CHRISTIANSTED HARBOR, ST. CROIX: A STUDY OF ITS DEPOSITIONAL ENVIRONMENTS AND SEDIMENT TRANSPORT AND THEIR EFFECTS ON THE ECOLOGY OF LONG REEF

by

JEFFREY KEITH ROSENFELD

Submitted in Partial Fulfillment
of the Requirements for the Degree of
Bachelor of Science
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
December, 1972 (i.e. Feb. 1973)

Signature of Author . . . .
Department of Earth and Planetary Sciences

Certified by . . . .
Thesis Supervisor

Accepted by . . . .
Chairman, Departmental Committee on Theses

Author miss numbered pages. Page 9 does not exist.

CHRISTIANSTED HARBOR, ST. CROIX: A STUDY OF ITS DEPOSITIONAL ENVIRONMENTS AND SEDIMENT TRANSPORT AND THEIR EFFECTS ON THE ECOLOGY OF LONG REEF

Jeffrey Keith Rosenfeld

Submitted to the Department of Earth and Planetary Sciences on December 1, 1972 in partial fulfillment of the requirements for the degree of Bachelor of Science.

Abstract

There is a distinct east-west gradient of species diversity along Long Reef, a coral reef community, which protects Christiansted Harbor, St. Croix, U.S. Virgin Islands from the open sea. This thesis attempts to isolate those geologic processes which are placing a stress on the ecological environment of Long Reef through the study of past and present depositional environments and means of sediment transport. The important factors determined include: return of inner harbor sediments over the reef due to an eddying effect around the easternmost end of the reef, high levels of turbidity due to land runoff, dredging, and beach erosion, and lack of firm substrate due to the movement of bottom sediments. Whether this gradient of species diversity is man-induced (dredging, raw sewage disposal, and poor land management) has not been conclusively determined.

Thesis Supervisor: Dr. John B. Southard, Assistant Professor of Geology

Table of Contents

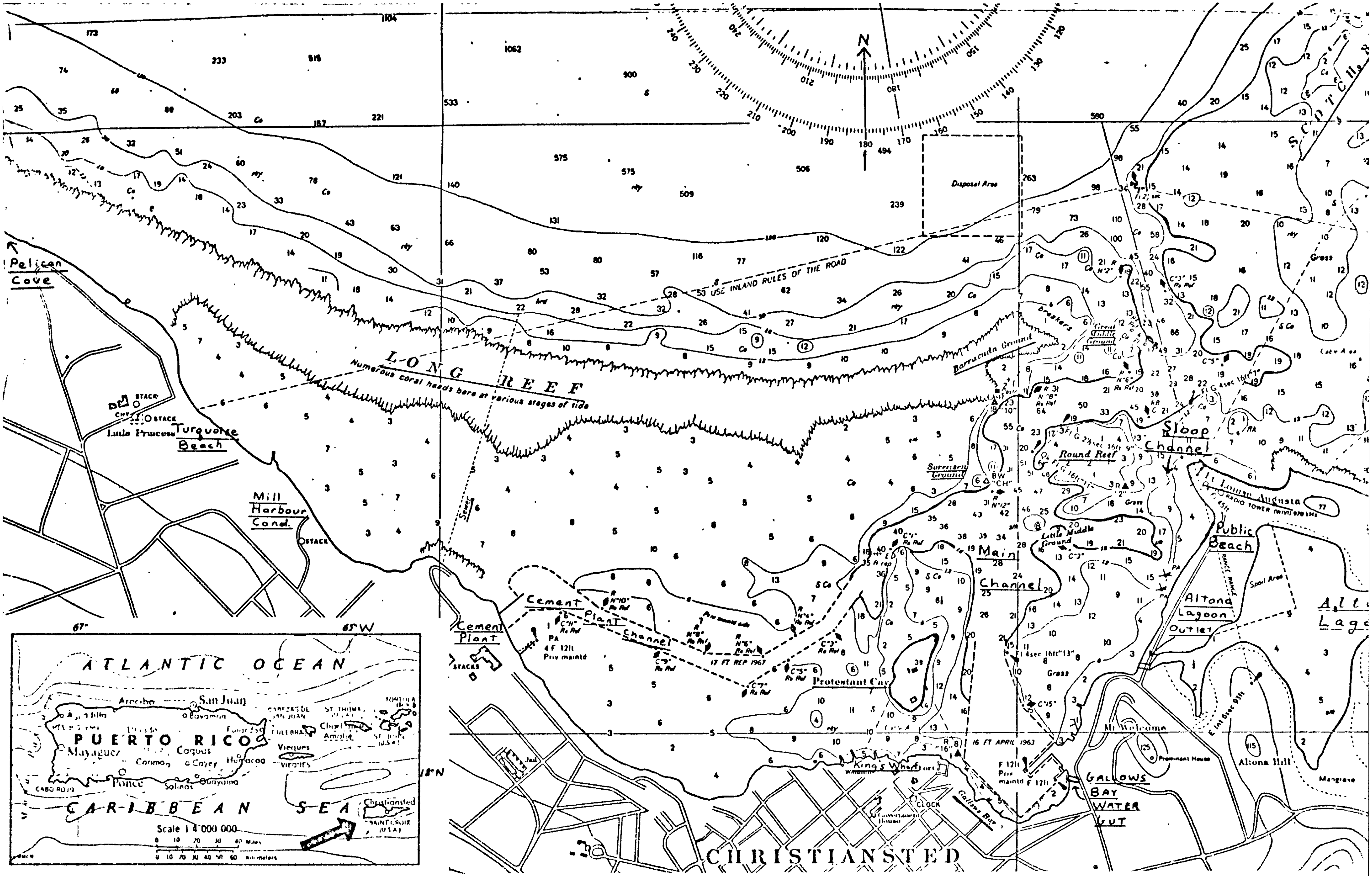
Table of Figures

0 1/4

Nautical Miles

Christiansted Harbor - C.&G. S. 1971

Soundings in Feet



Introduction

Christiansted Harbor, the most important harbor of St. Croix, U.S. Virgin Islands, is naturally protected from the open sea by Long Reef, a coral reef which stretches over two miles from its nearshore origins eastward to the entrance to the harbor. It has been observed that there is a distinct east-west gradient of species diversity along the reef. The western end of Long Reef is a flourishing Caribbean reef environment, while the eastern end, Barracuda Ground, is a barren, lifeless reef-rock environment.

The plan of the Virgin Island Project for Environmental Research[1] was to investigate the constructive and destructive forces acting on the reef using four approaches: biological, chemical, hydrographical, and geological. We attempted to separate the natural forces, such as wave action on the reef crest, from the man-induced forces, such as dredging and raw sewage disposal, and to weigh the significance of each of these factors.

