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REEF SEDIMENT TRANSPORT AND DEPOSITION OFF THE EAST COAST OF CARRIACOU, WEST INDIES

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ABSTRACT

Two, previously unstudied, back-reef bays have differeng patterns of reef sediment transport and deposition. In Grand Bay, four log normal grain size populations and the patterns of their mixing and occurrence are consistent with the transport competence of observed waves and represent lag, rolling, saltating and suspended sediment populations. They are deposited as bimodal fine grained lagoonal sand and as an overlying, shoreward prograding body of bimodal medium grained sand.

In Watering Bay, bottom sediment is in equilibrium with the strongest tidal currents and is transported into deeper water at the northern, open end of the bay. Current velocities can be closely estimated using bottom sediment grain size distributions, transport competence curves, and the von Karman-Prandtl equation for flow over a hydrodynamically rough surface.

Carbonate sedimentation has gradually filled the back-reef lagoons since the last sea level rise. Grand Bay represents a partially filled lagoon, whereas Watering Bay represents a filled lagoon that is in equilibrium with restricted, but stronger tidal flow.

KEY WORDS: Carriacou, West Indies, Sediment Transport, Deposition.

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Bathymetry and Hydrology

The barrier coral reef and Grand and Grand and Watering Bays in the back reef were studied in terms of bathymetry, environments, hydrology and sediment transport (Fig. 1). The same major reef and back reef environments occur in both bays: reef crest, unstable sand, stable sand, grass beds, patch reefs and beaches. Differences in their development are related to variations in bathymetry and hydrology. Grand Bay is more exposed, larger, deeper and has larger waves than Watering Bay (Fig. 1). The bottom of Watering Bay is scoured by strong dominantly semi-diurnal, reversing tidal currents. These variations in size, exposure, bathymetry and hydrology cause differences in development and character of the environments as follows:

Beaches in Grand Bay are developed and are composed of carbonate sand transported shoreward by waves. Beaches in Watering Bay are poorly developed and are composed mainly of black, terrigenous sand transported to the shore by ephemeral streams and sheet wash during rain storms. Shoreward Thalassia beds have a much more extensive and varied associated flora and fauna in Grand Bay than in Watering Bay. The unstable sand substrate in Grand Bay is transported shoreward from the barrier reef into the deeper lagoon by secondary waves whereas in Watering Bays these sands are transported mainly laterally by strong tidal currents.

Nearly half of Grand Bay, between the shoreward Thalassia beds and the barrier reef, is deeper than 20 feet (6.1 m) and is floored

