Physical Processes as Agents of Sediment Transport in Carbonate Systems; Examples From St. Croix, U.S.V.I.

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INTRODUCTION

The inset to Figure 1 clearly indicates the dominance of the northeasterly trade winds on the island of St. Croix, and by extension, throughout the Caribbean region. Not surprisingly, this nearly unidirectional wind field is directly reflected in local wind-driven wave power-variations around the island. Furthermore, while waves generated outside local conditions to the west are severely fetch limited, to the east the island is open to mid-Atlantic swells. As a result, total wave power is very asymmetrically distributed around St. Croix. Generally, the northern and eastern coastlines are "windward" whereas the southern and western coastlines are "leeward."

Linear and quasilinear reefs and their enclosed lagoons situated close to island or continental landmasses comprise coastal cells common to many carbonate depositional systems. In the Caribbean province, these reefs tend to be narrow and the lagoons shallow, generally less than 10-m deep. Although relatively narrow, the reefs function as a renewable source of skeletal sediment, deposited not only in the reef interior, but also in the wider backreef lagoon and seaward shelf. The sedimentary processes involved in sediment transport are governed both directly and indirectly by the physical forcing functions acting on the reef, processes that also condition many of the chemical and biological fluxes through the reef system (Roberts *et al.*, 1975).

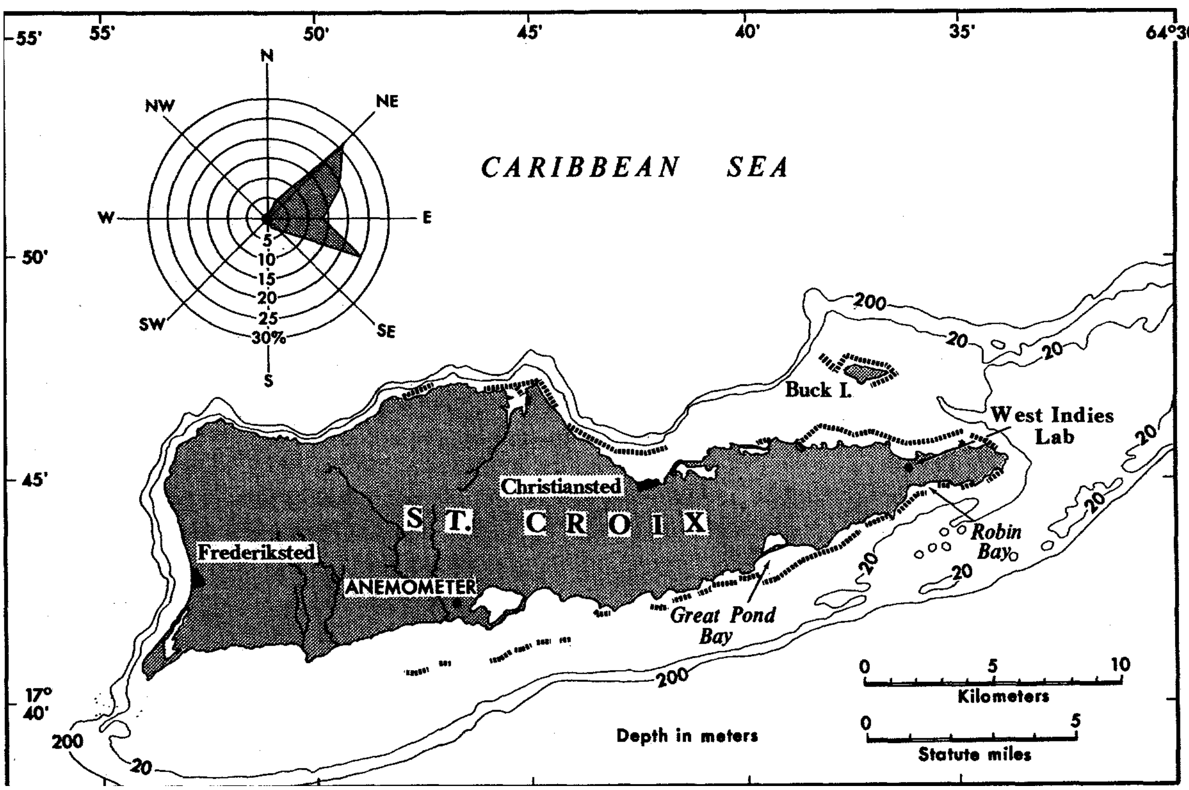

Figure 1. Index map of St. Croix, US. Virgin Islands, and the Great Pond Bay study site. Wind frequency data are summarized in the inset.