This thesis represents the geological approach to the study of the harbor and consists of the geological description of the past and present depositional environments and means of sediment transport. It is hoped that through the examination of bottom sediments, core sections,

---

[1]Project name for the National Science Foundation Student Originated Studies Grant GY-9678.

and bottom currents, those geologic processes which are placing stresses on the ecological environment of Long Reef and Christiansted Harbor can be determined.

Methodology

The harbor was divided into thirty-four sampling areas by an approximate thousand-foot-square grid and a bottom sediment sample was taken at each grid point; additional samples were taken to make the sampling more representative. All the sampling points are shown in Figure 1. The samples were collected by divers, who sampled only the top few centimeters of sediment. These samples were manually wet sieved at 4ϕ (.062 mm) to separate the sand fraction from the mud fraction. The size distribution of the mud fraction from 4ϕ to 9ϕ (.002 mm) was determined by pipette analysis using a solution of 2.55 grams of Calgon per liter of distilled water as a dispersant. The size distribution of the sand fraction was determined by drying the sand and then dry sieving it with sieves from -1ϕ (2mm) to 4ϕ. Cumulative curves were plotted on arithmetic graph paper and the graphic mean size and the graphic standard deviation (Folk, 1968) were determined, as well as the percentage mud.

$$\text{Graphic Mean Size} = (\phi 16 + \phi 50 + \phi 84)/3$$
$$\text{Graphic Standard Deviation} = (\phi 84 - \phi 16)/2$$

The lithology of the constituent grains was determined by microscopic examination of the sand fraction, and the

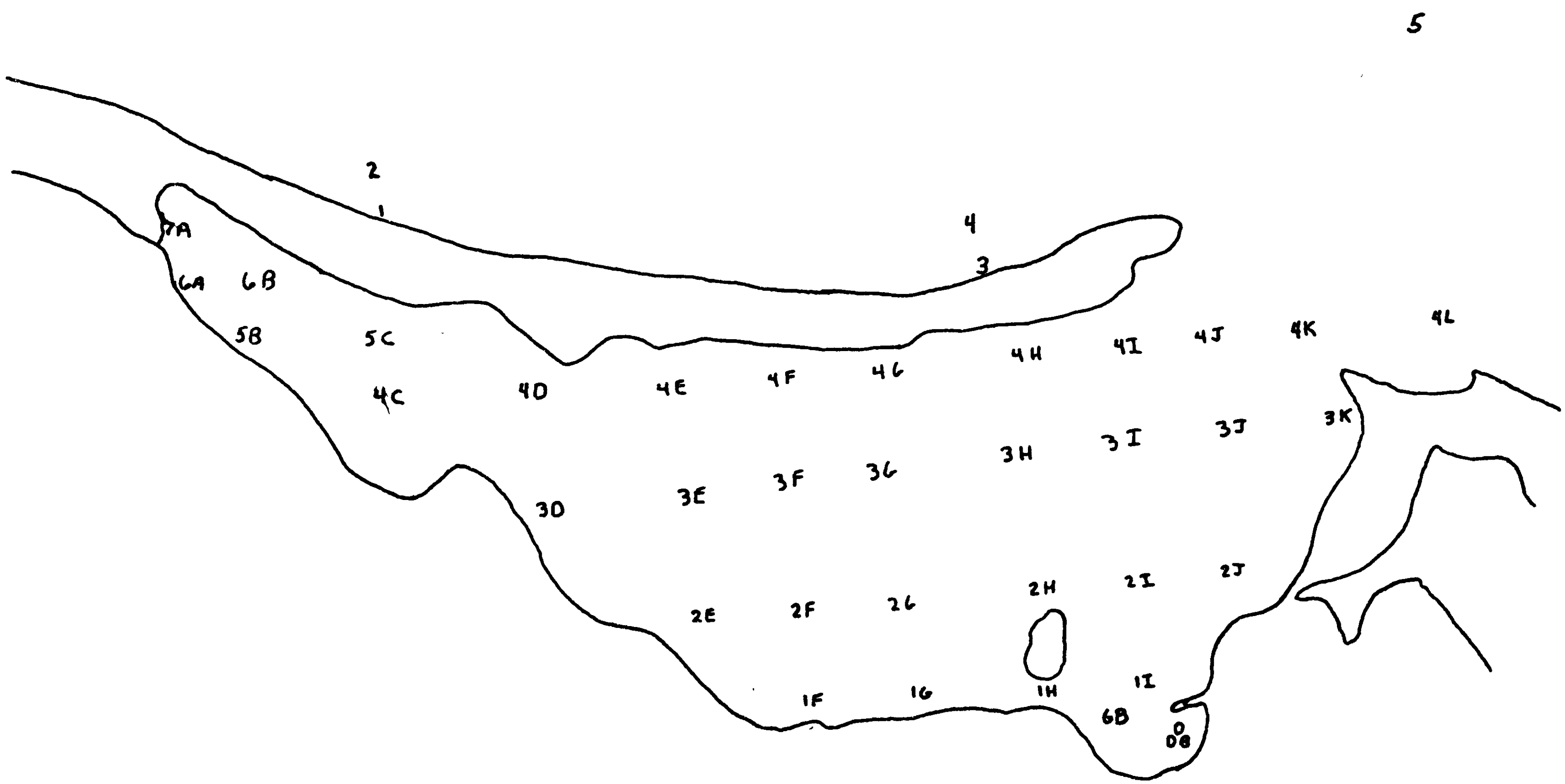


Figure 1. Location of bottom sediment samples

percentage of each sediment type was approximated.

A hammer-driven coring device was built according to the design suggested by Sanders (1968). Using this device, SCUBA divers took fifteen cores as shown in Figure 2. The stratigraphy of each core was observed and the changes in the depositional environment were studied by comparison of size distribution (wet sieving) and lithology (microscopic examination) throughout the cores.

Sedimentation rates were determined by placing sediment traps in the harbor (Figure 2). These traps were # 10 size food cans (six inch diameter), which were weighted down with cement, secured with stakes, and covered with marine mesh. Sediment transport was determined by studying bottom currents, turbidity, ripple marks, and beach erosion.

Topography

The topography of the harbor consists of four general features: the reef, the shoals, the channels, and an island, Protestant Cay. The main reefs are Long Reef, which extends for over two miles from Pelican Cove to the harbor entrance, and Round Reef, which is located west of Fort Louise Augusta between the Main Channel and the Sloop Channel. There are also patch reefs scattered throughout the harbor, especially near the entrance. The entire harbor west of Protestant Cay is a shoal, except for the Cement Plant Channel and the deep areas east of the Mill Harbour

Condominiums and the LBJ Public Housing Project, which are the result of dredging. The harbor east of the Main Channel, between Gallows Bay and Fort Louise Augusta, is also a shoal area, which has been greatly disturbed by dredging. Scotch Bank, which is north of Fort Louise Augusta and extends to the east, is also a shoal.

