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Parameters Controlling Sediment Composition of Modern and Pleistocene Jamaican Reefs

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PARAMETERS CONTROLLING SEDIMENT COMPOSITION OF MODERN AND PLEISTOCENE JAMAICAN REEFS

by

Stephen K. Boss

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of

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in

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1985

To my family
for their love and support in
helping me to complete this work.

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Stephen K. Boss

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ABSTRACT

Parameters Controlling Sediment Composition of Modern and Pleistocene Jamaican Reefs

by

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Utah State University, 1985

Major Professor: Dr. W. David Liddell
Department: Geology

Recent carbonate sediments from Jamaican north coast fringing reefs display variation in constituent composition, texture, and mineralogy related to their location on the reef. Samples were collected along lines which traversed the back reef and fore reef (0.5m to 70m).

The sediment is dominated by highly comminuted coral fragments, plates of the calcareous green alga, Halimeda, coralline algae, and the encrusting Foraminifera, Homotrema rubrum, with lesser amounts of other taxonomic groups (Foraminifera; molluscs; echinoderms). Relative abundances of these biotic components vary between sites. Q-mode cluster analysis indicates that constituent composition can be used to delineate the different reef zones which have been described from analyses of the macrofauna.

For most sediment, grain-size frequency distributions indicate that greater than 90% (by weight) of the sample is contained in the interval of 0.125mm to 2.000mm. Mean grain size approaches 0.5mm for most sites with little depth related variation. Sorting, however, becomes progressively poorer from the shallow (5m) fore reef terrace to the upper deep fore reef (70m).

X-ray diffraction and insoluble residue analyses indicate that total $CaCO_3$ in these sediments is generally greater than 95% by weight. Aragonite is the most abundant carbonate phase, followed by high-Mg calcite, and low-Mg calcite. Amorphous siliceous sponge spicules and organic matter comprise the remaining non-carbonate fraction of these sands. Significant differences in the proportions of aragonite and high-Mg calcite between fore reef terrace sediments and sediments from other reef zones results from the contribution of high-Mg calcite to fore reef terrace sediments by coralline algae, Foraminifera (principally *Homotrema rubrum*) and echinoderms, which are relatively less abundant sediment constituents elsewhere on the reef.

The 120,000y.b.p.(Sangamon) Falmouth Formation along the north coast of Jamaica displays variability in sedimentological and faunal components analogous to that of back reef and shallow fore reef environments of the modern Jamaican fringing reef system.

X-ray analysis of the mineralogy of Falmouth limestones reveals that surface exposures of fore reef grainstones exhibit greater diagenetic alteration than surface exposures of back reef packstones. This indicates variability in diagenetic processes most likely related to original sediment textural characteristics.

(101 pages)

CHAPTER I

INTRODUCTION

In recent years, geologists have turned to the study of Holocene carbonate accumulations in an attempt to better understand the physical factors involved in the development of ancient carbonate rocks. Much of the work of geologists has centered on peripheral areas of the Caribbean such as South Florida (Ginsburg, 1956), the Belize Shelf (Wantland and Pusey, 1975), and Barbados (Scoffin, *et al*., 1980). These studies have done much to increase our knowledge of carbonate depositional environments.

The north coast of Jamaica provides a unique opportunity for detailed analysis of a classic fringing reef environment. For the present study, quantitative measurements of reef biota were made by transecting a number of reef zones (Liddell, *et al*., 1984a and b). This information will be used in analyses of sediment constituents to reveal the relationship between reef-community composition and the biological, textural, and mineralogical composition of reef-derived sediments.

Finally, the utility of using sediment constituent composition as an indicator of specific reef-environment will be tested. By applying information gained from study of the Holocene sediments, an interpretation of the paleoenvironments of the Pleistocene Falmouth Fm. will be made.

CHAPTER II

PATTERNS OF CONSTITUENT COMPOSITION AND TEXTURE OF JAMAICAN FRINGING REEF SEDIMENTS

INTRODUCTION

Fringing coral reefs along the north coast of Jamaica display a striking pattern of biological zonation which is related to the environmental tolerances of the reef biota (Goreau, 1959; Goreau and Goreau, 1973; Kinzie, 1973; Ohlhorst, 1980; Liddell and Ohlhorst, 1981; Liddell, *et al.*, 1984a). The continual degradation of the calcareous skeletons of these organisms by biological and mechanical processes produces sediment which accumulates in reef interstices and in sand channels (grooves) adjacent to reef spurs.

Extensive sampling and analysis of these Recent carbonate sands was undertaken in an effort to better understand the physical and biological aspects of sediment production, composition, and transport within the fringing reef system. In order to accomplish this, it was necessary to: 1) determine the constituent composition and textural features of reef sediments; 2) determine the relationship of sediment composition to reef community structure; and 3) determine if sediment composition alone could be used to delineate reef microfacies.

PREVIOUS WORK

Modern efforts to quantify the composition of Recent calcareous deposits were begun by Thorp (1934; 1936). He described the composition of carbonate sediments from southeastern Florida and the Bahamas, and from the Pearl and Hermes reefs of the central Pacific. In reading Thorp's accounts, one is impressed by his apparent surprise that skeletal remains of calcium-carbonate secreting organisms were the dominant components of these sediments. He also recognized the importance of calcareous algae as sediment contributors.