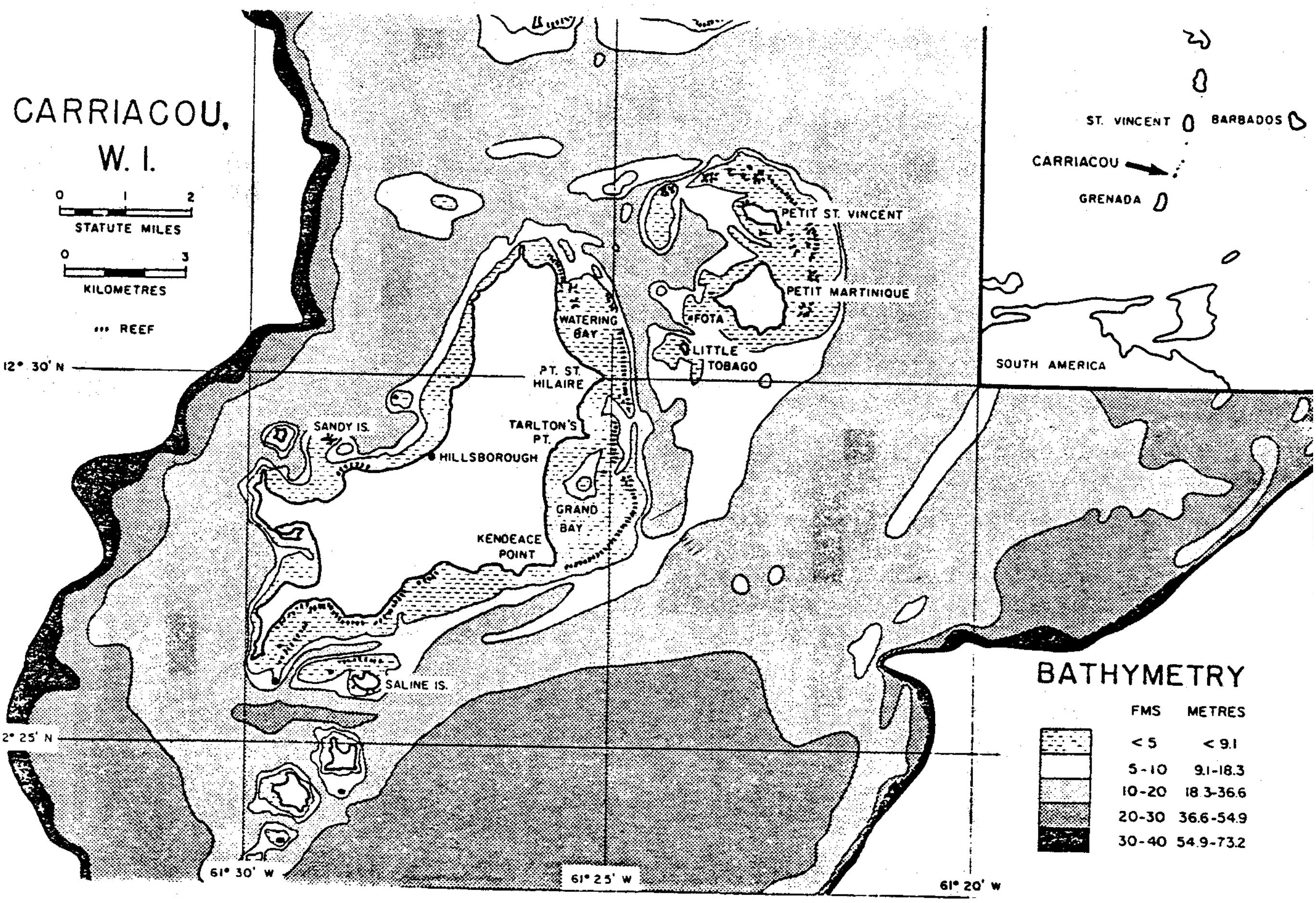

Fig. 1. Location and bathymetry vicinity of Carriacou, W.I. modified from Br. Adm. Chart 2872

by stable sand which is not moved by normal waves. Stable sand substrate is uncommon in Watering Bay and occurs mainly in small areas associated with the shoreward Thalassia beds behind Grand Cay. A back-reef radial zone is well developed on the landward side of the barrier reef crest only in southern Watering Bay and in Grand Bay.

The main sources of bioclastic carbonate sediments east of Carriacou are the barrier reefs. Maps and scatter plots of the statistical parameters of grain size distributions of sediment samples are consistent with the relative intensities of waves and currents as determined by seabed surface features and direct observations. Used in conjunction with one another, the maps and scatter plots allow some general interpretations of sediment transport and deposition.

A much fuller understanding of sediment transport and deposition was obtained by considering the grain size distributions as mix-aures of log normal populations represented by cumulative curves or histograms rather than by derived numbers. Use of populations allows interpretation of the complete grain size distributions as responses to processes, for which there is a considerable fund of theory and experimental data.

Grand Bay

Sediment transport in Grand Bay is dominated by waves crossing the back-reef unstable sand flat. Increasing mean grain size and coarse skewness of grain size distributions of sediment samples across the back-reef flat away from the reef attest to the transport and progressive winnowing effects of the waves. The finer grain sizes winnowed from the flat come to rest in the deeper water stable sand environment of central Grand Bay (Fig. 1).

To progress beyond the above interpretation it was necessary to consider the sampled grain size distributions as mixtures of basic log normal grain size distributions. Determination of the grain size distributions of different types of organic constituents in three representative samples demonstrated that the basic populations are not a result of organic skeletal structural units controlling the grain sizes of the products of abrasion and breakage.

