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ABSTRACT

Long-term sediment-transport measurements made between 1977 and 1981, along with diver observations and oceanographic measurements, indicate the dominance of wave-induced processes in moving reefal detritus off the insular shelf of St. Croix, U.S.V.I. In the shore zone, the longshore transport rate of $0.1 - 1.0 \times 10^6$ m^3/yr is entirely wave-induced. In the nearshore zone, the relative importance of physical, biological and gravitational processes is related to reef presence. In protected lagoons, biological reworking dominates, but no net transport results from this random process. While such non-directional processes induce sediment suspension, the magnitude and direction of the net transport is primarily a function of weaker wave-induced flows, and the settling velocities of the grains. On the open shelf, strong wave-generated oscillatory and unidirectional currents move large quantities of carbonate material offshore, primarily during storms. Open-shelf transport rates up to 4.60 Kg/m · day were measured during storms, compared to 0.03 — 1.19 Kg/m · day during fair weather.

INTRODUCTION

The importance of sedimentation in the reef environment is little contested. Sediments can control reef distribution and growth rate, and can be used to interpret the environment of deposition based on constituent particles and grain character. In many cases, the existence of a "reef" is expressed not by in-situ framework, but in the nature of the sediments that are left behind.

In light of estimations that more than 50% of annual reef-carbonate production is typically reduced to sediment (Stearn and Scoffin 1977, Land 1979), reefal sediments take on added significance. An understanding of the processes that the reef uses to rid itself of these large quantities of debris (5-10 $Kg/m^2 \cdot yr$) is of paramount importance in understanding larger-scale controls of reef development.

The general role of physical energy in carbonate sedimentation has been discussed in a broad sense, and is reflected in the classifications of Folk (1962) and Dunham (1962). While the importance of physical processes in controlling reef and sand-body distribution on the large scale has been acknowledged (Purdy 1963, Ball 1967, Roberts 1974, Hubbard et al. 1976 a and b, Hine 1977), quantitative discussions of the specific relationships between process and transport are lacking. As Ginsburg and Lowenstam demonstrated as early as 1958, the sedimentary record is a result of the complex interaction between physical and biological factors. We must fully understand the respective end-members before we can adequately discuss this interplay.

STUDY AREA

St. Croix is located at the northeastern corner of the Caribbean Sea 100 km southeast of Puerto Rico (Fig. 1). Unlike other islands in the Lesser Antillean chain, St. Croix is primarily sedimentary in origin (Whetten 1966). Shelf morphology around the island is highly variable, and the processes responsible for the production and transport of carbonate sediments and biological material change accordingly. The northern shelf varies in width from several km in the east to less than 0.20 km to the west. The wider eastern shelf is rimmed by emergent Holocene reefs; the western portion is traversed by two small submarine canyons which serve as focal points for sediment transport. In contrast, the south shore has a wider (up to 4 km) shelf. Principal sediment producers include calcareous algae (primarily *Halimeda* spp.) and molluscs.

The major wind and wave patterns affecting the Virgin Islands are related to westerly "tradewinds" circulation around the Bermuda High to the north. Severe winds occur during intensification of the high in winter, and hurricanes in the fall. Tides on St. Croix vary between diurnal and semi-diurnal, with a spring-tidal range of 0.24 m. Annual rainfall varies between 75 and 125 cm, with heavy fall and winter rains having profound effects on local marine sedimentation. Wave heights are typically 1-2 m (T = 5-7 sec), increasing to over 5 m (T > 10 sec) during storms.