In the period following the pioneering studies of Thorp, a tremendous volume of geological research has been dedicated to the analysis of Recent carbonate facies and their relationship to specific depositional environments. These studies have centered on the classic tropical localities of the Caribbean (Illing, 1954; Ginsburg, 1956; Purdy, 1963a and b; Milliman, 1967; Wantland and Pusey, 1975) and Australia (Fairbridge, 1950; Maxwell, et al., 1961; Maxwell, et al., 1963; Maiklem, 1970; Davies and West; 1981) but, have also come from the Central Pacific (Chave, et al., 1972), the Middle East (Friedman, 1968), and the Indian Ocean (Stoddardt and Yonge, 1971). Excellent reviews of this subject have been authored by Bathurst (1971) and Milliman (1974). The reader is referred to these works for additional background information.

Illing (1954) produced a monumental treatise on the calcareous sands of the Bahamas. This work illustrated, through aerial photographs, thin-section analysis, and description of grain-types, the carbonate facies of the Bahama Bank. Also, Illing made speculative judgements concerning the origin of non-skeletal grains such as pellets, ooids, and grapestones.

Ginsburg (1956) continued the study of Recent carbonates with a survey of carbonate sedimentation in south Florida. Ginsburg was able to recognize two distinct sedimentary environments in this region: Florida Bay and an Outer Reef Tract seaward of the Florida Keys. He noted that faunal components in sediments from these two areas were quite distinct. He attributed variation in constituent composition of these sediments to variation in the abundance of sediment-contributing organisms due to their environmental tolerances.

Purdy (1963a) extended Illing's (1954) observations of sedimentation around the Bahamas using newly developed multivariate techniques. Using a computer to measure the correlation between all pairs of sediment grain-types, he was able to delineate several "reaction groups" or clusters of grain-types which were found to occur together. Based upon these reaction groups, Purdy was able to define and map five distinct sedimentary facies within the Bahama Platform.

In similar fashion, Pusey (1975) conducted a study of carbonate sediments on the Belize Shelf in Central America. In this case, factor analysis was used to delineate eight sedimentary facies which were related to physical (wave and current energy) and biological (constituent composition) aspects of the various shelf environments.

Goreau and Goreau (1973) discussed some general aspects of the composition of sediments from Jamaican north coast reefs. In particular, they noted changes in the proportions and species composition of Halimeda plates in the sediment with depth, and suggested that the different Halimeda species could serve as excellent environmental indicators. Moore, et al. (1976) used the Halimeda species composition of island slope sediments as evidence of the transport of reef sand from the fore reef slope (24-55m) to the upper island slope (122-295m).

Several quantitative studies of reef-community structure have been conducted on Discovery Bay reefs (Bonem and Stanley, 1977; Ohlhorst, 1980; Liddell and Ohlhorst, 1981; Liddell, et al., 1984a; Liddell, et al., 1984b). These studies extended observations from the back reef to the near limit of scleractinian-dominated reef growth on the fore reef slope (55m). In general, each of these studies has found similar patterns of community composition, bottom cover, and species diversity. Coral cover is high throughout the depth range studied, although a distinct reduction is found at 24m due to the unstable nature of the fore reef escarpment. Cover by macroalgae (including Halimeda), filamentous algae and fleshy sponges increases with depth from 5m to 55m, whereas cover by coralline algae and boring sponges decreases with depth.

This investigation presents the results of analyses of the sediments accumulating on reefs at Discovery Bay and relates sediment composition and texture to changes in biological (reef community structure) and physical (wave energy) processes occurring within the fringing reef system.

LOCATION OF STUDY

Field work for this study was conducted from the Discovery Bay Marine Laboratory of the University of the West Indies during the summer of 1982. This facility is located on the Jamaican north coast at Discovery Bay (lat. 18° 30' N, long. 77° 20' W) and provides easy access to the modern fringing reef (Fig. 1). Following this period of field work, detailed analyses of sediment samples and data were conducted at Utah State University.

METHODS

Sampling Procedures

Divers using SCUBA collected shallow cores of sediment on the fringing reef in 15cm length x 5cm diameter plastic cylinders. Approximately 200g of sediment were collected in each of 125 cores. Samples were collected along three parallel transects on the fringing reef (Fig. 1). Each of these transects extended from near shore and across the back reef (1-5m), fore reef terrace (5-14m), fore reef escarpment (14-24m), fore reef slope (24-55m) and upper deep fore reef