By comparing the basic grain size component populations with competence curves for transport by waves and the competence of the observed waves, the following model of reef sediment transport and deposition in Grand Bay was developed (Fig. 2).

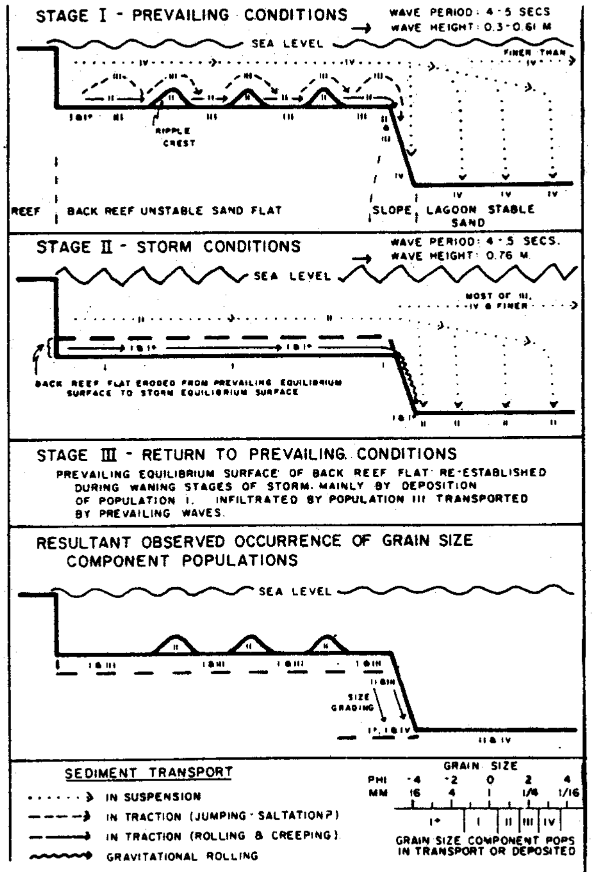

Fig. 2. Summary of four sediment populations and model of sediment transport and deposition.

During observed normal weather conditions, waves in Grand Bay have periods of 4 to 5 seconds and heights of 1 to 2 feet (0.3 to 0.6 m). These waves are capable of transporting grain sizes finer than 0.43 phi (0.74 mm) in 12 feet (3.6 m) of water. Grain size component population I (x = -0.7 to -0.25 phi; = 0.72 to 0.85 phi), occurring as the coarse mode of bimodal reef and back-reef ripple trough samples, is not transported and remains as a coarse lag deposit. Component population II (x = 1.05 to 1.40 phi; - 0.75 to 0.95 phi) is transported slowly by rolling and sliding and is organized into ripple crests on the back-reef sand flat. Those grains that reach the steep slope between the back-reef and the deeper water stable sand (lagoon) are deposited as part of the subordinate coarse grain size population of the bimodal slope deposits.

Population III (x = 1.80 to 2.10 phi; = 0.59 to 0.70 phi) is transported rapidly across the back-reef flat as bouncing (saltating?) traction load. It is present as a transitory population in the back-reef flat ripple trough samples and as the main grain size mode of the slope deposits.

Population IV (x = 3.15 to 3.20 phi; = 0.45 to 0.66 phi) is transported most rapidly across the back-reef flat, probably in suspension. The population is not recognized in bottom samples of the reef and back-reef flat environments.

In summary, the various sediment size distributions originated as follows: population I - lag, population II - traction - rolling?, population III - traction - saltating?, and population IV - suspension.

Down the slope, progressively more and finer portions of population IV are mixed with population III to produce an inverse grain size grading in the fine mode of the slope deposits. Most of population IV comes to rest as the fine grain size mode of the bimodal sands of the stable sand (lagoon) environment (Fig. 2).