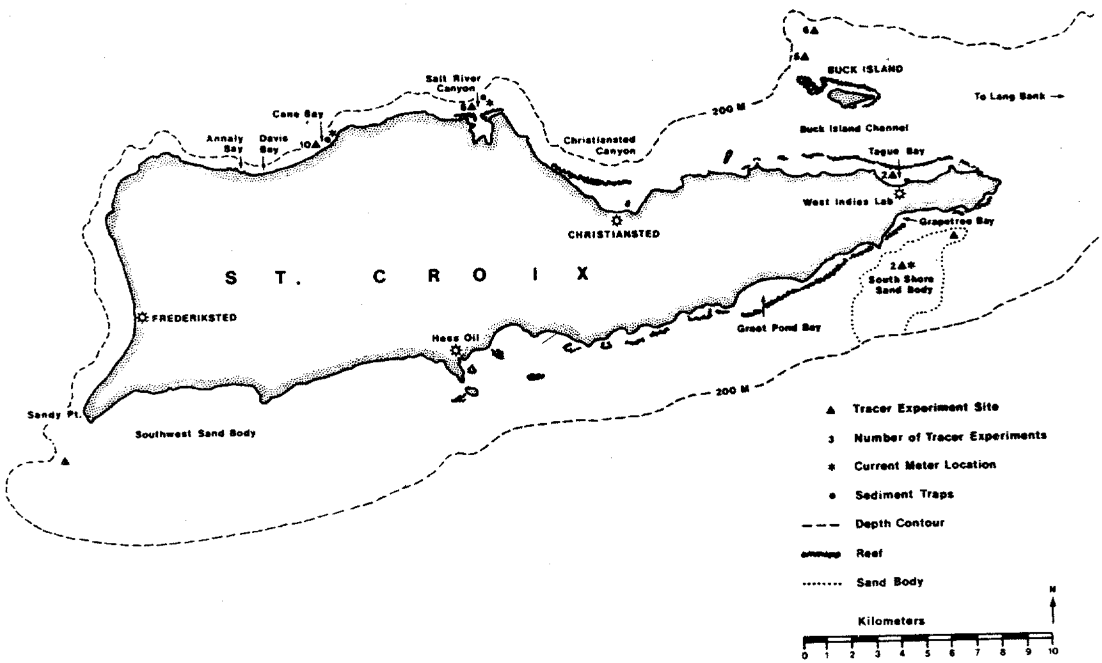


Figure 1. Map showing experiments discussed in the text. For a larger scale location map, see Hubbard et al. (this symp.).

METHODS

Sediment transport rate was measured using two methods. On vertical faces which form the "drop-off" around St. Croix, 19 sediment traps were placed to catch material moving into deeper water as bed-load (Fig. 1). In open sandy areas, sediment transport was monitored using a Lagrangian fluorescent-tracer technique modified from Yasso (1965) and Hubbard et al. (1976). The distribution of dyed sediment (and calculated transport rate) was determined by manually counting the number of dyed grains in regularly-spaced (1 m) cores taken downdrift of the tracer injection point (Fig. 2). Transport experiments were sampled after both long periods of calm weather and storms. Experimental design is discussed in detail by Hubbard et al. (1981).

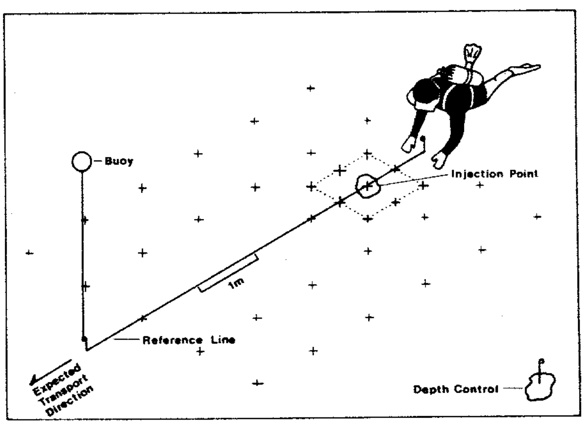


Figure 2. Diagram illustrating tracer sampling scheme. Each *X* is a sample location.

SHELF-SEDIMENT TRANSPORT

CONTROLS

Space limitations preclude lengthy discussion of each transport-controlling variable individually and all the interactive effects. The following discussion is therefore limited to the dominant factors that result in the greatest net transport. These include: 1) biological, 2) gravitational, and 3) physical effects. The dominant biological processes are enhancement by bioturbation and inhibition by sediment binding. Gravitational controls are highly specialized inasmuch as their major importance tends to be confined to areas of very steep slope. Because of the low tidal range, wind- and wave-driven currents play the dominant physical role on the St. Croix shelf. Wave-driven oscillatory currents are more important in shallower areas because of the exponential decay of wave-induced current velocity with depth. During fair weather, weak, wave-induced unidirectional flow normally carries sediment suspended by some other mechanism (e.g. bioturbation). During storms, however, strong wave surge and seaward-directed flows occur, and large quantities of sediment are transported in a relatively short period of time.