The Main Channel, which extends north from Gallows Bay, turns to the east around Round Reef and then proceeds north to the open sea. The channel was charted on Danish maps (around 1800), which suggests that it might be a natural geologic feature. The channel and Gallows Bay dock area were dredged to their present depths in the early Sixties. In 1968, the Cement Plant Channel was dredged.

The flow of water in and out of Altona Lagoon is tidally controlled. It is a restricted flow because the only outlet is a pipe, four feet in diameter, between the lagoon and the harbor. The lagoon is generally shallow and stretches over one mile to the east from the outlet pipe.

General Lithology

The major sources of sediment in Christiansted Harbor are: the coral reef; algae, especially *Halimeda*; land runoff from the Gallows Bay and King's Wharf water guts; and beach erosion. There is no permanent fresh-water river or stream emptying into the harbor. The general lithology of the harbor sediments is presented in Figure 3. There is a zonation of bottom sediments in the harbor according

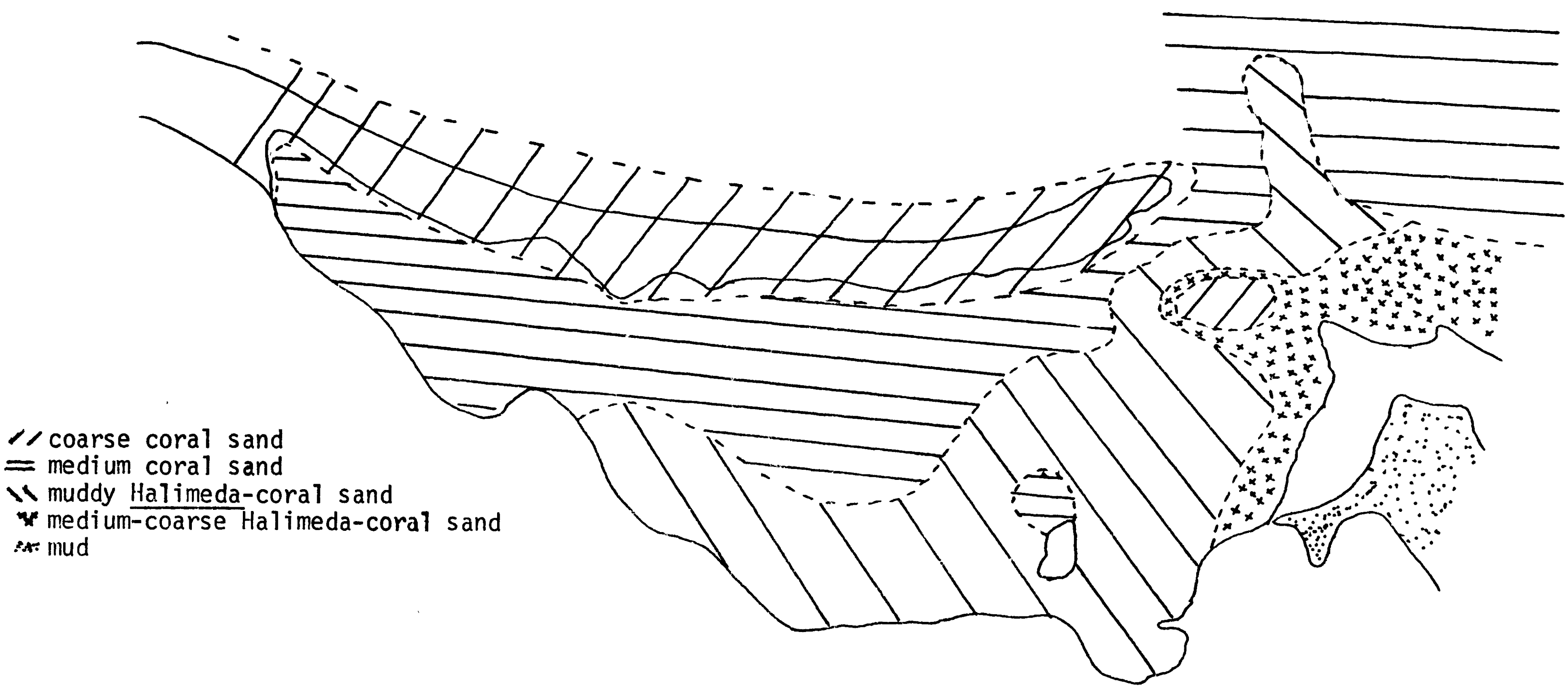


Figure 3. General lithology of Christiansted Harbor

to composition and size.

Coarse coral sand is present on all of Long Reef and its forereef zone, as well as on Round Reef and the patch reefs. Medium coral sand is present on the backreef zone (most of the Western Harbor), north of Protestant Cay, along the western side of the outer Main Channel, and on Scotch Bank. There is a mixture of Halimeda sand, coral sand, and mud in the Main Channel and south of the Cement Plant Channel from the Cement Plant to Gallows Bay. This indicates the abundant presence of Halimeda, in the harbor in the past, because at the present, the algae are found only in the far western end of the harbor. The mud seems to come from two sources: land runoff through the water guts and the improper use of sedimentation basins during dredging operations in the Western Harbor. Less important sources are: beach erosion at Turquoise Beach and at the landfill beaches, especially the public beach south of Fort Louise Augusta and the Mill Harbour Condominium Beach, and loading operations and stockpiles of sand at the Cement Plant. There is medium to coarse Halimeda-coral sand (Halimeda is predominant) along the eastern shore of the harbor and north and east of Fort Louise Augusta. This sand is similar to the muddy Halimeda-coral sand found in the channels except that the mud fraction in these areas has been washed away by either nearshore littoral currents or strong currents outside the harbor. Mud, rich in organic matter, is the predominant sediment type in Altona Lagoon.

Sediment Size Distribution

Both the mean size and the standard deviation, which quantifies the sorting of a sediment sample, serve as good indicators of different depositional environments. The mean size is related to the sources of the sediment while the standard deviation indicates the disturbance of an environment or multiple sources. It has been found that plotting the mean size versus the standard deviation in a scatter diagram serves to differentiate the environments even further (Folk and Ward, 1957). The map of the distribution of the mean sediment size is Figure 4 and the scatter diagram is Figure 5. The data for the mean size and the standard deviation as well the sediment composition and percentage mud data, which were also helpful in determining environments, can be found in Table 1.