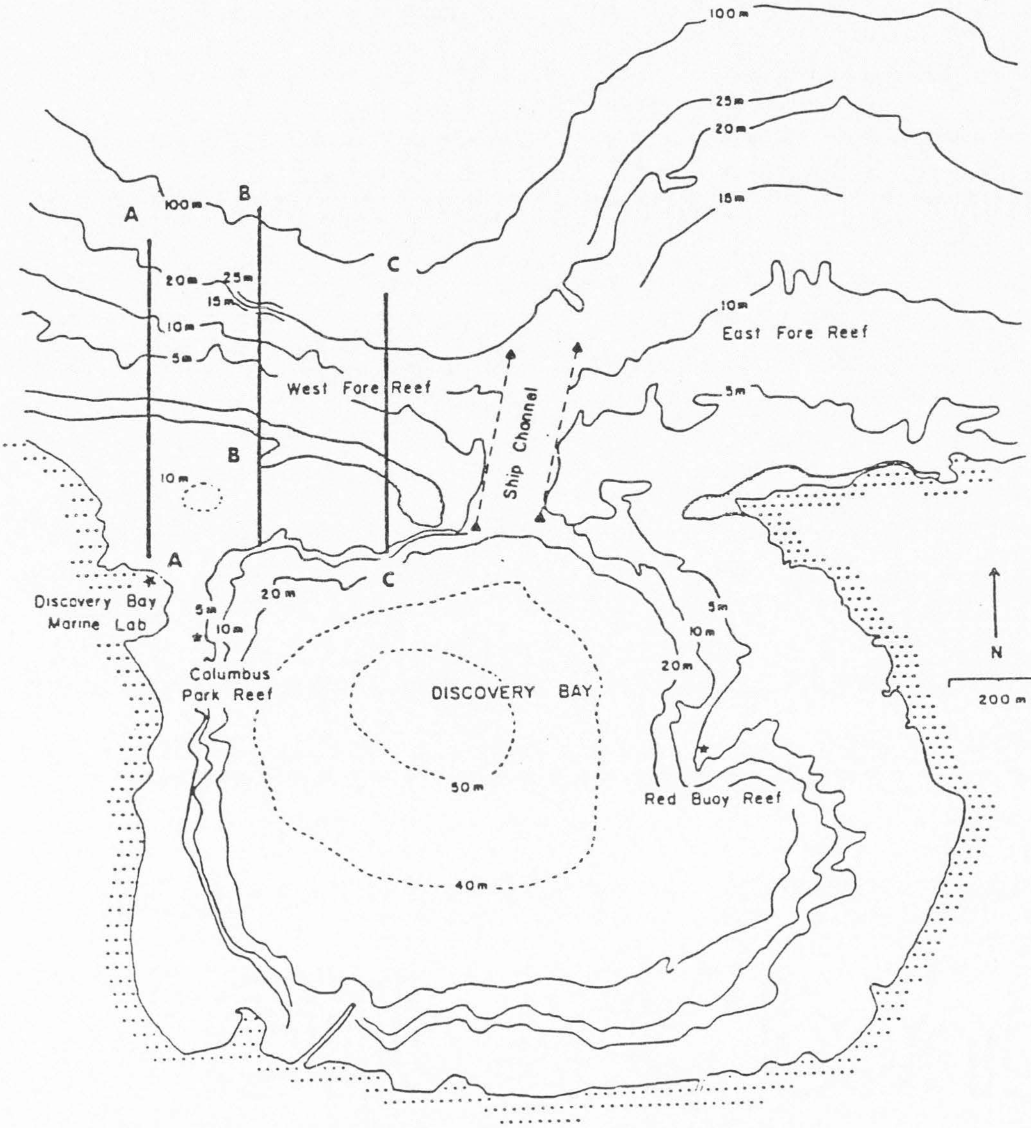


FIG. 1. Bathymetric map showing Discovery Bay, Jamaica, adjacent reefs, and location of three reef transects of this study (modified from Liddell and Ohlhorst, 1981).

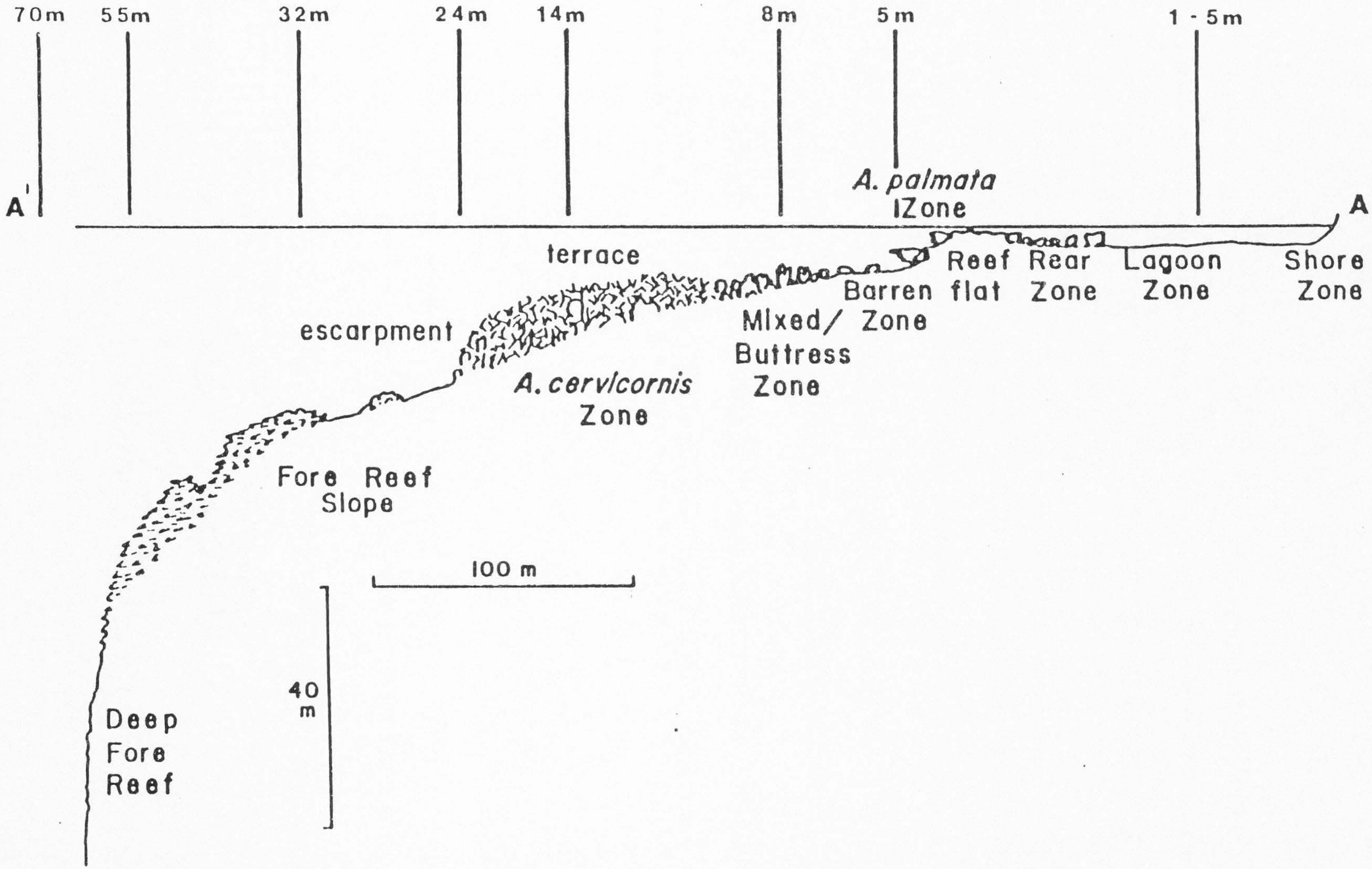
(70m)(Fig. 2; terminology after Goreau, 1959; Goreau and Goreau, 1973; Goreau and Land, 1974). Detailed descriptions of collection methods in each reef zone are presented below.

