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Coral Reefs

Wave-Current Interactions on a Shallow Reef (Nicaragua, Central America)

Harry H. Roberts and Joseph N. Suhayda

Coastal Studies Institute, Louisiana State University, Baton Rouge, Louisiana 70803–7527, and Department of Civil Engineering, Louisiana State University, Baton Rouge, Louisiana 70803–6400, USA

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Abstract. Measurements of wave height and currents associated with normal trade-wind conditions have been made on a linear reef that parallels the northern and northeastern coast of Great Corn Island, eastern shelf of Nicaragua, Central America. Analyses indicate that waves breaking over the reef crest generate lagoonward flow normal to the reef. Average reef-normal flow was in the range of 10 to 20 cm/s; however, individual wave surges reached values of up to 180 cm/s. The strength of the over-the-reef flow is modulated by the tide. Lagoon currents are weak (2–5 cm/s) and change direction with the tide as the lagoon fills and drains. Long-period oscillations in water level (30 s to 20 min) and in the current were observed, and may be important in transporting fine-grained sediments out of the reef-lagoon system. Strong, short-duration surge currents (<5 s) transport coarse sediment from the breaker zone to the seaward margin of the backreef lagoon.

Introduction

Wave and current studies conducted in carbonate environments have identified a close relationship between physical processes, reef geometry, and sediment distribution (Inman et al. 1963; Roberts et al. 1975; Davies 1977; Roberts 1980; and others). While coral reef workers agree that waves and currents play an important role in carbonate systems, a role which ranges from modifying gross reef geometry to controlling sediment and nutrient flux, the number of investigations that have actually focused on physical process interactions with reefs is small. Consequently, our understanding of the magnitudes and spatial/temporal variations of physical processes on reefs of differing geometries is very limited. Since many biological and geological processes are either driven or regulated by water motion, it is important to understand that these processes operate and are affected by the geometric framework provided by the reef. Site-specific studies must be conducted on many different reef types before generalities concerning process-response interactions can be formulated. The objective of this paper is to present a case study of wave-current interactions with a nearshore, discontinuous Caribbean reef. Results are presented with regard to details of physical processes and geological impacts on the reef, especially sediment transport.

The experiment was conducted on a shallow coral-algal reef set in a microtidal and trade-wind wave environment. The study site was a small, 400-m segment of a larger linear reef trend that parallels the northern and northeastern coast of Great Corn Island, eastern shelf of Nicaragua, Central America (Fig. 1). Field studies were conducted during August 1976 and September 1977. The reef experiments were part of a more comprehensive shelf-scale investigation of the entire shelf (Murray et al. 1982; Owens and Roberts 1978).

At the reef crest, *Acropora palmata* and *Montastrea annularis* are the dominant frame-building corals. As shown in Fig. 2, the breaker line defines a very straight reef crest, the landward limit of which is characterized by abundant corals and a rather abrupt change in topography (2 to 3 m) to the backreef lagoon floor. This channel-like feature between the backreef and lagoon is referred to throughout this paper as the moat.

The forereef slopes uniformly to a depth of 12–15 m, where it merges with a zone of sediment accumulation and deep patch reef development. This slope is characterized by isolated colonies of *A. palmata;* heads of *M. annularis*, *Porites astreoides*, *Diploria clivosa*, and *D. strigosa;* and abundant coralline algae in both encrusting and rhodolith forms.

The lagoon is floored by coral sand and rubble, which is colonized by *Thalassia testudinum* and a variety of small coral heads. Well-defined lobes of sediment which are relatively free of colonization by sessile organisms occur along the flanks of the Cana Point reef.