During storms, which were not observed, grain sizes finer than approximately -1.15 phi (2.2 mm) are transported from the reef and across the back reef flat (Fig. 2). Component population I forms the coarse grained portion of the traction load. At the top of the steep slope, which is at or near the angle of repose for finer grain sizes, the coarse grain fractions of population I roll to the bottom where they form a discontinuous bottom-set deposit of the shoreward prograding back-reef sand body. Clogging of population I on the slope may occur to produce a coarse grained storm cross-set bed in the sand body. During the waning stages of a storm population I is deposited on the top of the back-reef flat where it forms the coarse grain size mode of the normal weather ripple trough samples.

Population II, in the normal wave ripple crests, is the most exposed grain size population on the back-reef flat at the start of a storm and is rapidly trans rted across the back-reef flat as the finest portion of the bed load. It is swept down the slope i to deeper water where storm waves are still capable of distributing it as the coarse fraction of the traction load (Fig. 2). It forms the coarse grained component population of the bimodal lagoonal deposits. Biogenic reworking of the lagoonal deposits during non-stormy weather intimately mixes population II and IV into a homogeneous deposit.

Component population III, in the normal weather ripple troughs, is probably put into suspension on the back-reef flat during storms. Increased water circulation during storms probably removes this population from the study area. Some of population IV, originally deposited in the lagoon during normal weather may be disturbed during storms, placed in suspension, and removed from the study area. It would not be placed into suspension as high in the water column as population III on the back-reef flat. however, so much would remain in the lagoon and be redeposited after the storm.

The net result of the above model is to deposit a shoreward prograding sand body with a discontinuous, coarse grained bottom-set over homogeneous, fine grained, bimodal (populations II and IV) lagoonal deposits. The grain size distributions of the sands in the main body are bimodal (populations I to II plus III to IV). The grain sizes of the modes decreases downwards within the sand body. The mean grain size of whole sample grain size distributions increases downwards however, because of the increasing proportion of the coarse mode. The sand body is capped by a coarse grained, bimodal (populations I and III) top-set deposit, the thickness of which depends on the difference in scouring abilities of normal weather and storm waves.

Watering Bay

Sediment transport in Watering Bay is dominated by unequal, reversing tidal currents of which the northward flow is the strongest. Sand sized sediment, supplied by the barrier reefs, is moved into the bay by waves and transported northward by the tidal currents. Waves during normal weather have little or no effect on the bottom sediments over most of the bay.

Sediment Traps

Grain size distributions of samples collected in cloth mesh sediment traps at the sediment surface and at various heights above bottom correlate well with traction and suspended load grain size ranges defined by maximum shear velocity calculated from current measurements (Fig. 3) and plotted on transport competence curves (Fig. 4, shear velocity vs. grain size). All traps were placed parallel with the ripples within ripple troughs and facing the current flow at the time. The grain size distributions of the sediment collected in the traps are compared to the competence curves for carbonate grains in sea water and to the relevant calculated shear velocities (Fig. 4).

The results of sediment trap 24-1, emplaced for 3 hours and 47 minutes during the waning southward current, are presented in Figure 4. It was located about 50 m lagoonward from the north end of the Watering Bay barrier reef. The grain size separating bed load from suspended load on the basis of the trapped sediment histograms is 1.25 ∅ (0.43 mm). From the suspended load competence curve a shear velocity of 4.35 cm/sec is required to suspend grains finer than 1.25 ∅ (0.43 mm).

Another estimate of shear velocity is possible using the maximum grain size collected in the bottom trap. Ignoring the 0.03 percent of the sample occurring in the -1.5 to -2.0 (2.83