Following the pioneer work of Munk and Sargent (1954) and von Arx (1954) on the physical processes and circulation systems of Pacific reef/lagoon systems, Roberts (1974, 1980), Roberts *et al.* (1975, 1977), Roberts and Suhayda (1983), Murray *et al.*, (1982), and others have deployed instrumentation in Caribbean reef systems in order to define the physical conditions under which these environments function (Fig. 2). These methods have included the use of specially designed tide gauges and *in situ* recording current meters, along with drogue tracking and dye drops to ascertain the spatial variability of flows in carbonate systems. Waves have been measured with field-adapted absolute pressure sensors. These hydrodynamic data have been interpreted within the framework of meteorological parameters such as wind speed and direction.

This paper offers a general discussion of physical processes as important agents of carbonate sedimentation. Most of the examples have been chosen from our work on St. Croix over the past decade, although information is also presented from other Caribbean sites. Other examples can be found in the "Modern Carbonates" article preceding this paper. In addition to providing site-specific information for the island of St. Croix, the following pages will hopefully illustrate the importance of physical processes in carbonate systems and stimulate a greater interest in this often-neglected aspect of carbonate sedimentology.

WAVES

Across-the-reef currents and backreef lagoon circulation are, to a large extent, driven by waves breaking on the reef crest (Inman *et al.*, 1963; Suhayda and Roberts, 1977). As they aproach the reef crest, shoaling waves increase in height and steepness until the breaking point, when wave energy is rapidly transformed into strong, landward-directed surge currents, turbulence, and other minor residual sinks. Input wave heights are significantly reduced and high-frequency waves are produced as waves propagate beyond the reef crest. The degree to which wave energy is modified by this process depends on overall reef geometry, width of the shallow reef flat, uniformity of depth along and across the reef, and most importantly, the water depth at the reef crest. Consequently, in the microtidal Caribbean, the process of wave breaking intensifies as water depth over the reef crest declines during the dropping tide. At lower tidal levels, energy loss is accelerated and wave conditions in the backreef are significantly reduced. Figure 3 presents a forereef, reef crest, and backreef comparison of wave spectra from Great Pond Bay. The major mechanisms for the attenuation of incomming waves are frictional effects, and more importantly, breaking activity at the reef crest. A 97% energy loss in incident wave energy between the forereef and backreef during low tide compares with a 92% loss at high tide (Roberts, 1980). Roberts and Suhayda