Back Reef (1-5m)

The back reef lagoon at Discovery Bay extends from the shore to the reef crest through a distance of approximately 300m. Paired cores of sediment were collected from four co-equally spaced sites extending from near shore to the reef crest. These sites were: 1) shallow water (1m) in the rocky and turbulent near-shore zone of the back reef; 2) a patch of the turtle grass, *Thalassia testudinum* (160m behind the reef crest and 80m from shore); 3) an area inhabited and highly bioturbated by callianassid decapods (80m behind the reef crest and 160m from shore); and 4) immediately behind the reef crest (240m from shore). Sample sites ranged in depth from 1m to 5m.

Fore Reef Terrace (5-14m)

Sediment collections on the fore reef terrace were taken at depth intervals of 3m between 5m and 14m. This depth interval was chosen because of its coincidence with the striking biological zonation which has been described for Jamaican reefs (Goreau, 1959; Goreau and Goreau, 1973; Kinzie, 1973) as well as its correlation to distinct physical changes in reef morphology. Thus, it was potentially possible to relate sediment composition to the biota and struc-


70m
55m
32m
24m
14m
8m
5m
1 - 5m
A'
A
A. palmata
Zone
terrace
Reef flat
Rear Zone
Lagoon Zone
Shore Zone
Barren Zone
Mixed/ Buttress Zone
escarpment
A. cervicornis Zone
Fore Reef Slope
100 m
40 m
Deep Fore Reef

ture of each reef zone.

At each site on the fore reef terrace, two shallow sample cores were taken from sediment which was ponded on or within reef framework, and two samples were collected from adjacent sand channels. This allowed for comparison of sediment deposited on the reef proper (and presumably derived from reef framework very near the site of deposition) and sediment which had been sloughed into the sand channels (which may have been transported from other reef zones).

Fore Reef Escarpment and Slope, and Deep Fore Reef (14-70m)

Sampling in these areas was restricted by constraints on usable bottom time using SCUBA and by the physiological limitations imposed by deep diving. As a result, fewer samples were collected, and they were collected over a greater interval of depth than the shallower samples. Sediments were taken from the fore reef escarpment (24m), fore reef slope (32m, 46m, and 55m) and the upper deep fore reef (70m). Where possible, the sampling procedure was the same as that for the fore reef terrace (i.e., 2 samples from reef framework, and 2 samples from adjacent sand channels). However, on the vertical to overhanging wall of the deep fore reef, samples were collected on small ledges which provide the only available sites for sediment accumulation.

Processing of Sediment Samples

Following collection of each core, the sediment was placed into a 1000ml graduated cylinder and washed with distilled water. The sediment was then allowed to settle for 6 hours in order to limit the loss of fine-grained particles. After this period of settling, the water was removed from the cylinder with a siphon, and the sediment again washed with distilled water. The supernatant from each wash was passed through a Buchner Funnel apparatus and pre-weighed Whatman's #1 Filter Paper to capture any remaining suspended sediment. This process was repeated 3 times for each sample, after which the sediment was removed from the cylinder and dried at 105oC. Following the drying period, each sample was placed into a plastic bag for shipment. The filters containing suspended sediment were also dried and weighed to determine the amount of fine-grained carbonate which was lost from the bulk sample. In all cases, this was found to be a negligible amount (averaging only a few tenths of a gram per 200g sample).