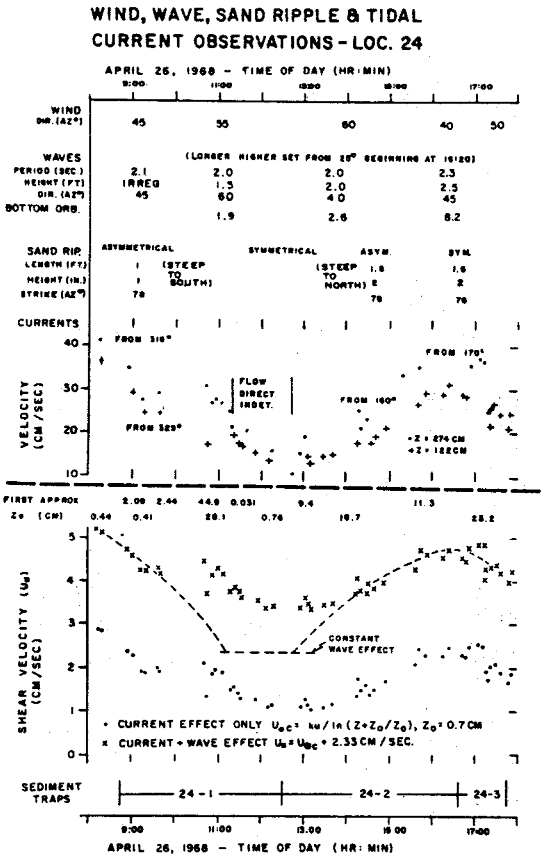

Fig. 3. Wind, wave, sand ripple and tidal current observations at location 24, northern Watering Bay.

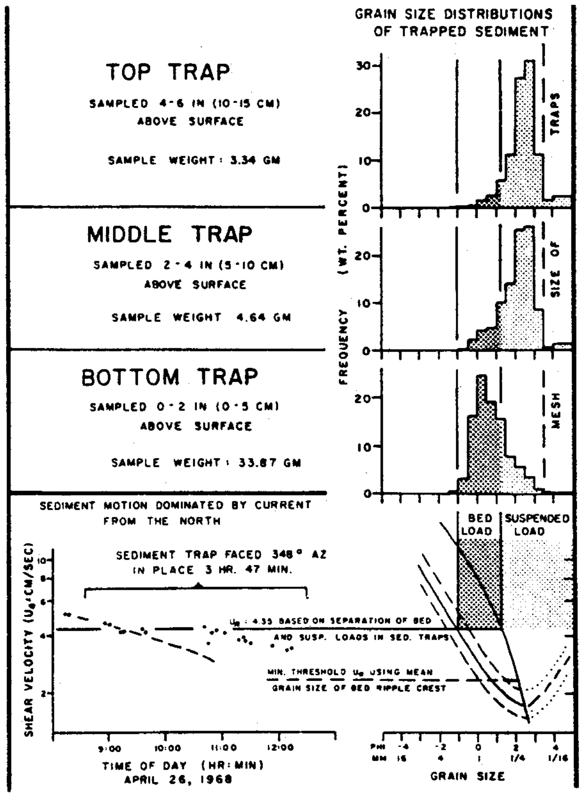

Fig. 4. Results of sediment trap 24-1 compared to transport competences of calculated shear velocities.

to 4 mm) size range the maximum grain size is -1.5 Ø (2.84 mm) which corresponds to a sheer velocity of 5.2 cm/sec capable of suspending grain sizes finer than 0.9 Ø (0.53 mm).

The estimates of shear velocity (4.35 and 5.2 cm/sec) derived from the sediment trap data are of the same order as the maximum calculated shear velocity (4.80 cm/sec) cting while the trap was in place (Fig. 4). The maximum calculated shear velocity is capable of suspending grain sizes finer than 1.04 Ø (0.48 mm) in diameter. This upper grain size limit of the suspended load is equivalent to the 50th and 66th percentiles of the grain size distributions of the bed material ripple crest and bed material ripple trough samples respectively.

From the sediment trap results (Fig. 5) it was found that the grain size distributions of bottom sediment samples in equilibrium with the currents could be used to define the grain size boundary between traction and suspended load and the roughness length. The grain size boundary between bed and suspended loads corresponds to a narrow range of percentiles of the bed material grain sizes, and the average for three sediment traps is the 64th percentile (illustrated in Fig. 6). This grain size was used in conjunction with the transport competence curve graph (Fig. 4) to derive the maximum shear velocity acting on the bottom. The mean average current velocities at 1.52 m (5 feet) were calculated (Fig. 7) using shear velocity, roughness length values, and water depths in the von Karman-Prandtl equation. These variations in flow speed compare favorably with measured values (within ± 12%). They are also reasonable and expected assuming constant volume of flow through a varying cross-sectional area. During northward tidal flow the residence time of water in Watering Bay is about 1.5 hours and therefore particles put into suspension are flushed into deeper water in one tidal cycle.