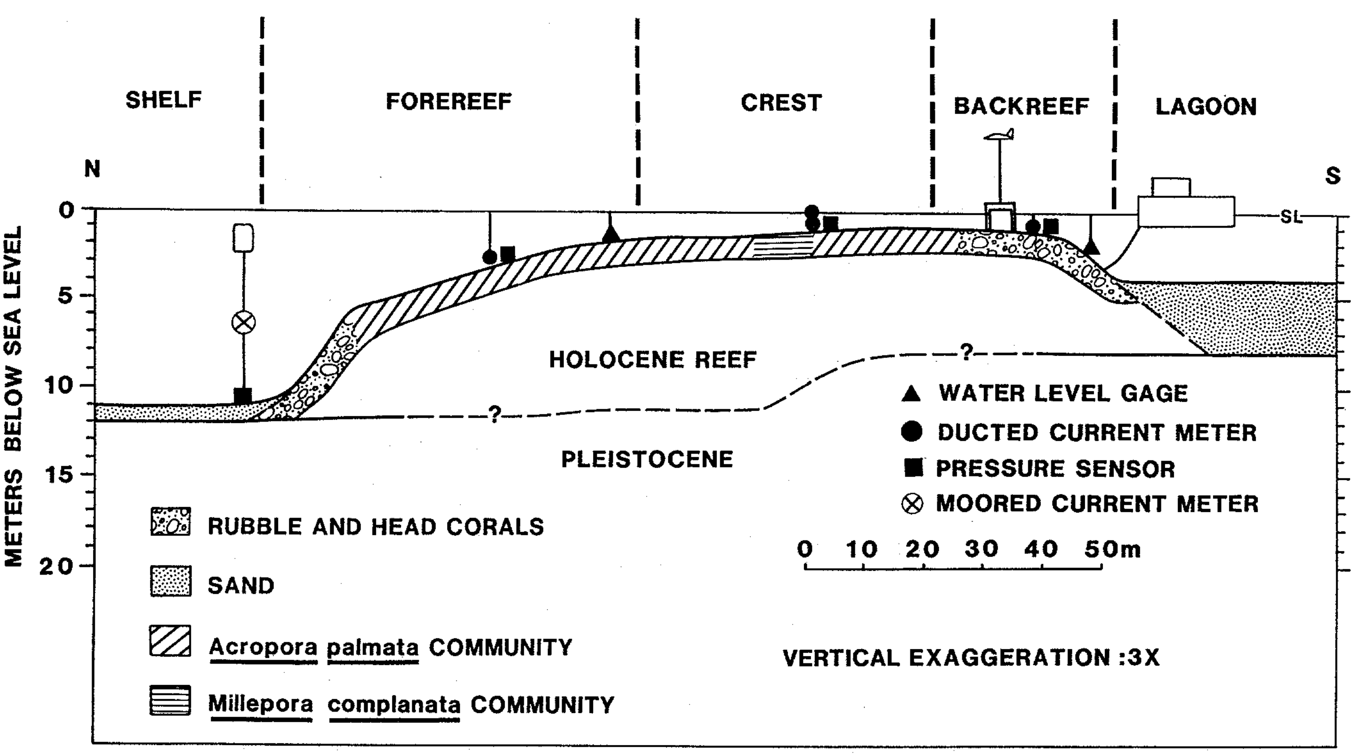

***Figure 2**. Typical **instrument-deployment** scheme used in the study of physical processes in reef systems at both Great **Pond** Bay and Tague Bay. This profile is from Tague Reef*

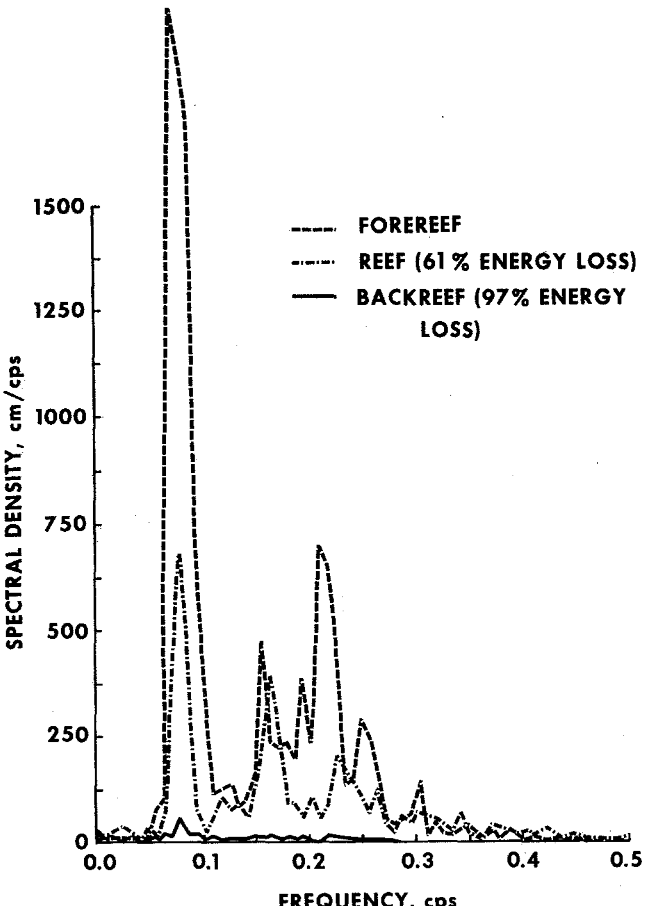

Figure 3. *Comparison of forereef, reef crest, and backreef spectra derived from wave data collected at low tide from a continuous linear reef separating Great Pond Bay, along the south coast of St. Croix, from the forereef shelf. The reef-crest spectrum is uncorrected for sensor depth and thereby represents a very conservative estimate of the energy loss.*

(1983) compare these values from Great Pond Bay (a continuous liner reef system) with similar data from Great Corn Island, Nicaragua (a discontinuous linear reef system). Discontinuity of the Nicaraguan reefs reduces their efficiency as a wave energy baffle to 68% energy loss at high tide and 77% energy loss at low tide.

Although shoaling trade-wind waves and wave-induced currents dominate the total energy expenditure within the reef complex, the physical processes occurring on the reef actually consist of many different scales and intensities of motion. Particularly important components of the physical process suite are low-frequency water-level changes and currents whose periods are in the range between 30 sec and about 30 min (e.g., Fig. 4). Such infragravity waves, known to be associated with surf beat, tsunamis, shelf seiche, and internal waves produce small but significant variations in sea level. Because they have long wavelengths and very low height to wavelength ratios, they are highly reflected at the shoreline and can produce standing waves. Such waves can spatially modulate flow across the reef.