At Utah State University, the sediment samples were split into co-equal portions using a mechanical splitter. Each of these portions was used for either point-counting to determine constituent composition or, sieve analysis of grain-size characteristics.

Constituent Particle Analysis

Subsamples of each of 125 sediment samples were impregnated with a commercial casting resin and sectioned for petrographic analysis. Standard point-counting techniques were utilized, and rarefaction analysis (Hurlbert, 1971; Heck, et. al., 1975) used to determine the adequacy of points counted for each section. Using this method, a curve is constructed which shows the number of "species" (grain types) present in the sample per unit measure (points counted). As can be seen in Figure 3, these curves rise rapidly at first, but soon begin to level off, and at some point become asymptotic. After this point is reached, the curve can be expected to rise only slightly and at long intervals due to the addition of exceedingly rare constituents. No significant changes in constituent proportions are expected beyond the asymptotic point and one may be confident that the sample is an adequate representation of constituent diversity. For this study it was found that 600 points were necessary to sufficiently describe the constituent composition of each sediment sample. Results of constituent particle analysis are presented in Tables 1-3.

Grain Size Analysis

Sieve analysis was used to determine the grain size characteristics of the 125 sediment samples. Subsets of 12 samples (4 from the back reef and 1 each from the remaining sites on the fore reef) were sieved at 1 ϕ intervals using both wet- and dry-sieving techniques to determine which method would yield the most satisfactory results. To test the significance of variation in grain-size frequencies resulting from these two techniques, the Chi-squared statis-

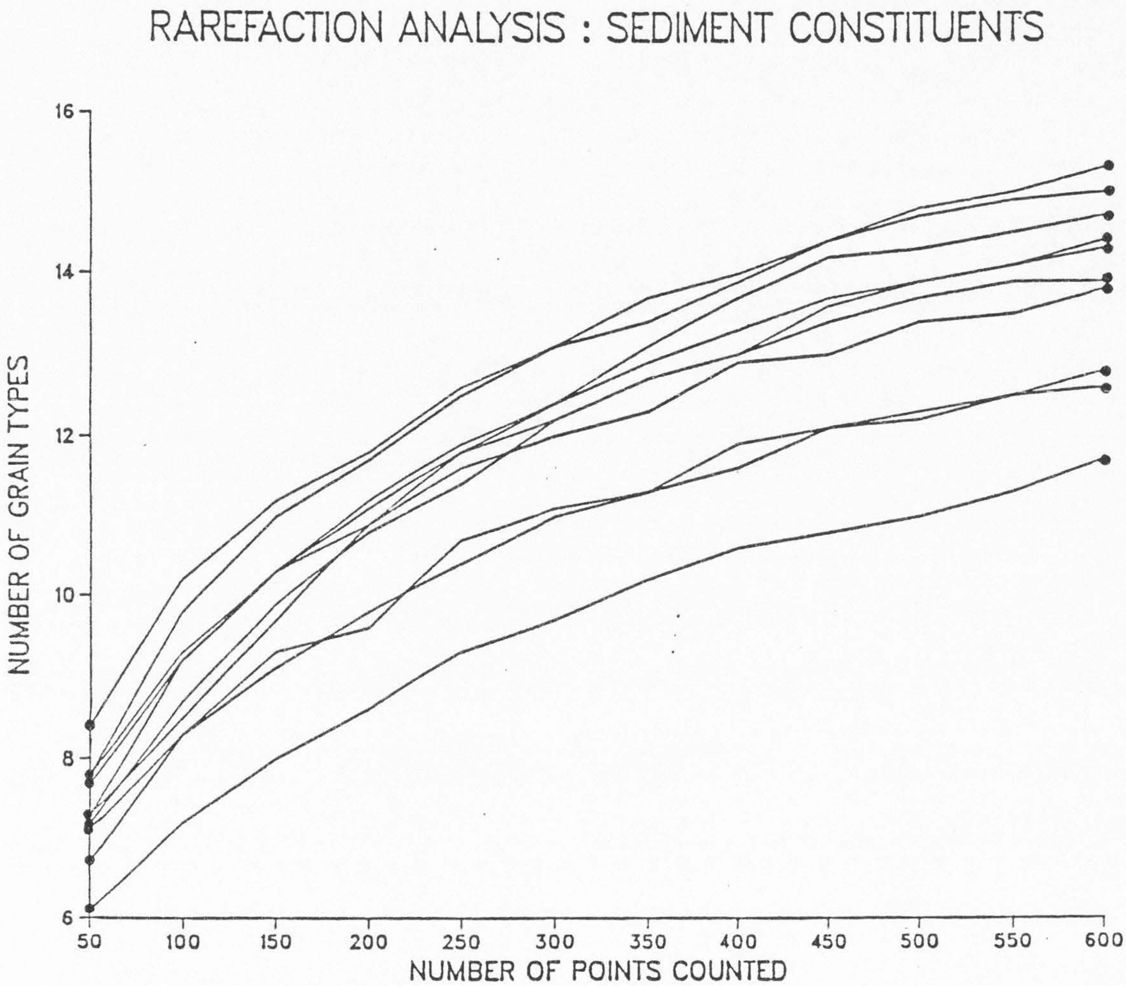


FIG. 3. Rarefaction curves constructed from sediment thin-section point-counts. These curves represent average curves for sediments collected from back reef (1-5m), fore reef terrace (5, 8, 11, 14m), escarpment (24m), slope (32, 46, 55m), and deep fore reef (70m) sites.