Reef model

Maps of maximum shear velocity and current velocity (Fig. 7), the results of the sediment traps and current measurements, and maps of grain size distribution statistical parameters were all used to develop a model of reef sediment

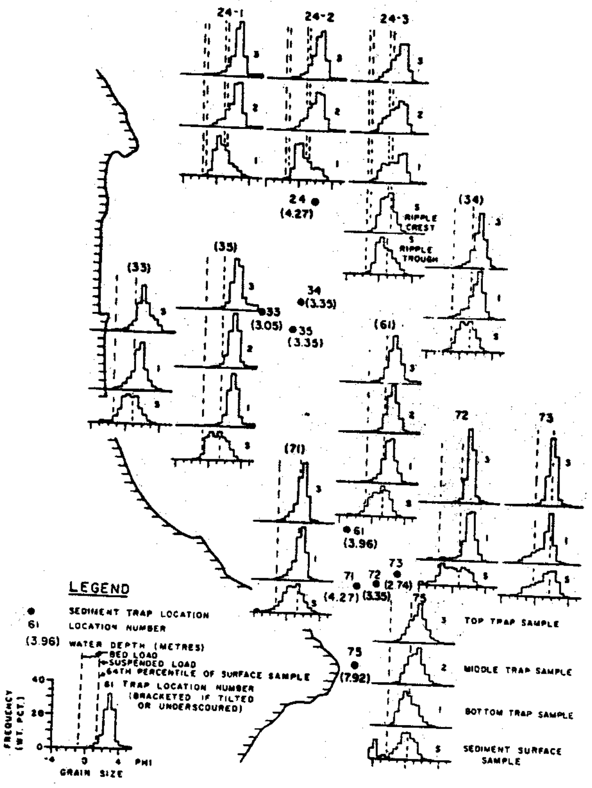

Fig. 5. Sediment trap and surface sample grain size distributions for all traps, Watering Bay.

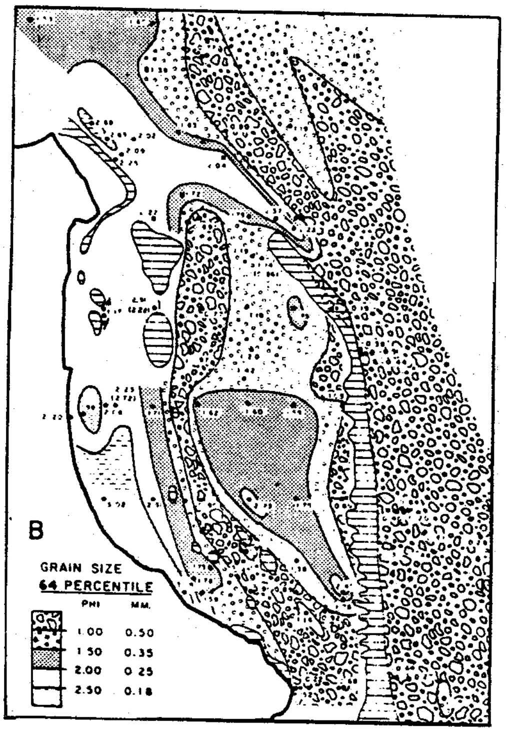

Fig. 6. Watering Bay 64th percentiles of bed sample grain size distributions.

transport and deposition in Watering Bay. The only sites of sediment deposition in Watering Bay are the beaches, mangroves, shoreward *Thalassia* beds and patch reefs which could conceivably eventually lead to filling most of the bay to sea level. The unstable sand environments are sediment bypass areas, in equilibrium with the currents. The grain size distributions of the bed materials accurately reflect the sediment transported by the currents, and are not deposited except temporarily, when the currents are slack or weak.