TRANSPORT WITHIN ENVIRONMENTS

For the purpose of discussion, the insular shelf is divided into three zones: 1) the shore zone, 2) the nearshore zone, and 3) the outer shelf zone. The shore zone is that area normally affected by surf action. In areas of emergent or near-emergent reefs, the nearshore zone is occupied by a sheltered, 2-10 m deep lagoon. Where a reef is absent, the open shelf nearshore zone slopes gradually into deeper water. The outer shelf zone extends seaward to just beyond the shelf break in water depths of 10 to 60 m. The following discussion will not treat the nearshore open shelf environment separately, as is done for the lagoon. In areas around St. Croix where reef/lagoon systems do not occur, the open shelf simply exhibits a general seaward-decrease in sediment-transport rate, as a function of the decrease in the effectiveness of waves with depth.

The Shore Zone

The shore zone is overwhelmingly dominated by wave-induced physical processes. Turbulent suspension by breaking waves, and mass transport by unidirectional longshore currents are responsible for virtually all sediment transport. Transport rates on the open beaches in Cane Bay vary between 0.2-1.2 $\times$ 10^5 m^3/yr during fair weather (Mattioli 1978) and 1.0 $\times$ 10^6 m^3/yr or greater during storms. Transport rates on lagoonal beaches are lower. Some limited stands of hardier seagrasses may occur in the lower shore zone and can locally diminish physical transport.

Within this zone, overall beach stability and onshore-offshore transport patterns are related to grain settling-velocity compared to wave period, as discussed by Galvin (1973). In the supercritical flow of the beachface, median cross-sectional area of the sediment controls the transport threshold, and in this special case, a grain-size distribution based on sieving appears to be a better predictor of sediment behavior than one based on settling velocity (Hubbard et al. 1981).

Nearshore Lagoon Zone

In the protected nearshore lagoon, the bottom is dominated by extensive grass beds and mounds associated with a variety of burrowing organisms. The present emphasis on the importance of biologically-induced transport is not surprising given the ubiquitous nature of the organisms in this zone where much of the early "classic" studies were done. Under normal conditions, marine grasses effectively stabilize the substrate unless disrupted by mound-building shrimp (*Callianassa* sp.) or various polychaetes which can overturn up to 1000-2000 cm^3/m^2 day individual (DeCombo 1973, Kenny, 1980, Suchanek pers. comm.). Reworking to depths of over one meter causes selective movement of coarse sediment down into the substrate (Pitkin 1977, Suchanek pers. comm.). This reduction of grain-size at the sediment surface, and the local steepening of the bottom slope reduce the transport threshold. Preliminary experiments using a submersible flume indicate a threshold velocity of 0.20 m/sec for sediments in small polychaete mounds, compared to 0.30 m/sec for the surrounding sediments.

Despite the tremendous amount of reworking by such organisms, net transport is improbable in the absence of accompanying physical or gravitational effects. The major interaction in this environment occurs between sediment suspended by *Callianassa* spp. and weak physically-induced flows, otherwise incapable of moving sediment. Kenny (1980) calculated a sediment transport rate of 288 Kg/m · yr by this mechanism. Based on our observations and measurements, a transport rate more on the order of 60-120 Kg/m · yr is indicated. Of lesser importance is the interaction between weaker background flows and wave-induced oscillatory currents. Because of the efficient energy-buffer provided by the reef, transport related to this process is less than might be expected in this shallow environment. During Hurricane David and Tropical Storm Frederick in 1979, two tracer experiments deployed in 5 m of water in Tague Bay did not move, while similar experiments placed in water up to 25 m deep on the open shelf were either destroyed or showed tremendous transport.