The map for the mean sediment size corresponds quite strongly to the general lithology map, as well as to a map of the percentage mud contained in a sample of bottom sediments. The size distribution will be discussed in relation to the environments suggested by the scatter diagram.

Using the scatter diagram, the harbor can be separated into five main depositional environments (Table 2). The five environments were determined principally by field observations and the scatter diagram quantifies their size and sorting parameters. The scatter diagram also identifies those locations in a particular environment

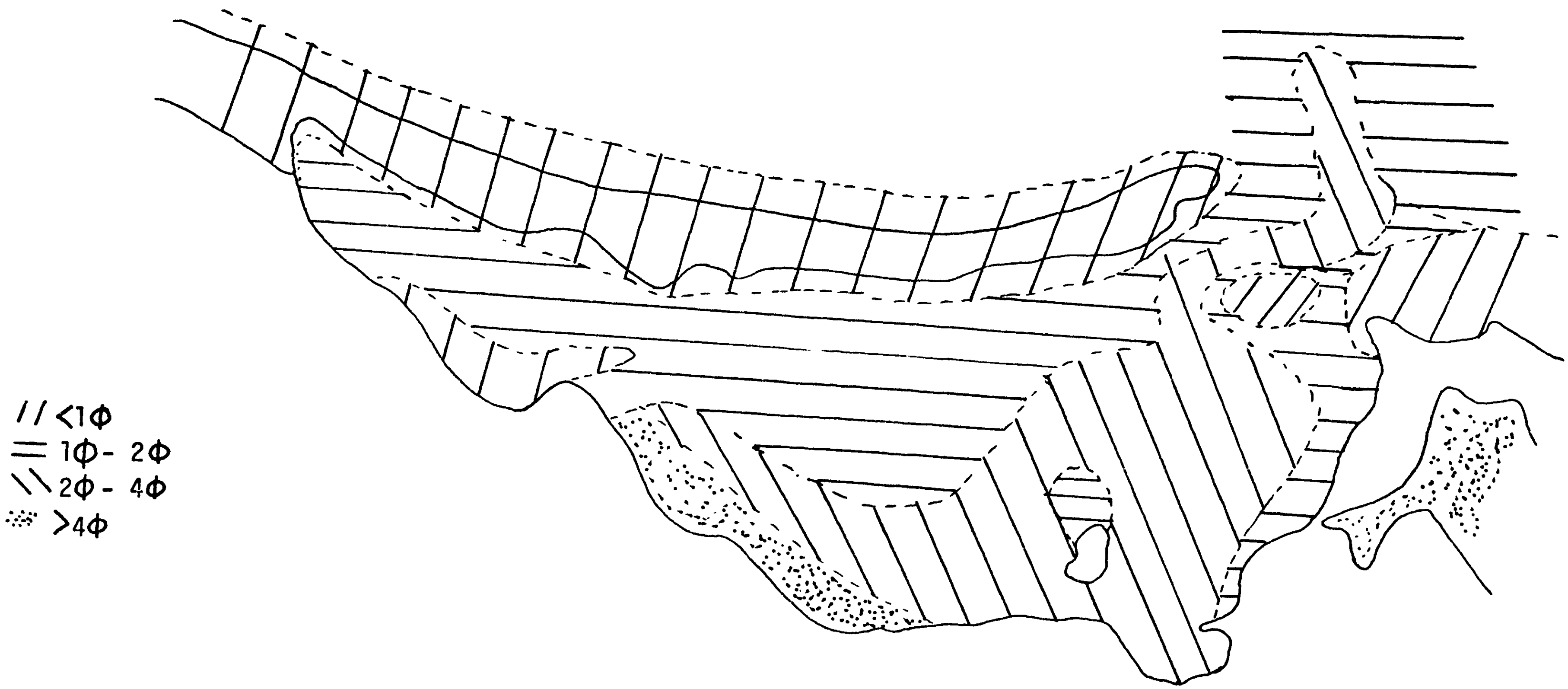


Figure 4. Distribution of mean sediment sizes in Christiansted Harbor

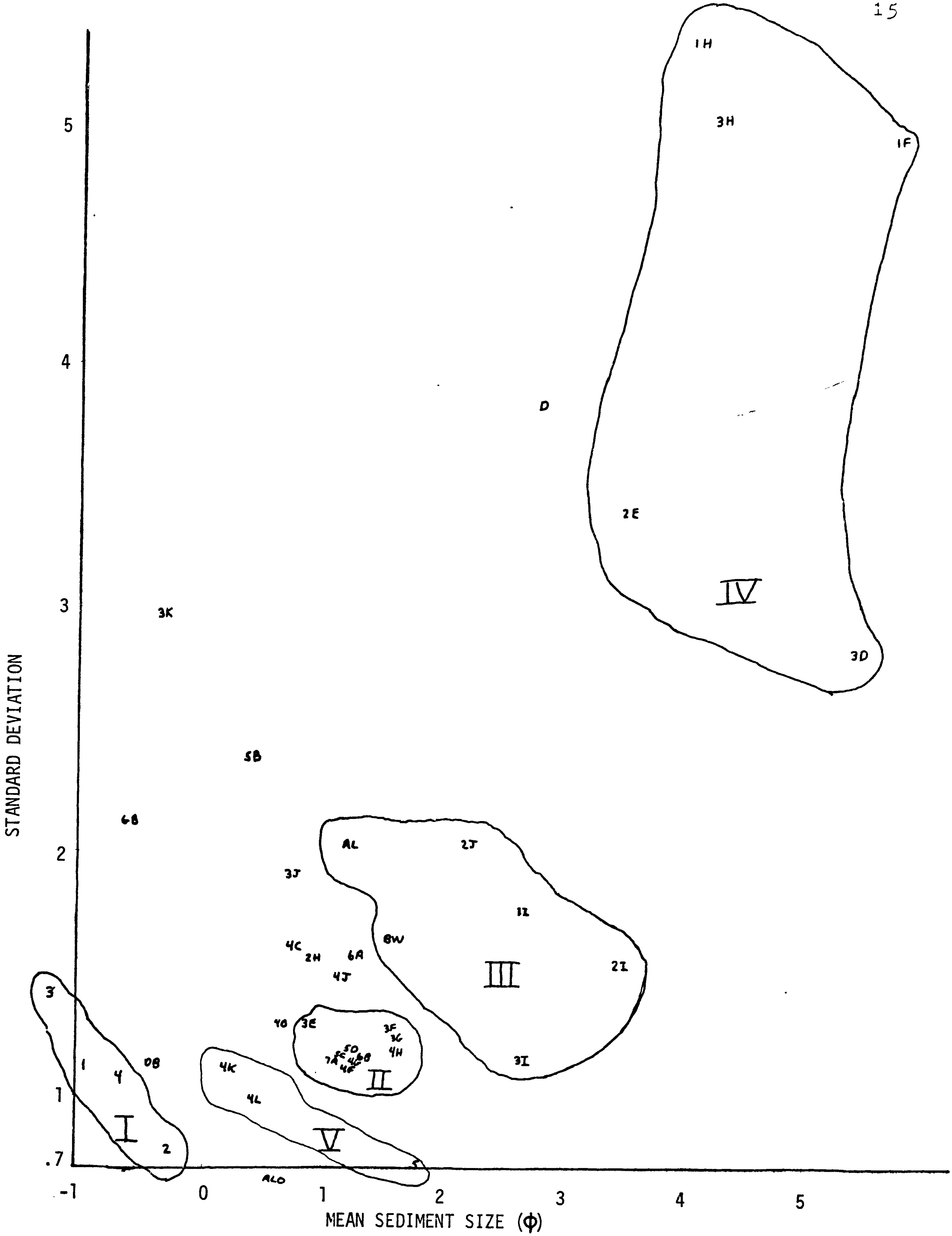


Figure 5. Scatter diagram of mean sediment size versus standard deviation

Table 1 - Bottom Sediment Sample Data

Sample #	Mean Size	Stand. Deviation	% Mud	% Coral	Halimeda/Coral
1F	5.78 Φ	4.88	58.7	35	1.4
1G	1.97	1.77	10.1	40	1.1
1H	4.1	5.31	31.3	30	2.0
1I	2.67	1.74	17.8	23	2.9
2E	3.51	3.38	33.5	64	.38
2F	2.23	.88	4.8	62	.24
2G	1.06	1.25	3.2	80	.06
2H	.95	1.55	5.9	65	.38
2I	3.48	1.50	38.2	35	1.6
2J	2.19	2.02	18.4	25	2.5
3D	5.44	2.8	65.9	85	.07
3E	.97	1.26	3.5	90	.02
3F	1.61	1.17	3.7	93	.02
3G	1.59	1.22	3.0	89	.03
3H	4.3	5.01	24.5	87	.05
3I	2.67	1.14	11.3	35	1.2
3J	.77	1.86	9.6	35	1.6
3K	-.37	2.95	6.6	20	2.0
4C	.79	1.58	2.7	80	.06
4D	.73	1.25	2.6	87	.01
4E	.50	1.04	3.5	86	.01
4F	1.31	1.11	2.6	93	.02
4G	1.39	1.13	1.9	88	.01
4H	1.62	1.18	3.7	82	.04
4I	.92	1.67	7.0	88	.04
4J	1.18	1.49	7.4	88	.06
4K	.27	1.10	4.0	10	6.0
4L	.50	.99	2.2	45	1.0
5B	.38	2.39	4.7	65	.20
5C	1.22	1.16	2.8	77	.03
5D	1.29	1.17	3.4	85	.04
6A	1.29	1.56	2.6	80	.09
6B	1.31	1.18	2.3	92	.01
7A	1.14	1.19	2.3	90	.01
AL	1.23	2.04	2.8	47	.80
ALO	.60	.64	1.7	85	.08
BW	1.42	1.62	10.6	10	6.0
D1	2.64	3.84	30.4	5	14.0
D2	-.38	1.12	2.0	64	.2
GB	-.59	2.11	8.6	5	10.0
1	-.90	1.12	0.0	90	.01
2	-.22	.74	0.0	92	.01
3	-1.2	1.4	0.0	93	.01
4	-.6	1.06	0.0	95	.01
5	1.92	.71	0.0	87	.08

which have been altered in some way. Many of these locations will be discussed after the five environments are described.

Table 2 - Depositional Environments

Environment	Mean Size (ϕ)	Standard Deviation
I Reef	-1.20 to -.22	.71 to 1.40
II Backreef	.97 to 1.61	1.11 to 1.26
III Eastern Harbor and Main Channel	1.23 to 3.48	1.14 to 2.04
IV Nearshore from Cement Plant to King's Wharf	3.51 to 5.78	2.80 to 5.31
V Scotch Bank and N. of Fort Louise Augusta	.27 to 1.92	.71 to 1.10