Significant deposition in Watering Bay would occur only if there were a rise in relative sea level or an increase in the grain sizes supplied by the reef. Deposition would continue until tidal flow was constricted sufficiently that shear velocities were competent to transport all sediment supplied by the reef. The new equilibrium surface so established would be at original water depths if a sea level rise had occurred and at shallower depths if an increase in grain size had occurred.

Much of the sediment swept from the bay at present is deposited on the slope into deeper water at the northern end of the bay to form a slowly northward prograding sand body. Continued progradation northward is dependent on extension of the barrier reef to protect the deposit from strong tidal currents sweeping around the north end of the reef. An unknown,

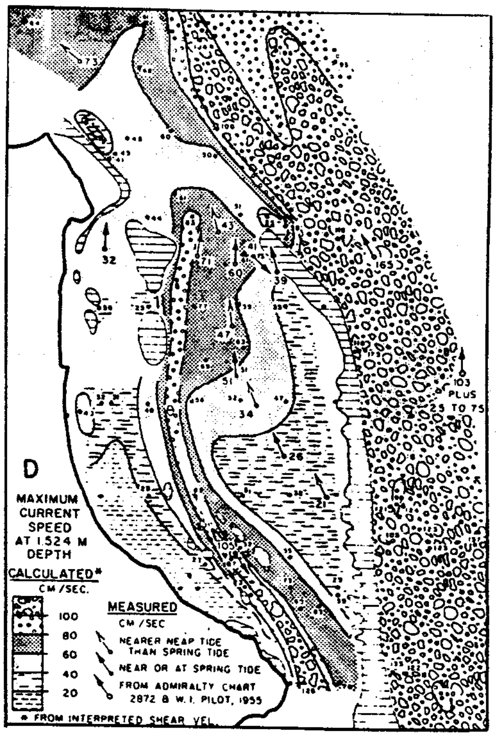

Fig. 7. Watering Bay calculated maximum current speeds at 1.524 m (5 feet) depth.

but probably major, portion of the sand swept from the bay continues to be transported outside of the study area by the currents from outside of the reef.

Conclusions

1. Cumulative curves, histograms, and the concept of mixtures of log normal populations provide a much more complete representation of bottom sample grain size distributions than do derived statistical parameters. They are also more easily and completely related to transport and depositional processes.
2. Grain size component populations and the pattern of their occurrence in Grand Bay are consistent with the transport competence of observed waves and do not reflect structural units of different organic skeletons.
3. Alternation of normal and storm conditions in Grand Bay results in transport and deposition of reef derived sediment as a shoreward prograding, cross bedded body of bimodal, medium grained sand. The top of the sand body is a ripple marked, non-depositional surface at approximately 12 feet (3.6 m) water depth. The depth represents an equilibrium between grain sizes supplied from the reef and the transport competence of the waves. The base of the sand body is a discontinuous bed of dominantly molluscan gravel overlying bimodal, fine grained lagoonal sand at 20 to 30 feet (6.1 to 9.1 m) water depth.
4. In Watering Bay sediment transport and deposition in the back reef is controlled by semi-diurnal, reversing tidal currents. Net sediment transport is towards the north, parallel to the reef. The south flowing current is very seldom competent to transport sediment.
5. Grain size distributions of bottom sediment samples from Watering Bay reflect the maximum shear velocities attained during peak northward tidal flow. The 64th percentile of a bottom sediment grain size distribution may be used as an estimate of the boundary between bed and suspended load, and plotted on the suspension transport competence curve to estimate the maximum shear velocity. An estimate of maximum flow velocity at any water depth may then be calculated using the von Karman-Prandtl equation for flow above a rough boundary.
6. The floor of Watering Bay is a non-depositional surface across which tidal cuurents sweep all reef sediment supplied to it. The sediment is either deposited on a slope into deeper water at the northern end of the bay or removed from the immediate area by strong tidal currents from outside the reef.

A more detailed account of this research, including depositional environments, grain size data and analysis, sediment transport, and a general reef model will be published elsewhere.

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