TABLE 1. Mean constituent composition (%) and 95 % confidence limits for back reef sediments, Discovery Bay, Jamaica.

LOCATION	BACK REEF				
DEPTH*	NS	TH	CA	CR	All Sites
SAMPLE SIZE (n)	3	4	6	5	18
BOTTOM TYPE**	S	S	S	S	S
CONSTITUENTS					
Coral	27.1 ± 4.2	51.2 ± 15.7	38.2 ± 14.2	45.8 ± 16.7	41.3 ± 6.8
Halimeda	38.7 ± 17.3	16.6 ± 14.4	27.2 ± 14.9	17.2 ± 8.7	24.0 ± 9.6
Coralline algae	16.2 ± 14.3	11.7 ± 1.0	12.5 ± 4.5	13.4 ± 4.0	13.2 ± 1.9
Homotrema	0.7 ± 0.6	1.8 ± 1.7	2.3 ± 2.1	7.8 ± 13.5	3.5 ± 3.5
Foraminifera	1.7 ± 0.9	3.3 ± 1.9	1.9 ± 1.9	1.8 ± 2.1	2.1 ± 0.7
Mollusca	2.2 ± 3.2	4.2 ± 3.6	3.6 ± 1.8	3.7 ± 3.1	3.5 ± 1.0
Echinoderms	5.0 ± 14.6	2.1 ± 3.7	2.8 ± 1.4	2.0 ± 3.0	2.8 ± 1.4
Cryptocrystalline	6.6 ± 11.2	6.7 ± 4.0	8.8 ± 3.3	5.9 ± 5.5	7.5 ± 1.8
Composite	0.9 ± 1.3	1.5 ± 1.7	1.8 ± 1.8	0.5 ± 1.0	1.2 ± 0.6
Unidentified	0.6 ± 2.3	0.4 ± 0.6	0.4 ± 0.4	1.2 ± 1.8	0.7 ± 0.5
Other	0.3 ± 1.2	0.6 ± 1.2	0.4 ± 0.3	0.4 ± 0.5	0.4 ± 0.2

*BACK REEF DEPTHS VARY FROM 1 - 5M; NS = BACK REEF, NEAR SHORE; TH = BACK REEF, *THALASSIA* BEDS; CA = BACK REEF, *CALLIANASSA* MOUNDS; CR = BACK REEF, BEHIND REEF CREST.

**BOTTOM TYPE REFERS TO BOTTOM SUBSTRATE: R = REEF FRAMEWORK; S = UNSTABLE SAND.

TABLE 2. Mean constituent composition (%) and 95 % confidence limits for fore reef terrace sediments, Discovery Bay, Jamaica.

LOCATION	FORE REEF TERRACE							
DEPTH	5m		8m		11m		14m	
SAMPLE SIZE (n)	6	-	6	6	6	8	6	6
BOTTOM TYPE*	R	S	R	S	R	S	R	S
CONSTITUENTS								
Coral	62.6 ± 6.8	——	60.3 ± 6.8	61.7 ± 7.5	63.1 ± 6.8	58.8 ± 4.3	54.5 ± 3.6	56.2 ± 5.3
Halimeda	0.4 ± 0.4	——	3.6 ± 3.6	3.4 ± 2.9	3.0 ± 1.6	8.2 ± 6.1	10.1 ± 9.5	6.3 ± 5.2
Coralline algae	13.5 ± 6.7	——	13.7 ± 10.1	11.6 ± 6.6	8.4 ± 3.8	9.0 ± 3.4	5.8 ± 3.0	9.3 ± 3.6
Homotrema	8.1 ± 5.6	——	8.6 ± 6.0	9.2 ± 3.7	9.5 ± 5.9	6.4 ± 2.8	8.3 ± 5.6	7.3 ± 1.9
Foraminifera	1.8 ± 1.6	——	1.5 ± 1.4	1.3 ± 0.5	2.4 ± 1.2	3.2 ± 1.0	2.5 ± 2.2	3.3 ± 1.2
Mollusca	1.4 ± 0.8	——	2.7 ± 1.7	2.8 ± 2.0	2.4 ± 1.5	2.4 ± 0.9	4.6 ± 2.7	3.8 ± 1.5
Echinoderma	1.7 ± 1.7	——	2.0 ± 1.0	2.1 ± 1.6	3.3 ± 2.7	3.6 ± 2.2	2.2 ± 0.4	3.0 ± 2.4
Cryptocrystalline	6.6 ± 3.8	——	5.3 ± 3.7	6.3 ± 2.3	6.0 ± 3.1	6.2 ± 4.7	8.9 ± 5.7	6.9 ± 5.1
Composite	3.2 ± 3.6	——	1.5 ± 1.2	1.0 ± 0.9	1.2 ± 0.6	0.8 ± 0.4	2.2 ± 1.2	2.8 ± 2.2
Unidentified	0.4 ± 0.7	——	0.3 ± 0.5	0.3 ± 0.6	0.4 ± 0.6	0.9 ± 1.9	0.6 ± 0.9	0.6 ± 0.8
Other	0.4 ± 0.4	——	0.5 ± 0.5	0.4 ± 0.2	0.4 ± 0.3	0.5 ± 0.2	0.3 ± 0.3	0.7 ± 0.5

*BOTTOM TYPE REFERS TO BOTTOM SUBSTRATE: R = REEF FRAMEWORK; S = UNSTABLE SAND.

