during storms. It appears that an interaction between bioturbation and the mean lagoon drift may also be a significant process of sediment transport under ambient conditions, even though data specific to this subject have not been collected.

5. Discontinuous reefs store coarse backreef sediments in sand bodies oriented at high angles to the reef trend. These features are shaped by tidal exchange and wave refraction/diffraction through breaks between reef elements. Cuspate shorelines commonly develop in response to the sheltering effects of discontinuous reefs.

6. Backreef sand bodies associated with continuous reefs tend to parallel the reef trend.

7. Lagoon sediments are transported through tidal passes to the forereef shelf, where sediment sinks commonly occur behind an actively growing shelf-margin reef. These sediments are nonrenewable to the coast. Some are transported through shelf-edge grooves and channels to deeper slope and basinal environments. Morphology of the shelf-margin reef is a clue to important avenues for offshelf sediment transport.

Acknowledgments

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