Materials and Methods

Figure 3 illustrates the instrument deployment scheme on a profile of the reef and adjacent backreef lagoon. Reef-normal currents at the crest and reef-parallel flow in the backreef moat were measured with low-inertia

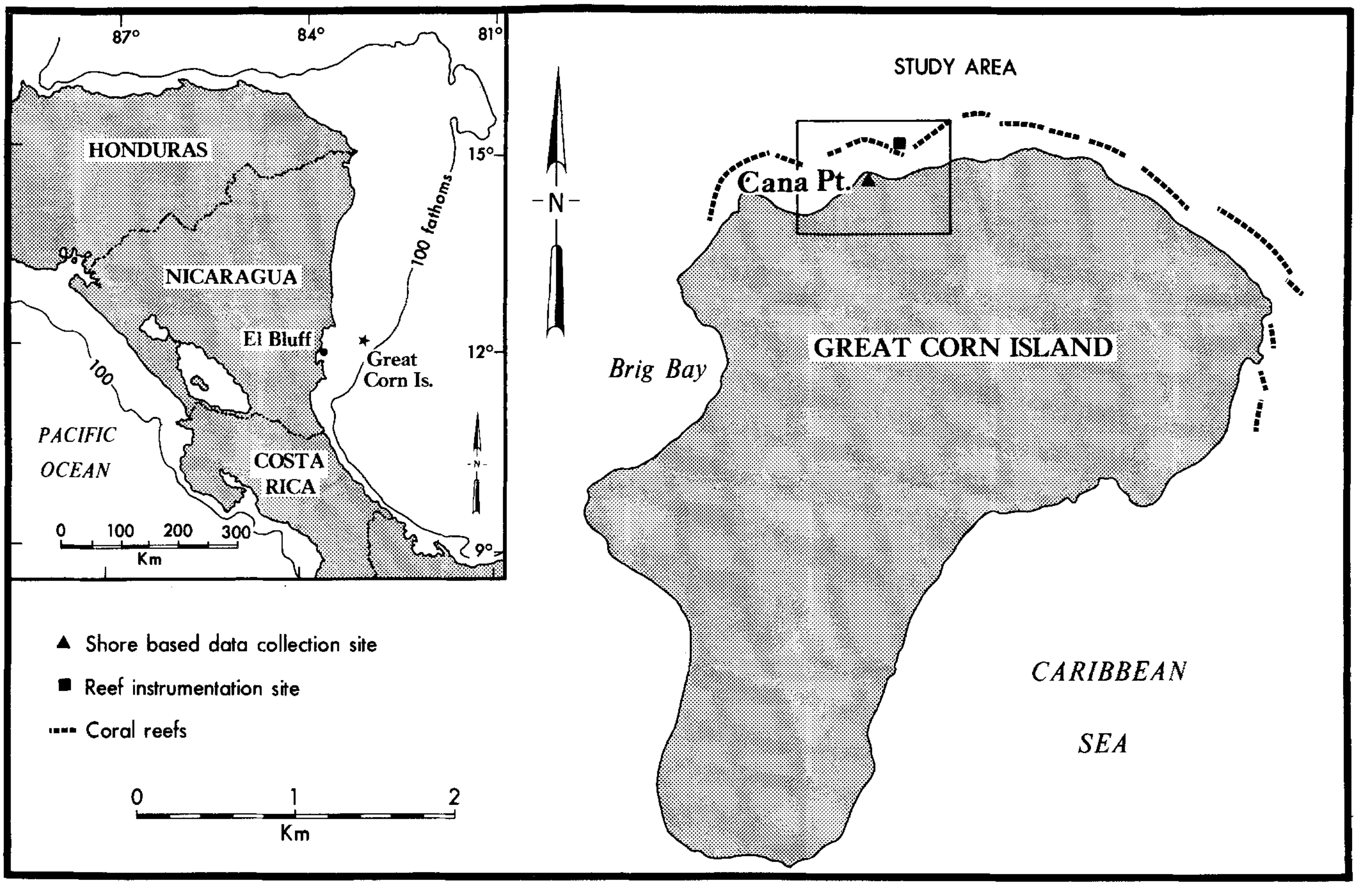

Fig. 1. Location map of study area, Cana reef, along the north coast of Great Corn Island, Nicaragua. Trade wind driven waves arrive dominantly from the northeast