TABLE 3. Mean constituent composition (%) and 95 % confidence limits for sediments from the fore reef escarpment, fore reef slope, and upper deep fore reef, Discovery Bay, Jamaica.

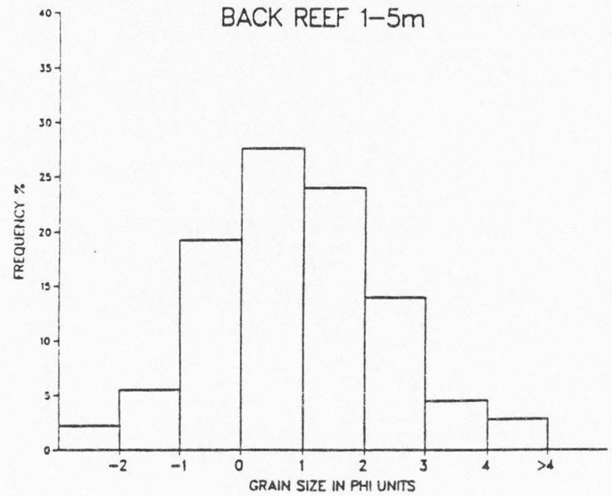
LOCATION	FORE REEF ESCARPMENT		FORE REEF SLOPE						DEEP FORE REEF
DEPTH	24m		32m		46m		55m		70m
SAMPLE SIZE (n)	7	7	5	6	6	6	7	6	11
BOTTOM TYPE	R	S	R	S	R	S	R	S	R
CONSTITUENTS									
Coral	46.2 ± 9.7	39.7 ± 6.4	44.9 ± 5.6	41.6 ± 7.7	50.8 ± 4.8	44.5 ± 5.5	39.9 ± 8.1	40.3 ± 7.1	30.9 ± 4.1
Halimeda	14.0 ± 12.0	25.0 ± 12.1	15.0 ± 7.2	13.5 ± 6.1	15.0 ± 6.4	14.2 ± 3.3	19.5 ± 10.6	18.5 ± 10.9	29.2 ± 9.2
Coralline algae	8.7 ± 6.0	9.3 ± 4.3	9.3 ± 6.2	14.3 ± 7.4	4.7 ± 1.9	10.7 ± 5.0	7.5 ± 6.1	10.6 ± 2.9	5.3 ± 2.5
Homotrema	7.2 ± 2.3	3.8 ± 2.1	4.3 ± 4.5	1.9 ± 1.9	2.0 ± 0.9	1.6 ± 1.4	2.7 ± 3.2	2.6 ± 2.0	1.1 ± 0.8
Foraminifera	2.9 ± 0.9	4.5 ± 2.1	3.5 ± 0.7	4.6 ± 2.8	3.2 ± 0.4	5.5 ± 2.0	4.6 ± 2.1	4.7 ± 2.5	3.4 ± 1.8
Mollusca	4.5 ± 3.0	3.2 ± 2.5	5.1 ± 3.7	7.0 ± 6.0	4.5 ± 2.2	3.3 ± 1.1	4.3 ± 1.1	4.9 ± 2.4	3.5 ± 1.2
Echinoderms	1.8 ± 1.0	0.9 ± 0.4	1.8 ± 1.0	1.8 ± 1.4	1.4 ± 0.4	2.1 ± 1.3	2.0 ± 1.7	1.7 ± 0.8	1.6 ± 0.4
Cryptocrystalline	10.1 ± 6.2	8.9 ± 3.9	10.7 ± 0.7	10.1 ± 6.9	13.6 ± 4.2	13.7 ± 3.1	14.0 ± 4.8	12.1 ± 2.8	14.4 ± 2.5
Composite	3.9 ± 1.8	3.7 ± 3.3	4.9 ± 3.9	3.9 ± 3.2	3.8 ± 2.1	3.0 ± 2.7	3.9 ± 2.3	3.4 ± 1.6	8.1 ± 4.8
Unidentified	0.3 ± 0.4	0.6 ± 0.7	0.1 ± 0.2	1.1 ± 1.5	0.6 ± 0.8	0.8 ± 1.5	1.0 ± 1.6	0.5 ± 0.4	1.7 ± 1.8
Other	0.4 ± 0.2	0.4 ± 0.3	0.4 ± 0.5	0.5 ± 0.5	0.6 ± 0.3	0.8 ± 0.5	0.7 ± 0.4	0.5 ± 0.2	0.7 ± 0.4

*BOTTOM TYPE REFERS TO BOTTOM SUBSTRATE: R = REEF FRAMEWORK; S = UNSTABLE SAND.