Environment I consists of coarse coral sand and rubble with the standard deviation depending largely on the amount of rubble included with the sand. Environment II is a medium coral sand whose source is the reef and has undergone reworking and transportation which provide good sorting. Environment III shows the contibution of a mud fraction, primarily from land runoff through the Gallows Bay water gut, to a medium _Halimeda_-coral sand. There appears to be better sorting the further from the water gut the sample was collected. Environment IV combines three sources. The first is mud, which was placed into suspension during dredging operations and the second is a coral sand which has been transported from the reef. The third is _Halimeda_ sand, which in the past must have been abundant in the inner harbor. Environment V really consists of two separate environments. One is Scotch Bank, which has medium coral sand and good sorting due to extensive transportation. The other is the area closer to Fort Louise Augusta, which is coarser and

and less well sorted. This is due to the addition of _Halimeda_ either naturally deposited there or transported from inside the harbor through the Sloop Channel.

One group of samples which did not define an environment on the scatter diagram are those from Gallows Bay (GB, DB, D). There is an unusual mixture of mud, _Halimeda_, and shells there, with the latter possibly being a lag deposit either of dredging or some other human activity. Samples 3J and 4J show the effect of proximity to Round Reef by having a larger mean size as compared to other Environment III samples. Sample 2H is indicative of the addition of sand to the environment from the erosion of a landfill beach on the north side of Protestant Cay. In the Altona Lagoon outlet pipe, ALO, the rapid flow of water into the harbor during low tide removes all of the mud from the dredge spoils near the outlet pipe. This results in the best sorted material in the harbor. The other non-conforming points can also be explained by multiple sources of sediment which affect the natural depositional environments.

Sediment Composition

The sediment samples were examined microscopically, and the percentage of coral, _Halimeda_, shells, foraminifera, gray carbonates, and coralline algae in each sample was estimated. Coral was the predominant constituent in the harbor; it was recognized by its white or yellow color and irregular shape. _Halimeda_, a calcareous green algae, was the second most predominant sediment type; it was recognized by its white color and multiple pore spaces. The other constituents were subordinate. The shells were mostly either gastropods or pelecypods. The recognizable foraminifera were predominantly Homotrea, which are indicative of a reef environment. Nichols, et al. (1972) considered the gray carbonates to be older sediments which had undergone partial diagenesis and therefore were good indicators of dredging. The coralline algae were reddish purple in color and either cylindrical or crustose in form.