Fig. 2. Cana reef (area of breaking waves) and backreef lagoon (dots = instrument locations, triangle = data collection site at Cana Point)

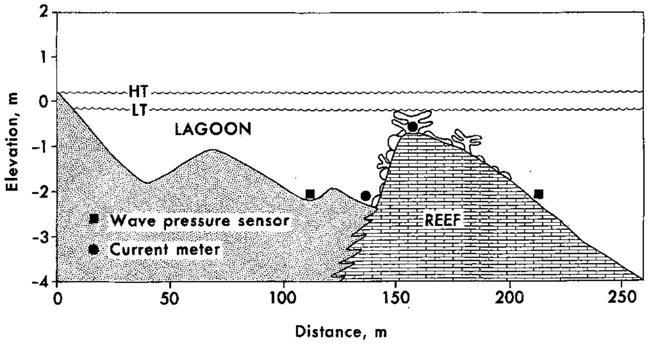

Fig. 3. Surveyed profile of Cana reef and backreef lagoon showing deployment sites of wave sensors and current meters (water depth 2.5 m)

ducted current meters designed and built by Coastal Studies Institute personnel. The rationale for this deployment scheme was to study the changes in across-reef flow as well as along-reef currents associated with filling and draining of the lagoon. The backreef meter was installed 1 m above the bottom, and the reef crest meter was located at a water depth midway between mean tide level and the reef floor, approximately 50 cm above the bottom. Wave sensors (absolute pressure transducers) were placed in both forereef and backreef locations at a water depth of 2 m below mean tide level. This instrument configuration monitored modifications of incoming waves as they transited the reef to the backreef lagoon, as well as simultaneous response of reef crest and moat currents. Data on both waves and currents were collected throughout a complete 25-h tidal cycle. Data were cabled back to a central recording station on land, where they were registered in analog format. Twenty minutes of continuous data were recorded hourly. Long-period variations were observed during a single continuous 60-min data collection period.

Results

Waves

Previous studies of reef-lagoon systems have emphasized that across-the-reef currents and backreef lagoon circula-