Lagoonal organisms can also inhibit transport by either binding the grains together or isolating them from physical processes. Algal coverings can range from thin granular coatings to complex filamentous networks and heavy mats that completely cover the sediment surface and greatly limit or eliminate transport under all but the most energetic conditions (Scoffin 1970, Neumann et al. 1970, Okita 1979). This is discussed in more detail below.

Outer Shelf

Along shelves with emergent reefs, the outer shelf zone begins at the seaward base of the reef. Along open shelves with no emergent reef, the transition from inner to outer shelf does not occur along a distinct boundary or at a set depth. The effects of physical processes, and particularly waves, are noticeably increased in open-shelf environments. Biological factors are similar to those described for the lagoon, but their occurrence is less widespread. Gravitational effects are confined to areas of high slopes, and even then are effective only in conjunction with biological or physical processes.

During fair weather, transport rates are low (14-437 Kg/m·yr), and biological inhibitory effects dominate. Sediments are stabilized by mucilagenous grain-coatings, thin filamentous mats and extensive red-brown algal and diatomaceous mats which cover 1-2 m^2 sections of the bottom. As in the more protected lagoon, seagrasses either trap finer-grained material being moved along the bottom, or else create low energy zones on a micro-oceanographic scale that allow the sediments to settle out. Furthermore, grass beds provide an ideal environment for the sediment-stabilizing algal, bacterial, and fungal communities mentioned above. Preliminary flume experiments indicate that currents in excess of one meter per second are required to move the fine-medium sand found in St. Croix grass beds. Observations indicate that the binding effect of the algae harbored by the grass beds plays a more important role than physical baffling by the grass blades themselves.

In the open shelf environment, the interaction between background flows and oscillatory currents increase in importance. Sediment transport rates of 287-361 Kg/m · yr were measured on the south shore of St. Croix, despite the fact that average current velocities never exceeded the transport threshold during six months of continuous monitoring. This transport is apparently initiated through periodic suspension of sediments by instantaneous wave-induced currents (up to 0.35 m/sec, based on daily field measurements of wave regime). The transport rate is controlled by the percent of the time that the resultant currents are above the threshold velocity, the settling behavior of the grains being suspended, and the magnitude of the weaker, unidirectional currents.

Table 1. Open-shelf sediment transport rates, St. Croix, U.S. Virgin Islands.

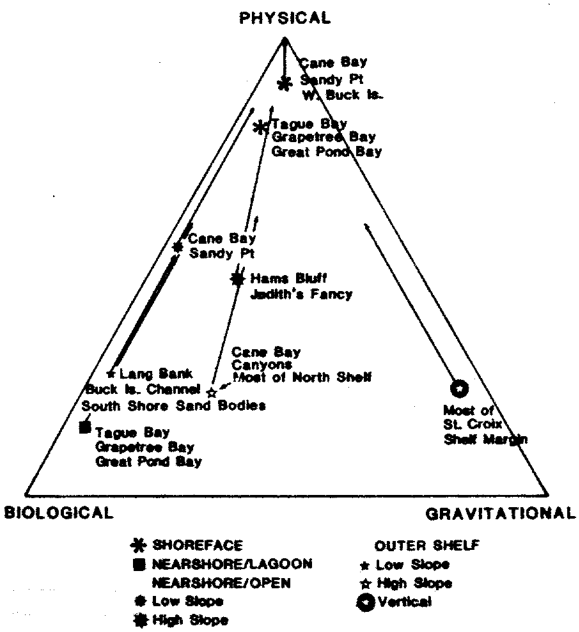
Location	Depth (m)	Transport rate (Kg/m·yr)		Method of Measurement
		Storm	Non-Storm	
Cane Bay (sand flat)	15+	—	74	Tracer
Cane Bay (sand flat)	18+	185	40	Tracer
Cane Bay (chute)	24	210	14	Tracer
Cane Bay (chute)	27	146	61	Tracer
Cane Bay (chute)	32	247	151	Trap
Cane Bay (open wall)	49	—	35	Trap
Salt R. Canyon (west wall)	15-30	1250	108	Trap
Salt R. Canyon (east wall)	15-30	769	52	Trap
Salt R. Canyon (axis)	20	316 (1336)*	80	Tracer
Salt R. Canyon (axis)	30	2431	—	Tracer
Buck Island (chute)++	12	—	437	Tracer
Buck Island (chute)++	21	854	—	Tracer
Buck Island (sand flat)++	27	380	179	Tracer
South Shore (open sand)	18	361	—	Tracer
South Shore (open sand)	20	—	287	

+ Data from Phillips (1978).
++ Data from Kirwan (1978).
* 316 is the transport rate over a longer period of time including a stormy period. 1136 represents the transport rate during the 5 days of storm.