The approximate percentage of coral and the Halimeda/coral ratio of the bottom samples are listed in Table 1. The latter is plotted on the map in Figure 6. The ratios confirm several of the depositional environments as obtained from the scatter diagram. They also pinpoint Gallows Bay as having the greatest abundance of Halimeda. This suggests that the Halimeda may have been destroyed during dredging operations in Gallows Bay ten years ago.

Coring

The cores provide a means for observing the changes in depositional environment in the recent past. The coring device worked quite well even without a core catcher; the only problem was compaction due to repeated hammering. Fifteen cores were taken in the harbor. Their locations are plotted in Figure 2 and their stratigraphy is described in Table 3.

Core #1 (Western Harbor) is an example of an undisturbed

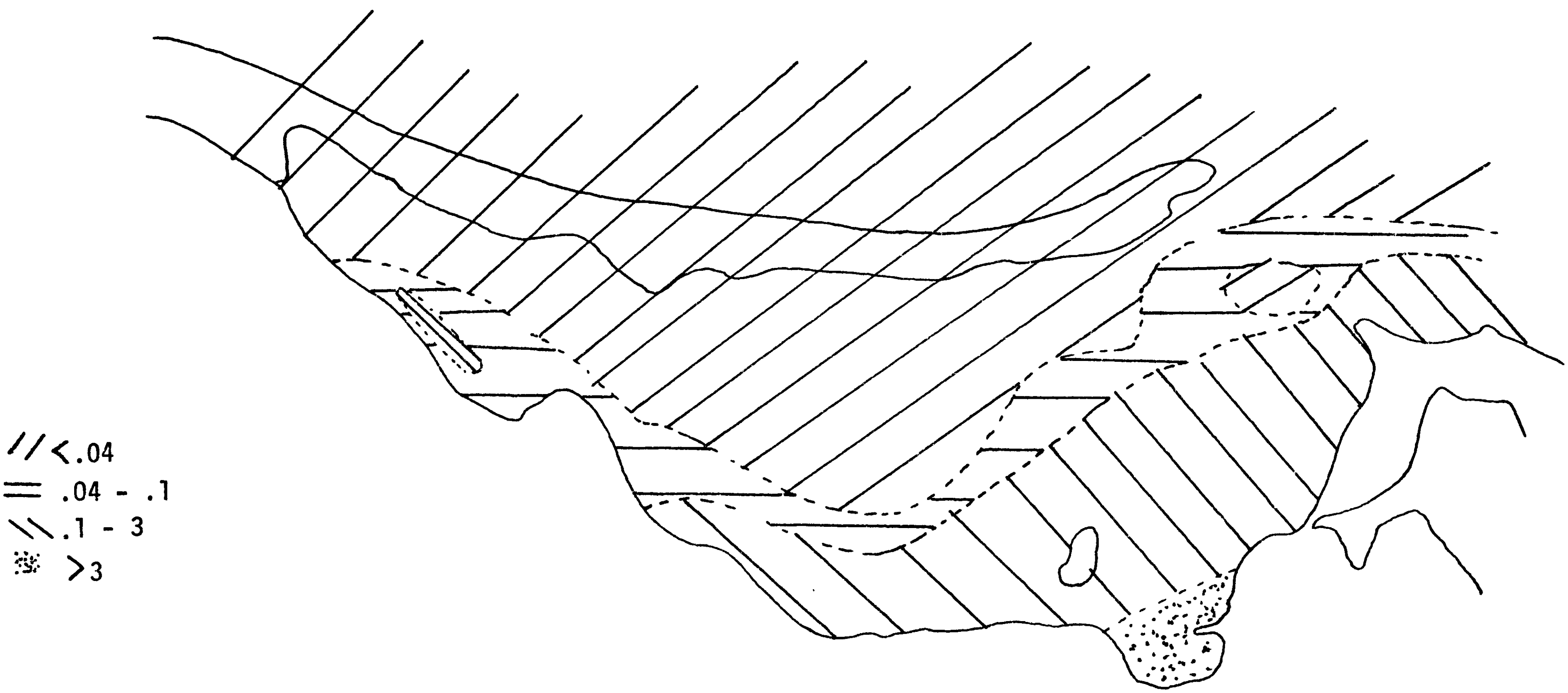


Figure 6. Distribution of Halimeda/coral ratios in Christiansted Harbor

Table 3 - General Stratigraphy of the Cores

Core # and Location	Length	Stratigraphy	
1. Western Harbor	50 cm.	0-50	homogeneous coarse coral sand
2. Top of dredge hole, Western Harbor	59	0-10	fine coral sand
		10-33	coarse coral sand with *Halimeda* and gray carbonates
		33-59	medium coral sand
3. Bottom of dredge hole, Western Harbor	60	0-15	fine coral sand
		15-60	medium coral sand
4. Nearshore - E of Mill Harbour Condominiums	25	0-8	black anerobic mud with dark gray carbonate pebbles
		8-25	yellow-brown clay with large pebbles
5. Nearshore - LBJ Beach	56	0-35	brown to black mud
		35-56	fine gray coral-*Halimeda* sand
6. Cement Plant channel	45	0-45	homogeneous light tan medium coral sand
7. Sorenson Ground	100	0-100	homogeneous light tan medium coral sand with a higher percentage of *Halimeda* below 30 cm.
8. Main Channel	94	0-94	homogeneous muddy fine gray coral sand
9. NE of Barracuda Ground	35	0-35	homogeneous medium coral sand
10. NE of Round Reef	26	0-10	yellow medium coral sand
		10-26	muddy medium gray coral sand with a higher percentage of mud below 18 cm.
11. Scotch Bank	54	0-25	medium yellowish coral sand
		25-54	fine white coral sand
12. Sloop Channel	30	0-25	medium gray sand-high organic content
		25-30	terrigenous non-carbonate dark gray pebbles and cobbles coated with white carbonate cement
13. Altona Lagoon	87	0-87	series of alternating bands of brown and gray muds and muddy *Halimeda* sand
14. Gallows Bay Dock	52	0-22	dark gray mud
		22-52	gray-brown clay
15. Gallows Bay Entrance	90	0-15	shelly layer
		15-90	light tan muddy sand with shells and *Halimeda*

backreef environment. There is no change in the stratigraphy because of the constant supply of medium to coarse white coral sand from the reef. Cores #2 and #3 (Dredge hole, Western Harbor), at a site which has been dredged within the last two years for landfill, are hard to interpret because of their constant composition. However, the fine coral sand at the top of both of these cores would seem to indicate deposition by siltation after the dredging activities, since fine sand is not normally deposited in the backreef environment. Cores #4 (Mill Harbour) and #5 (LBJ Beach) show the direct results of dredging operations in which the mud fraction was allowed to flow directly back into the harbor. This is especially shown in core #5, in which the top 35 cm is mud whereas there is fine coral-Halimeda sand at greater depths. The other core, which probably shows the effects of dredging, is core #10 from the forereef zone of Round Reef. The top 10 cm is medium yellow coral sand which is expected from a reef crest which is predominantly Acropora palmata. However, below that is a muddy medium coral sand, which suggests addition of mud to the normal forereef sand. In the early Sixties, both the Gallows Bay dock area and the Main Channel were dredged. Since the bottom currents flow north in the channel and both of these locations contain mud, it seems probable that the mud was placed in suspension during dredging. It was then deposited in front of Round Reef as it was being flushed out of the harbor. Also since this layer is anaerobic, and anaerobic conditions can be produced by rapid burial, the muddy layer would seem to be due to the work of man rather than natural causes.