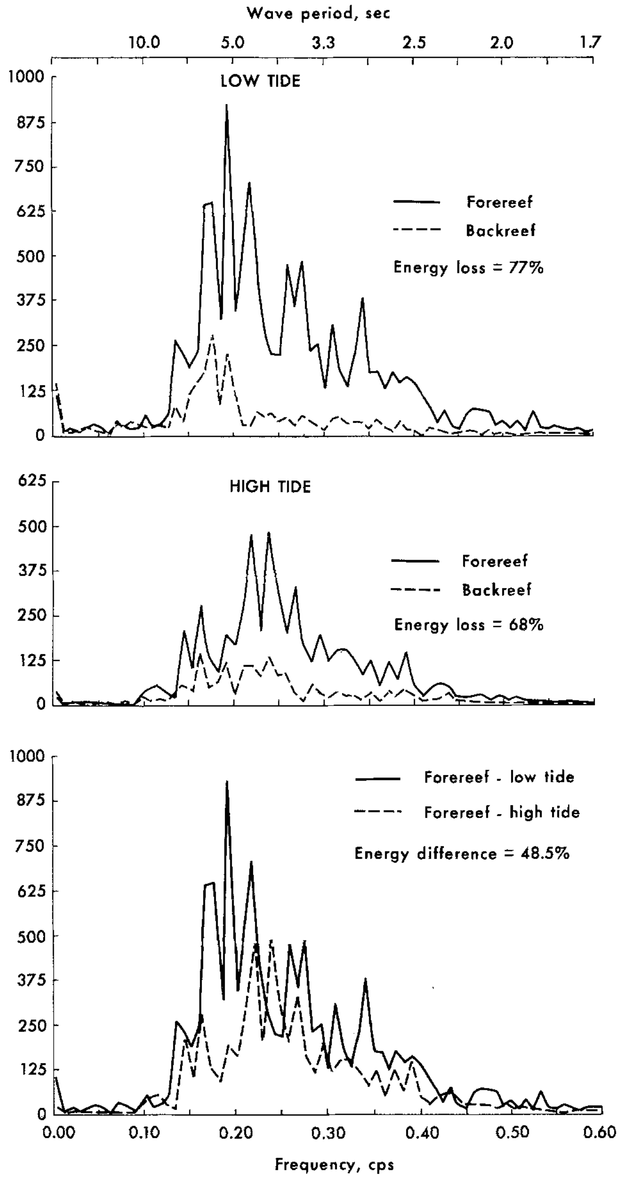

Fig. 4. Backreef and forereef wave spectra summarized from 20-min wave records taken at both low tide and high tide. The bottom panel represents wave spectra of low-tide and high-tide conditions on the forereef station to illustrate changes in the input wave state during the experiment

tion are to a large extent driven by the process of wave breaking on the reef crest (Inman et al. 1963; Suhayda and Roberts 1977; Roberts 1980). Shoaling waves increase in height and steepness as they approach the reef crest until breaking occurs. At this point wave energy is rapidly transformed into strong surge currents and turbulence among other minor energy sinks. Input wave heights are significantly reduced, and high-frequency waves are produced as waves propagate over the reef crest. The degree to which wave energy is modified or "filtered" by this process depends on several factors, including overall reef geometry, water depth at the reef crest, uniformity of depth along and across the reef, and width of the shallow reef flat. Inasmuch as the magnitude of this decrease depends primarily on water depth at the reef crest, wave conditions in the backreef undergo significant changes over a single tidal cycle.

Figure 4 illustrates the wave-filtering effect of the reef during low-tide and high-tide conditions. In both cases a significant proportion of the incoming wave energy is extracted by frictional attenuation and, more importantly, breaking activity at the reef crest. When water level across the reef is lowest, the breaking process is intensified and 77% of the incoming wave energy is filtered before reaching the backreef. Well-defined but greatly diminished 5–8 s waves are propagated to the backreef while waves are eliminated over a broad band of frequencies (Fig. 4a). Because of increased water levels over the reef during the high tide, wave breaking is less intense and energy loss is significantly less (68% as compared to 77% at low tide; Fig. 4b). Like the low-tide spectrum of Fig. 4a, a broad band of spectral wave components is filtered by the reef and only the lower frequency energy is transmitted to the backreef wave sensor site. Although wave state changed during the experiment (48.5% more incoming wave energy at low tide; Fig. 4c), other studies (Suhayda and Roberts 1977; Roberts 1980) have shown that energy loss is maximized at low tide independently of wave state.

Recent studies of a continuous linear reef along the south coast of St. Croix (USVI) illustrate that up to 97% of incoming wave energy is dissipated at the crest before reaching the backreef lagoon (Roberts 1980). Reef crests at both sites are at similar depths below mid-tide level. Therefore, significant differences in wave energy transmitted to the backreef lagoon between these two sites appear to arise from the discontinuous nature of the Nicaragua reef. Diffraction and refraction of waves around the flanks of this reef segment introduce energy to the backreef environment that has not been filtered by the reef crest. During the experiment some waves near the backreef sensor location were observed to be traveling roughly parallel to the reef trend. Further inspection showed that they resulted from bending of open shelf waves around the ends of Cana reef. Lagoons fronted by long, unbroken, shallow reefs receive only wave energy that has been modified by the breaking process at the reef crest or locally wind-generated waves.