The potential importance of low-frequency currents is illustrated by considering the distance a water particle would move during one cycle of a wave. Displacement of the particle is given by:

$$D=U_m T/\pi \qquad (1)$$

where D is displacement, Um is the mean flow velocity within the wave, and T is the wave period. For a 14-minute wave, the particle moves about 15 m in 4 m of water and about 40 m in 1 m of water. This relationship compares with a typical water-particle displacement of only 1 m for normal wind waves (Roberts and Suhayda, 1983).

WAVE-CURRENT INTERACTIONS

Reefs are able to supply sediment to depositional environments both lagoonward and seaward largely because the shallow reef is the critical zone for intense wave-related processes. The shallow reef depths (commonly about 1 m over the crest of reefs fringing St.

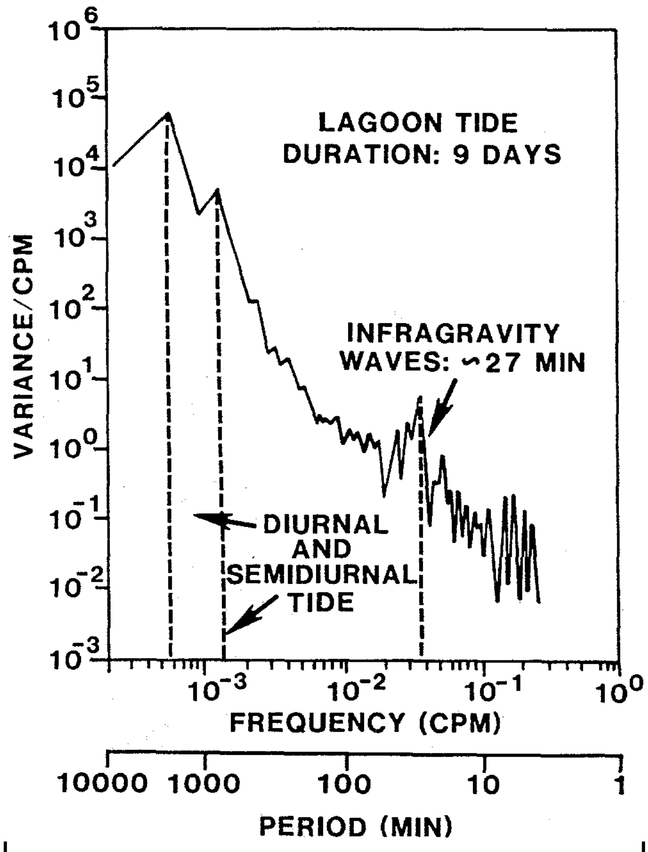

Figure 4. *Spectra of 9-day pressure gauge record from Tague Bay, near the reef, illustrating frequencies of important water-level changes. Note the well-defined tidal peaks and the infragravity peak at 27 min.*

Croix and many other Caribbean landmasses) induce extreme modification of incoming waves. Breaking may be continuous during reef transit, or waves may propagate unbroken until secondary wave crests are formed in the lagoon. The degree of wave transformation is highly dependent on water depth at the reef crest and incident wave characteristics.

The importance of overall reef geometry in attenuating incident wave power (continuous reef from St. Croix and Grand Cayman as compared with discontinuous Nicaraguan reefs) is attributed to refraction and diffraction around the ends of the discontinuous reefs (Roberts, 1980). In both the continuous and discontinuous examples, only the low-frequency peaks of the forereef spectra persist in the backreef, indicating that the reef more efficiently "filters" high-frequency waves.

Under reef-normal currents typical of trade-wind conditions at Great Pond Bay, averaged velocities do tic appear sufficient to be capable of efficient coarse-sedin en. transportation (Fig. 5). However, when mean current data are decomposed into increments small enough to permit discrimination of speeds associated with individual waves, short-lived but strong "surge currents" are revealed (Fig. 6). Although these pulses are brief, they occur frequently and are quite capable of lagoonward transport of reef sediments. Storm events are generally invoked to account for the movements of sand-sized and coarser particles, but Figure 6 suggests that normal trade-wind-forced reef-crest processes are sufficient to transport coarse sediment into the immediate backreef.

LAGOONAL CIRCULATION AND SEDIMENT TRANSPORT

Shallow backreef lagoons like Great Pond Bay, fronted by a continuous linear reef, are generally very well-mixed water bodies, in terms of density, and are relatively simple in terms of current structure. Currents near the reef are primarily the result of mass transport of water associated with the previously described processes of wave breaking at the reef crest. General lagoon circulation is commonly forced by some 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 tides, but empirical work suggests that wave input is the dominant process (von Arx, 1954; Inman *et al.*, 1963; Storr, 1964; Roberts *et al.*, 1975; Suhayda and Roberts, 1977).