The homogeneity of the Sorenson Ground (#7) and Main Channel (#8) cores is interesting in that it suggests that both of these areas are under the influence of continuous natural processes. Sorenson Ground is a shoal area where there is active deposition, as determined by comparing its present size with old aerial photographs. The source of these sediments is probably the backreef zone. The predominant source of sediments in the Main Channel is from land runoff through the Gallows Bay water gut. The Scotch Bank (#11) core was interesting because of the change in color and size of the coral sand at a depth of 25 cm. Presently the area is supplied with sediment from the east, and the change in color and size of the coral sand poses the problem of what change in the source of the sediments has occured. The Altona Lagoon (#13) core, which also poses a problem, has alternating mud and Halimeda sand layers as compared to the single change in stratigraphy exhibited in Nichols' (1972) core. This may have resulted from deposition of the dredge spoils in our more nearshore location. The source of the shelly surficial layer in the Gallows Bay Entrance (#15) core is also not readily explainable except possibly as a dredging or fishing lag deposit produced by man.

To determine whether the east-west gradient of species diversity along the reef is a recent or older phenomenon, we attempted to take a core in the reef crest. We used a hydraulic drilling rig with a diamond studded bit. The rig was mounted on a barge equipped with stabilizing legs, which could be used to lift the barge out of the water. However, two problems arose which prevented our successful drilling of the reef. The first was the heavy wave action of the reef crest, which made stabilizing the barge difficult. The second was sand layers, which affected both the bit and the flow of water necessary for drilling. This drilling is of the utmost importance in determining both the history of the reef and in planning for future utilization of the harbor. Therefore, it should be included in any future study of the harbor.

Sedimentation

The sediment traps were left in the harbor for seven weeks. The traps only measure sedimentation due to siltation. They cannot measure deposition due to sediment movement as bed load because the opening in the can was greater than eight inches above the harbor floor. For the same reason, erosional forces cannot effect the amount of collected sediment. Other problems with this method are finding the cans after the algae have covered them and securing the traps in reef-rock environments. The locations of the recovered sediment traps are shown in Figure 2.

To determine a sedimentation rate by siltation, we have assumed a composition of 100% calcium carbonate with a specific gravity of 2.7 and a porosity of 50%. The data are listed in Table 4 and can be assumed to be a minimum value for a sedimentation rate except where there are strong erosional forces at work.

Table 4 - Sedimentation Rates Due to Siltation

Sediment trap location	Wt. (7 weeks)	Sed. rate	Sediment description
1. Gallows Bay	235.5 gm.	7.2 cm./	*Halimeda* sand + mud
2. Altona Lagoon outlet	455.7	14.0	tan fine sand
3. N of Protestant Cay	1308.6	40.2	tan fine sand
4. Sorenson Ground	33.5	1.0	tan fine sand + mud
5. S of Barracuda Ground	280.9	8.6	tan fine sand + mud
6. Scotch Bank	15.4	0.4	tan fine sand
7. Cement Plant	138.5	4.2	black mud
8. SE of Turquoise Beach	74.6	2.2	black mud
9. Western Harbor	20.2	0.6	tan fine sand

The sedimentation rate NE of Protestant Cay is probably too large due to a strong wind-driven surface current, but that area is definitely a depositional environment, with the source of sand being the erosion of the landfill beaches on Protestant Cay. The deposition is probably caused by the interaction of the surface current with an opposite-flowing bottom current. The area in front of the Altona Lagoon outlet pipe is definitely a depositional environment, as shown by the necessity of periodic dredging to keep the outlet open. There is a small reef to the west of the pipe, which, when combined with the strong flow of water out of the pipe, explains the high deposition rate in the area. In Gallows

Bay and near the Cement Plant, the mud is placed in suspension by ships' propellers during docking operations. South of Barracuda Ground, the sediment is in suspension because of the heavy wave action on the reef. At Sorenson Ground and Scotch Bank, there was not much deposition in the traps because the primary sand movement is by bed load, as shown by the presence of ripple marks. The deposition SE of Turquoise Beach is confirmed by turbidity in the area, which is quite noticeable on aerial photographs.

Sediment Transport

Determination of sediment transport has depended heavily on knowledge of bottom currents and beach erosion, aerial photography of turbidity, presence of ripple marks, and bathymetry of the harbor.

The Main Channel and the Sloop Channel are the only exits for sediment leaving the harbor. The Main Channel has a path similar to a meandering stream, with the resulting deposition on the inside of each turn and erosion on the outside. This can be confirmed on the bathymetric map of the harbor by the erosion south of Barracuda Ground and the deposition directly east of Barracuda Ground. There is also deposition on the eastern wall of the outer channel due to the westward movement of sand on Scotch Bank. Sorenson Ground is an area of deposition, whose source is the reef and backreef, as shown by ripple marks. Deposition seems to be caused by the interaction of currents from the Main Channel, the Cement Plant Channel, and the backreef zone.

North of Barracuda Ground, there is a return of sediment from the channel back over the reef, as shown by bottom currents. However, at buoy #1, a turbid layer between 80 and 120 feet of depth has been observed moving to the north, which is probably the mud from the inner channel floor being carried out of the harbor. The surficial sediment at buoy #1 is a medium coral sand with little mud, whose source seems to be Scotch Bank. During normal sea and weather conditions, there may not be significant return of inner harbor sediments over the reef, but there is probably some return, especially from sediment transported from Great Middle Ground. Any sediment returned over the reef will play a role in the erosion of the reef crest and the subsequent destruction of the reef. Therefore, it is important to consider the effect of long-term dredging or extremely rough seas, both of which place larger than usual sediments into suspension, will have on Barracuda Ground, knowing that some of the sediment will be returned over the reef. It is also important to consider the possibility of sediment transport from Scotch Bank over the channel and the reef during extreme conditions, such as a hurricane.