Wave-Driven Currents

As waves break at the reef crest, reef-normal currents are directed into the backreef lagoon. Average low-tide speed was 17.3 cm/s, while average high-tide current speed was 7.1 cm/s. Figure 5 compares the distribution of speeds averaged at 1-s intervals for both extremes of the tide. From the mean data alone it would appear that across-the-reef flow is not sufficient to be an efficient coarse-sediment transport agent under normal trade-wind sea conditions. However, when averaged current data are decomposed into increments small enough to permit discrimination of speeds associated with individual waves, it can be seen that currents capable of transporting reef sediments occur frequently. Figure 6 illustrates a 30-s-long time series of near-

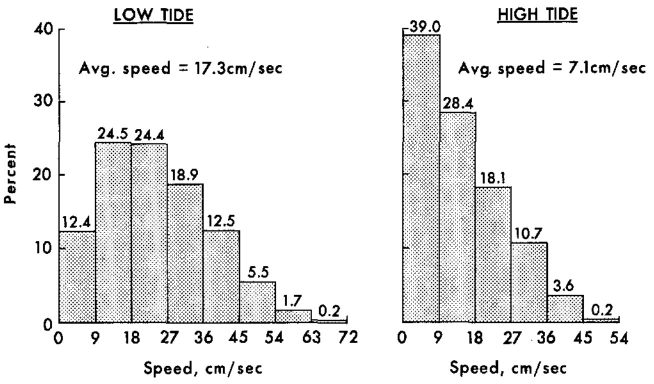

Fig. 5. Distribution of 1-s averaged reef crest speeds at low tide and the following high tide (record length = 27 min)

ly instantaneous current speeds extracted from a low-tide record. During this short period three velocity peaks occur near 90 cm/s, and two higher peaks approach 180 cm/s. These bursts of lagoonward-directed energy represent the short-term surge currents associated with wave breaking at the crest and propagation of a modified wave form into the backreef environment. Although storm events are generally called on to explain movement of sand-sized and coarser particles, the data shown in Fig. 6 suggest that normal reef-crest processes are sufficient to transport coarse sediment to the immediate backreef.

Low-Frequency Water Level Changes and Currents

Shoaling trade wind waves and wave-induced currents dominate the total energy expended within the reef complex. However, 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 between 30 s and 20 min. Waves are known to occur in this band associated with surf beat, tsunamis, shelf seiche, and internal waves.

Figure 7 shows a 60-min section of the water-level record from both pressure sensors in which the individual wind waves have been numerically filtered out. These data show a 4- to 8-cm variation in sea level associated with a wave whose period is 15 to 30 min. The water level rise occurs simultaneously at both sensors. Because the wave has a long wavelength and a very low height to wavelength ratio, it is highly reflected at the shoreline and can produce a standing wave. Under reasonably stable trade wind wave conditions, these standing waves may have a long-term morphological effect on the reef and its associated sediments. This forcing mechanism has never been adequately explored in carbonate systems. The maximum current (Um) generated by these long waves can be estimated using linear shallow-water wave theory as

$$Um = a/h \cdot C,$$

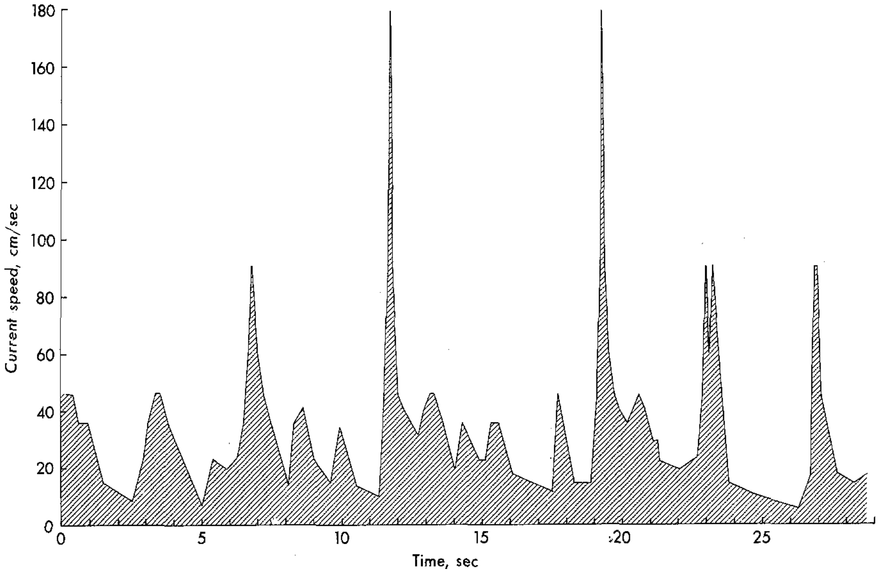

Fig. 6. Reef crest-normal unidirectional surge currents directed toward the lagoon at low tide. Data are plotted directly from ducted current meter analog readout