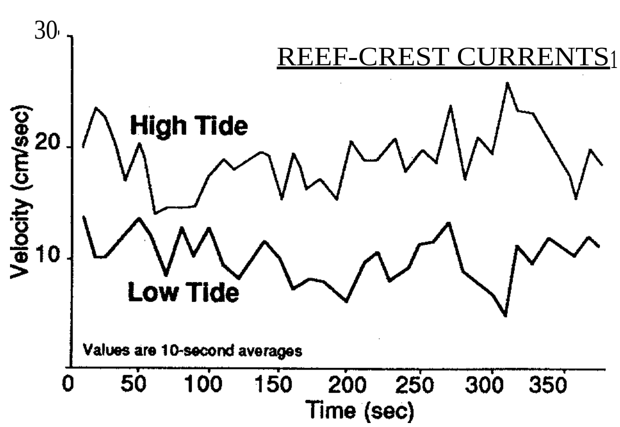

Figure S. Shoreward-directed reef-crest currents at high tide and low tide. Current velocities represent values derived from 10-sec averages. Data collected from Nicaragua.

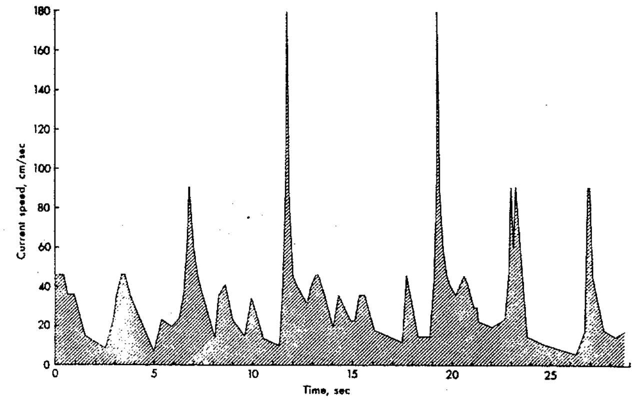

Figure 6. Unidirectional surge currents flowing in a crest-normal direcion toward the lagoon at low tide. Data are plotted directly from ducted current meter analog readout. Note the strong instantaneous currents.

Drifting-drogue studies, current-meter profiles, and data from *in situ* recording current meters from Great Pond Bay suggest that the 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). These data suggest rapid renewal of water, as a 10-cm/sec current results in a transit time of about 8 h for a water parcel through the length of the 3-km bay (Roberts *et al.*, 1981).

Drogue tracks in Figure 6 show flow through the lagoon to be directed slightly northwestward. Near the coast, continuity forces the currents to become more parallel to the shoreline. As source water from the small tidal pass at the east end of the lagoon (about 25% of total input), together with that contributed across the continuous reef (about 75% total input), is forced through the tidal pass at the west end of the lagoon, velocities increase. During Great Pond Bay studies, both drogue and current meters recorded a greatly increased flow through the tidal passes during the passage of squalls. Wave state in the lagoon increased significantly, and these events induced greater variability in current velocities than did tidal fluctuations. These short-lived, high-frequency squalls, which have yet to be studied in detail, may be very important in transporting sediment though these shallow environments.

Side-scan sonar records from the floor of Great Pond Bay illustrate that sediments have been generally scoured from the downwind-opening tidal pass between the lagoon and the shelf (Fig. 6). Because of the connection with the adjacent lagoon to the east, coarse sediments are imported 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 (Roberts, 1980). 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 with lagoon sediments. These mark the key routes of lagoonward transport for coarse-grained, reef-derived sediments, and help confirm the capacity of everyday reef-crest physical processes for removing sediments from the reef crest (Stoddart, 1969; Roberts, 1974). Larger bedforms axial to the lagoon (Fig. 7) were inactive during average conditions and probably represent remnants from a hurricane that passed near the island several weeks prior to the sonar survey (Roberts, 1980). These relict bedforms confirm sediment transport from east to west nearly down the lagoon axis.

Whereas large atoll lagoons have current regimes dominated by wind stress (von Arx, 1954), the narrow, shallow lagoonal systems discussed above are generally characterized by weak ambient currents incapable of moving sand-sized sediment (with the exception of well-defined tidal passes). Sediment transport by physical processes alone appears to be significant only during storms, and Figure 7 suggests, bedform migration as a major mechanism. However, the hummocky topography of lagoon floors reveals intense biological activity.