The major (and in some instances, only) transport in the open shelf environments around St. Croix is related to wave-generated currents during storm conditions. At Cane Bay, sediment transport rates of 146-247 Kg/m · yr were measured during storms, compared to rates of 14-151 Kg/m · yr during fair weather (Table 1). One experiment indicated offshore transport rates possibly as high as 1300 Kg/m · yr. during a storm in 1979. Hurricane David and Tropical Storm Frederick destroyed our tracer experiments on the south shore.

Transport rates at Cane Bay compare favorably with those measured in other similar environments. Hubbard et al. (1976) measured 100-120 Kg/m. yr of sediment moving through the sand chutes along the southern shelf edge of Little Bahama Bank. Meaney (1973) reported transport rates one of two orders of magnitude higher off Discovery Bay, Jamaica, but he assumed that the rate of movement of grains (or coral sticks) at the sediment surface could be applied evenly through the body of moving sediment. Subsequent experiments have shown this not to be the case.

At Salt River submarine canyon, similar patterns were observed. Sediment was transported into the canyon from the adjacent shelf at a rate of 2020 Kg/m · yr during storms, compared to a fair weather rate of 160 Kg/m · yr. At these rates, sediment transport during 3-4 weeks of reasonably high seas could equal that for the entire year under calm conditions. On the canyon floor, daily transport rates out of the canyon averaged 80 Kg/m · yr during calm weather, and varied between 1336 and 2431 Kg/m · yr during storms.



This dramatic change in transport rates along the north shore is a function of two processes. First, oscillatory wave motion is much more effective in suspending bottom sediments during storms (a 10-sec wave would produce an instantaneous near-bed current velocity of 0.61 m/sec in 30 m of water). A second, more dramatic process, is a seaward-flowing current that results from water being piled up against the shore (or in the estuary and against the reef face at Salt River) by storm waves. At a point when the waves can no longer sustain the resulting hydraulic head, water flows seaward along the bottom (because wave-orbital velocity decreases exponentially with depth) at velocities estimated at 0.5-0.8 m/sec. This process is proposed as the major mechanism responsible for the offshore sediment-transport observed during storms. Along the wider south shore of St. Croix where this mechanism is not important, the dominant westerly currents are weak during fair weather, with the exception of those in the Sandy Point area (Fig. 1), where wave-induced, unidirectional currents capable of suspending sediment often occur (see Roberts et al., this symp.).

SUMMARY

Figure 3 summarizes the relative importance of physical, biological and gravitational effects in the marine environment around St. Croix. Some of these relationships may be unique to St. Croix because of its narrow shelf margins. Even though a different picture may evolve from a similar treatment of other carbonate shelf areas, the basic interplays described above will undoubtedly still exist.

The shore zone is dominated by physical processes. In lagoons protected by reefs, reworking by grazers and burrowers greatly modifies sediment character and distribution. Bioturbation and wave suspension, in conjunction with weak wave- and wind-driven currents, can affect significant sediment transport. In contrast, the open shelf environment is characterized by active reworking by physical forces. Grass beds, algal mats, and all the other substrate-stabilizing fauna are effective in the lagoonal and open shelf environments during most fair weather conditions. During storms, however, strong wave-generated, oscillatory and unidirectional currents move large quantities of carbonate material off the shelf. Near the shelf edge, gravitational effects can locally enhance offshelf transport in areas of steep slopes but they are quantitatively unimportant.

Figure 3. Diagram illustrating the relative importance of biological and gravitational processes on the St. Croix shelf. Arrows show the general change during storms. For location names refer to Figure 1.

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