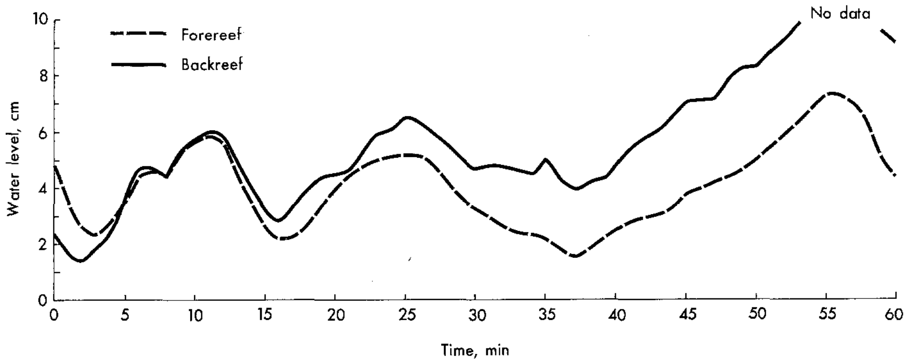

Fig. 7. Pressure sensor records from the reef crest and lagoon showing long-period waves. Wind-wave pressure variations have been filtered out of these records. Because of calibration problems relative water levels between the two monitoring stations are not obtainable from these data

where a is the wave amplitude, h is the water depth, and C is the phase speed of the wave, taken as $\sqrt{gh}$. Please note that for near-breaking waves nonlinear wave theory would give more accurate estimates. For an amplitude of 3 cm and a water depth of 4 m, the maximum current is about 5 cm/s. For a water depth of 1 m the maximum current is 16 cm/s. Variations in the observed currents were examined for low-frequency components. Current records from the reef crest and the moat suggest low-frequency variations of the current having amplitudes of 2 to 3 cm/s at the moat and 5 to 10 cm/s at the reef crest for both extremes of the tide.

The potential importance of such low-frequency currents can be illustrated by considering the distance a water particle would move during one cycle of a wave. The formula for the displacement of the particle is

$$D = Um \cdot T/\pi,$$

where T is the wave period. For a 14-min wave, the particle moves about 15 m in 4 m of water and about 40 m in 1 m of water. Since typical wind-wave-induced water particle displacement is 1 m, long-period waves cause a much greater relocation of water within the reef complex.

Tidal currents were also present at the study site. Figure 8 shows the reef crest and moat current data averaged over 20 min. The residual current shown indicates tidal components. The tidal current amplitude is in the range 5 to 10 cm/s, and the particle displacement for these tidal currents is about 4 km.

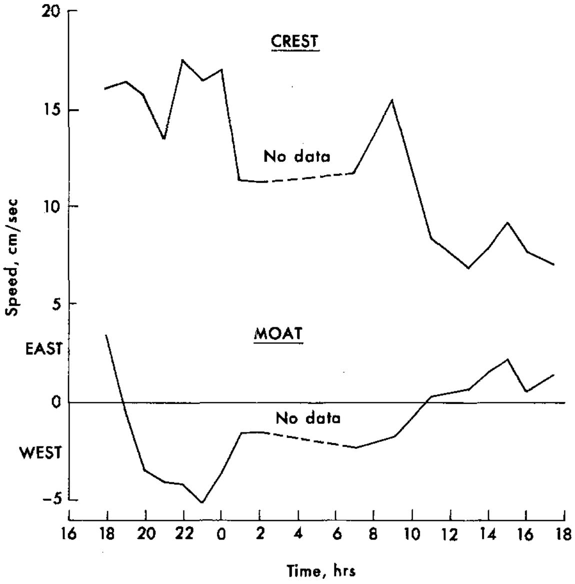

Fig. 8. Current records from the reef crest and moat showing tidal currents. Each data point is a 20-min average of the observed current