The next area of interest is along the eastern shore of the harbor. The sediment moves northward through the Sloop Channel and probably into the area directly north of Fort Louise Augusta, as shown by the presence of Halimeda, which appears to decrease with distance from the Sloop Channel. Inside the harbor, there is a littoral current to the south from Fort Louise Augusta to the Altona Lagoon outlet. There is also a littoral current northward from Gallows Bay to the bend in the shoreline (Mt. Welcome) directly west of the outlet pipe. At this bend, there is a turning of currents and the sediment is transported to the northwest. On the aerial photographs, a turbidity cloud was seen stretching to the northwest from Mt. Welcome to Protestant Cay. Possible causes of this current direction are the geography of the land, the littoral current caused by the Altona Lagoon outlet pipe, wind pressure from the east, and the interaction of the littoral and Main Channel currents.

In the Western Harbor, the principal current is a littoral current which moves generally to the southeast. There is sediment transport involved, as can be seen from the turbidity and presence of mud all the way from the Cement Plant to King's Wharf. In the reef zone, sediment transport is directly over the reef from the northeast. In the backreef zone, the bottom currents are turning slowly to the east as they approach the Cement Plant Channel. This is confirmed by the presence of ripples in the eastern half of the backreef. This sediment is the probable source of the medium coral sand of both Sorenson Ground and the western wall of the Main Channel.

Ecological Stresses

The two major geological stresses on the ecological environment of Christiansted Harbor are turbidity and the lack of firm substrate. Turbidity is harmful to coral in the following ways: it reduces the available light for the photosynthetic activity of zooanthellae, which lives symbiotically with the coral polyps; it may smother the corals if prolonged deposition occurs; it causes abrasion to the coral; and it creates an unfavorable substrate for the settling of coral planulae. Coral planulae need a firm bottom without loose sediments in order to settle successfully (Johannes, 1972).

Turbidity and substrate are interrelated, and the resulting problems are caused by a combination of land runoff, dredging, and the placement of bottom sediment into suspension by commercial ships during docking. Land runoff of terrigenous sediment and street debris is a most serious problem in Gallows Bay due to poor land management in the hills behind Christiansted. It is also a problem near the outlet of the King's Wharf water gut.

Dredging is another source of suspended sediments. In the last decade, a considerable amount of dredging has taken place (Table 5).

Table 5 - Dredging Operations in Christiansted Harbor[2]

Date	Volume of sand removed	Location
1962		Gallows Bay
1963	147,000 yd^3	Central and Western Harbor
1966	600,000	Central and Western Harbor
1966	350,000	Central Harbor
1968	670,000	Eastern Harbor
1968	150,000	Cement Plant Channel

[2]U.S. Army Dredging Permits and Nichols, et al. (1972).

No new dredging permits have been issued by the U.S. Army Corps of Engineers since 1968, and it has been slightly more than a year since the last dredging activities have occured. The turbidity results both from the actual dredging and also from the return of sediment-laden water to the harbor after settling has supposedly taken place in the sedimentation basins. It appears that the utilization of sedimentation basins in some of the dredging operations in Christiansted Harbor has been far from complete. The creation of landfill beaches, especially the public beach south of Fort Louise Augusta and the Mill Harbour Condominium Beach, has created additional sources of suspended sediment due to the erosion, which must occur until equilibrium between the landfill and the harbor is reached.

The other major source of turbidity is the churning of bottom sediments by commercial ships' propellers during docking operations. This is occuring in Gallows Bay and in the Cement Plant's turning basin at the western end of the Cement Plant Channel. Turbid conditions would also be prevalent in times of extreme storms, when not only the harbor sediments would be stirred into suspension but also sediment could be carried into the harbor from Scotch Bank.

The substrate is definitely unfavorable for coral planulae in these areas of high turbidity due to a rapid rate of sedimentation. It is also unfavorable in areas of strong sediment transport, which would include such areas as the channels, the shoal NW of Protestant Cay, and along the shoreline.

In conclusion, besides the problems of turbidity and substrate, a major factor in the destruction of Barracuda Ground may be the eddying of bottom currents around the easternmost point of the reef. Due to this return flow over the reef, some of the suspended sediments and pollutants released in the inner harbor will remain circulating in the harbor, causing a potential hazard to the health of the coral reef community. However, documentation of when the reef died is not available, and until it is, one cannot blame man, despite his dredging operations, raw sewage disposal, and poor land management, for the destruction of Long Reef.

Acknowledgments

This thesis was supported by the National Science Foundation Student Originated Studies Grant GY-9678. I would like to express my appreciation to the ten other undergraduates on the VIPER team: John B. Balazy, biologist; Christopher D. Cunningham, biologist; Mitchell L. Dong, Student Director; Michael B. Elliot, photographer; Curtis E.A. Karnow, chemist; David R. Kenigsberg, chemist; Paul M. Novak, biologist; Bruce M. Poole, biologist; Greg A. Redmann, biologist; and Keith B. Ronnholm, physicist.

I would like to thank Dr. John C. Ogden for being our faculty advisor and all the other members of the staff of the West Indies Laboratory of Fairleigh Dickinson University for their assistance. I would also like to acknowledge the help given the VIPER team by Soil Testing Services, Caribbean, Inc., Riggers and Erectors, Inc., Fischer Hess, Inc., and the West Indies Laboratory in obtaining, building, and operating the equipment necessary for our unsuccessful attempt to take a core in the reef crest.

I would also like to thank Dr. John B. Southard for being my thesis advisor.

Bibliography

Folk, Robert L. (1968), Petrology of Sedimentary Rocks, Hemphill's, Austin, Texas.

Folk, Robert L. and William C. Ward (1957), Brazos River Bar: A Study in the Significance of Grain-Size Parameters, Journal of Sedimentary Petrology 27, p. 3.

Johannes, R.E. (1970), How to Kill a Coral Reef, Marine Pollution Bulletin 1, p. 186.

Johannes, R.E. (1972), Coral Reefs and Pollution, Manuscript submitted at the U.N. Conference on the Human Environment, Stockholm, June, 1972.

Levin, James (1970), A Literature Review of the Effects of Sand Removal on a Coral Reef Community, University of Hawaii, Department of Ocean Engineering Report.

Nichols, Maynard, et al., (1972), Environment, Water and Sediments of Christiansted Harbor, St. Croix, Government of the Virgin Islands Department of Health, Division of Environmental Health, Water Pollution Report No. 16.

Sanders, John E. (1968), Diver-Operated Simple Hand Tools for Coring Nearshore Sands, Journal of Sedimentary Petrology 38, p. 1381.