Volcano-shaped mounds indicate the presence of subsurface bioturbators such as holothuroids (Rhoads and Young, 1971), enteropneusts, polychaetes, and most importantly, shrimp (Shinn, 1968; Aller and Dodge, 1974; Clifton and Hunter, 1973). Of prime importance in backreef lagoons is the highly industrious excavator *Callianassa,* a Thalassinid shrimp. In Great Pond Bay, mound densities may exceed 10 per square meter and mound heights may reach 30 cm (Roberts *et al.,* 1981). Sediment processed in intricate burrows is ejected 5-10 cm into the water column through an opening at the mound top. In the presence of waves and currents, these bioejections can be important transport processes. As the burrowing *Callianassa* ejects sediment, it is advected downdrift by the mean flow regime during settling (Fig. 8).

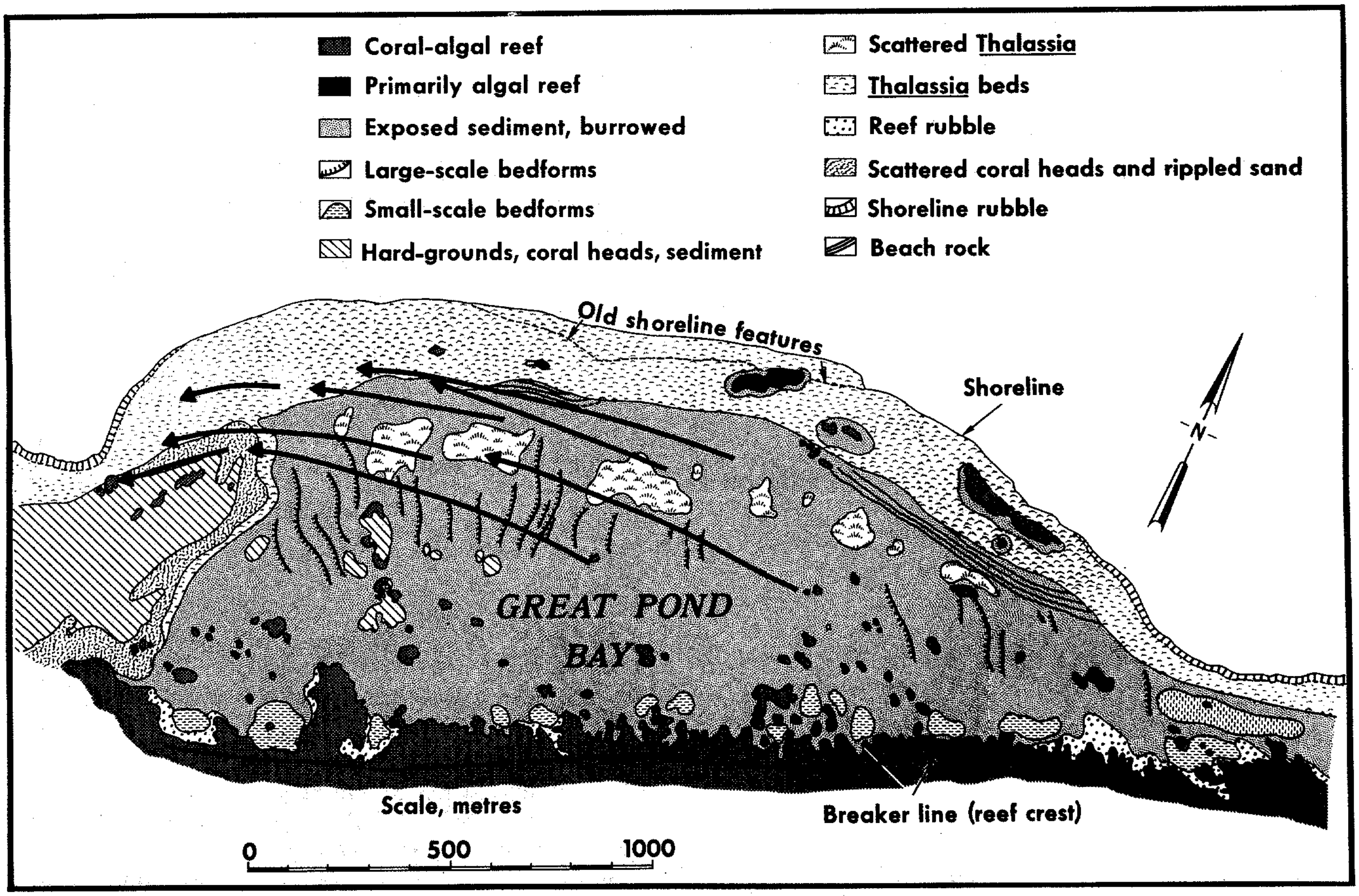

Figure 7. Lagoon circulation under typical easterly wind conditions as determined by drogue tracks (Great Pond Bay, St. Croix). Tracks are superimposed on bottom features. Bottom feature map is interpreted from side-scan-sonar data, bottom samples and diving. Arrows indicate the basic circulation pattern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