Table 1. Threshold and settling velocities for various sized sediments

Sediment type	Grain size (mm)	Threshold velocity[a] (cm/s)	Settling velocity[b] (cm/s)
Clay	0.001	~120	10^{-3}–10^{-4}
Silt	0.01	~ 70	10^{-2}
Fine sand	0.1	~ 30	0.7
Coarse sand	1	~ 20	10
Pebble	10	~110	45

[a] For steady currents measured 1 m above bottom (Shepard 1963)

[b] For quartz spheres of equivalent size (Shepard 1963)

Discussion

The current measurements indicate that reef sediments are subjected to a complex mixture of currents having various intensities and durations. In order to assess the impact of these currents on reef sediments, we consider two fundamental velocities associated with granular sediments; the first is the threshold velocity or minimum velocity needed to move sediments from the bottom, and the second is the settling velocity of individual grains of sediment through the water column. These values for selected grain sizes are given in Table 1. The values given are approximate, as the actual values depend specifically upon grain shape, density, and level of turbulence in the water column. In addition, since both threshold and settling velocities are calculated for quartz spheres, the case for carbonates presented in this paper is generally conservative by a few percent (Komar 1981). The values presented in the table indicate that, while fine-grained sediments require a higher threshold velocity to be removed from the bottom than coarser grained sediments, once in the water column they will remain in transport much longer than the coarse sediments. However, the reef crest is a high energy environment where the fines generated by biological and mechanical abrasion do not accumulate, but are contributed directly to the water column. Therefore, threshold velocities for fine-grained sediments are not especially meaningful in this sedimentological framework.

Consider the lateral transport of the various sizes of sediments given in Table 1 for the combination of currents observed on the reef crest. The high-velocity current pulses associated with wind waves and breakers reached values above 100 cm/s for short durations (<5 s) many times during the period of observation. These velocities are capable of suspending all grain sizes. Once suspended, the variation in settling velocity among the grain sizes means that the amount of time the grain is in a 1-m water column varies from several hours for clay-sized particles, to a few hours for silt, to ~4 min for fine sand, 10 s for coarse sand, and less than 1 s for larger grains. Therefore, suspended fine sediments are capable of being carried great distances horizontally by currents of long duration (surf beat periods and/or tidal frequencies). Fine-grained sediments generated in reef and near-reef environments will be removed from these source areas and possibly deposited at distant locations by this mechanism. Where lagoons are large, fine-grained sediment sinks can exist in the backreef. However, as in the Cana Point reef example, fines are flushed out of the system.

In contrast, coarse sediments which are also suspended by high velocity current pulses do not remain in the water column long enough to be transported by low-velocity and long-duration water motions. As a consequence, these particles will be deposited and resuspended at wind wave frequencies. Thus, while average current velocities on the reef crest over many minutes may be less than the threshold velocity of silt, sand, or coarser particles, the extremes in the spectrum of velocities associated with breaking waves promote coarse sediment transport. The net result of this wave-induced flow is coarse sediment transport from the shallow forereef and reef crest area to a depositional site slightly lagoonward of the breaker line where surge currents are rapidly attenuated. Storm waves intensify these processes by moving the breaker point seaward to the forereef and consequently affect a larger area and deeper part of the reef. Rubble zones and sand sheets commonly found on the lagoonward sides of linear reefs are in part fed by this over-the-reef transport process. At the Cana Point reef field site, coarse sediments are being deposited in the moat where current velocities are generally insufficient to transport sand-sized particles. Because of their relatively slow settling rates fine sediments are transported away from the reef crest and immediate backreef areas.

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