Table 1. *Statistics on* Callianassa *mound density, distribution, and sediment ejections for sandy bottom regions and grass beds in Great Pond Bay*

	Sandy Bottom	Grass Beds	Significance
Mound density (per m^2)	6.7 ± 2.4	2.1 ± 1.4	$p < 0.001$
Mound height	13.5 ± 3.3	5.6 ± 4.0	$p < 0.001$
Ejections/mound/hr	23.5 ± 3.5	11.0 ± 1.4	$p < 0.05$
Dry weight sediment ejected/mound/hr	508.2 ± 72.5	397.7 ± 23.5	$p < 0.01$
Mean grain size (u)	2.3 ± 0.2	1.7 ± 0.2	$p < 0.001$
Ejection height (cm)	5.4 ± 0.7	2.5 ± 1.1	$p < 0.05$
Ejection duration (sec)	10.5 ± 2.2	11.2 ± 1.9	ns
TOTAL SEDIMENT PROCESSED (kg/m^2-day)	3.395	0.819	

Callianassa-induced transport was estimated by Roberts *et al.* (1981) in Great Pond Bay under assumed mean-flow conditions: 10 cm/sec to represent flow 1 m off the bottom under ambient conditions, 25 cm/sec under accelerated flow conditions, such as might be expected with strong prolonged winds, and 50 cm/sec under storm conditions. Moreover, total transport catalyzed by the bioturbator through a cross section of the lagoon from reef to shore was estimated (Tables 1 and 2).

Over a sandy bottom substrate, sediment is ejected by *Callianassa* to an average height of 5.4 cm. Spherical particles of diameter 2.32 phi (Table 1) obey a viscous settling law (Inman, 1963). With an effective density of 2.7 g/cm^3, they require 1.3 sec to settle to the bottom. The particle shapes are not spherical, their density is probably less than assumed, and turbulence is ignored; all these factors suggest the particles actually spend longer than 1.3 sec in suspension. The assumed velocity profile near the bottom is logarithmic (Monin and Yaglom, 1971):

$$u_{(z)} = (u^*/c) \ln (z-z_1)/z_o \qquad (2)$$

where $u_{(z)}$ is the velocity at a height z above the bottom, c is von Karman's constant (0.4), u* is the shear velocity, z_1 is a displacement height of the order of the bottom roughness element height, and zo , the roughness length, is approximately 1/30 of the roughness element height, which was taken to be the mean *Callianassa* mound height. Using (2), u* was determined for various flow conditions. The average transport velocity (Table 2) over the 5.4-cm height of sediment ejection was determined by integration of (2). The mean transport rates were determined by multiplying the 3.395 kg/m^2-day of sediment ejected by the average transport velocity and the average settling time. The resulting figures (Table 2) are conservative for the reasons mentioned above.

Shear velocities obtained from (2) were used to estimate bedload transport under the same ambient, accelerated, and storm conditions (method of Sternberg, 1972). Under ambient conditions the critical threshold velocity for 2.32-phi sediment is not attained. It is only marginally attained for accelerated conditions. Under storm conditions, bedload transport is much greater than the transport induced by *Callianassa.* It is not clear whether these estimates are conservative. The mean sediment size on the bottom may be significantly larger that 2.32 phi, the mean size of ejected sediment, thus increasing the transport-threshold velocity. The u* values assumed the presence of mounds; without mounds, u* would be less and so would the sediment transport. Conversely, high-frequency bottom currents associated

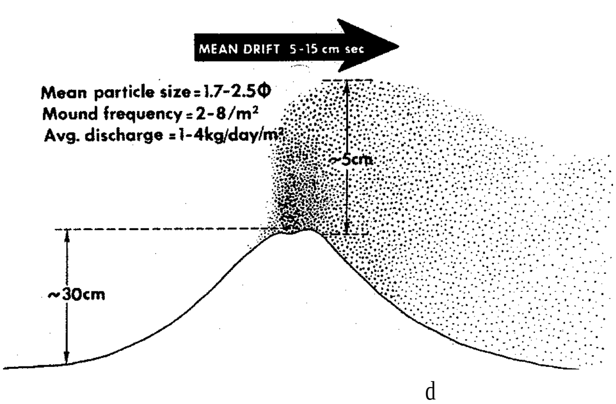

Figure 8. Schematic of Callianassa-enhanced *sediment transport process. Sediments are ejected an average height of 5 cm into a mean drift of 5-15 cm/sec in sandy bottom areas. Particles of mean size travel a distance (d) downdrift.*

Table 2. Sediment transport results

Conditions	Ambient	Accelerated	Storm
Current Velocity			
U_{100} (cm/sec)	10	25	50
Shear Velocity			
u_* (cm/sec)	0.75	1.87	3.74
Avg. Transport			
Velocity (cm/sec)	6	15	30
Transport Rates			
kg/m/day	0.27	0.66	1.32
Total Flux kg/day	216	528	1056
Bedload Only			
kg/m/day	0	0	20-30

with waves would resuspend sediment and increase the bedload transport.

Under ambient wind, wave, and current conditions, 216 kg/day of sand-sized sediment can be fluxed through a section across the central part of Great Pond Bay. No storm conditions were contained in the 2-week current meter record from the lagoon. Reasonable calculations suggest that the lagoon requires more than an hour of strong wind to come to equilibrium with the new wind stress; thus brief squalls will not be of sufficient duration to cause storm currents. Although bedload transport during major storms can be more vigorous, these conditions occur infrequently. *Callianassa-enhanced* transport is the dominant process for advecting sediment under normal and moderately accelerated flow.

Backreef lagoons are generally recognized as low-energy environments and sediment sinks, or at least as sites where sediment transport is minimal, except during storms (Moore *et. al.,* 1976; Land and Moore, 1977). Figure 3 quite clearly shows the backreef lagoon to be a low-energy environment in comparison with the forereef and reef crest. The active bedforms in Figure 6 also show Great Pond Bay to be a major sediment sink, and the relict bedforms in Figure 7 illustrate the importance of infrequent storms in transporting lagoonal sediments. However, by considering the role of biologically catalyzed sediment transport, the potency of everyday processes involved in exporting lagoonal sediment is emphasized. If it were not for the Callianassa-facilitated transport, we might expect Great Pond Bay to be considerably shallower.

ROUTES AND SINKS: REEF GEOMETRY AND PHYSICAL PROCESSES

In the case of both linear-continuous (St. Croix and Grand Cayman examples) and linear-discontinuous geometries (Nicaragua example), 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 case (Fig. 9), 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 spacing of the opening in the reef trend. Breaks in the general reef trend also function as sites for tidal exchange for lagoon and shelf waters. 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 discontinuous 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.

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 that originates from the reef and is transported to the lee of this structure by across-the-reef currents, previously described. Constituent particle sizes decrease in a lagoonward direction, but there is generally a very distinct transition between the coarse-derived material and the finer lagoonal facies. This lagoonal facies is generally an aragonitic mud composed largely of needles in the 2-4-micron range and the disintegration products of abundant calcareous green algae. Frequently it is only at the backreef shoreline that there is enough hydraulic energy (and limited enough bioturbation) to sort the sediments so that coarse particles are concentrated. Under these conditions a narrow, sandy beach develops, commonly oriented roughly parallel to the continuous reef trend.

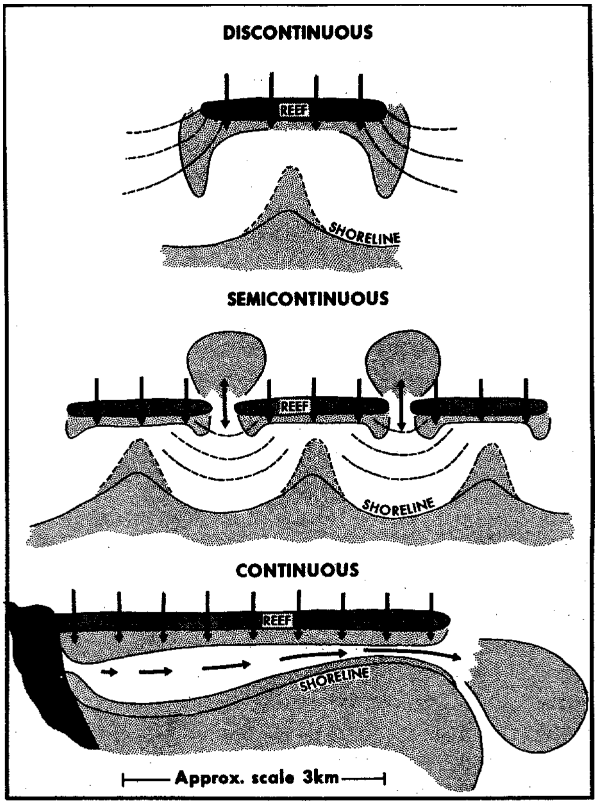

Figure 9. Schematic representation of sediment sinks and transport routes in discontinuous, semicontinuous, and continuous reef-lagoon systems.

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