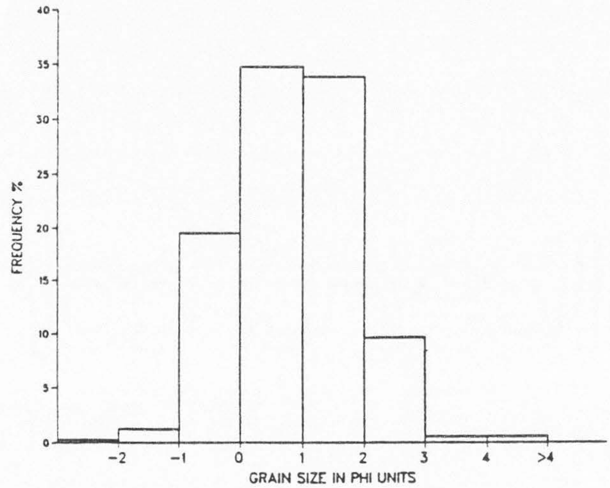
tic (Johnson, 1976) was employed ($\alpha = 0.05$). The results of X^2 testing indicate that the observed variation in grain size frequencies is not significantly different from the expected variability due to the action of random agencies. It was therefore decided to analyze the remaining samples with the more efficient and less time-consuming dry-sieve method. Each sample was loaded into a stack of standard 1 ø sieves (-2 ø to 4 ø) and placed on a Ro-Tap shaker for 10 minutes (Ingram, 1971). Then, the contents of each sieve were weighed with an electronic analytical balance and placed into a separate plastic bag for storage. Cumulative frequency curves were constructed from grain-size weight percentages and used to determine mean grain size (M_z; Folk and Ward, 1957). Frequency histograms were used to compare the gross textural characteristics of the sediments (Figs. 4 - 6). Tables 4 to 7 present the results of grain-size analyses.

Cluster Analysis

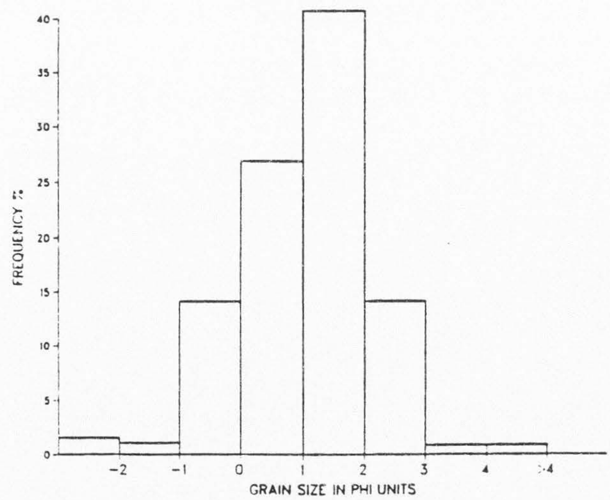
A computer-based program of hierarchical cluster analysis (CLUSTAR) was utilized (Romesburg, 1984; Romesburg and Marshall, 1984) to examine the constituent particle and grain-size data. It was believed that Q-mode analysis of multivariate sediment constituent and textural data would assist in delineating patterns of association which could not be resolved using simpler statistical methods. For this study, mean values for constituent proportions from each



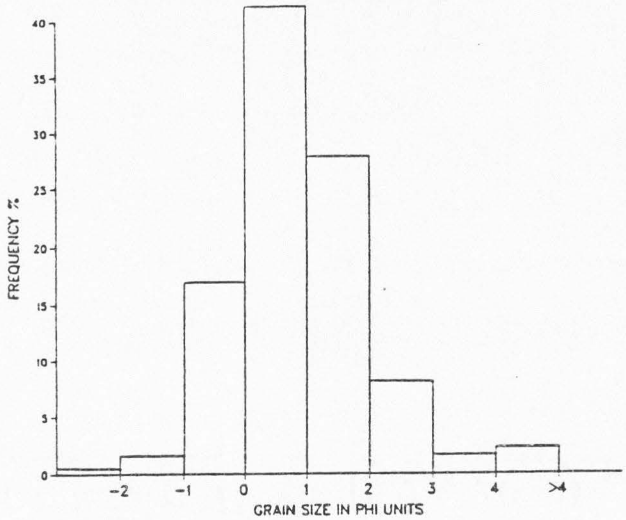
FORE REEF TERRACE 5m



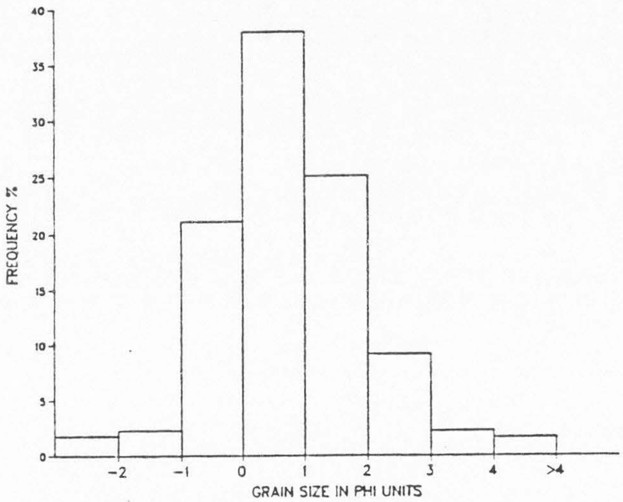
FORE REEF TERRACE 8m



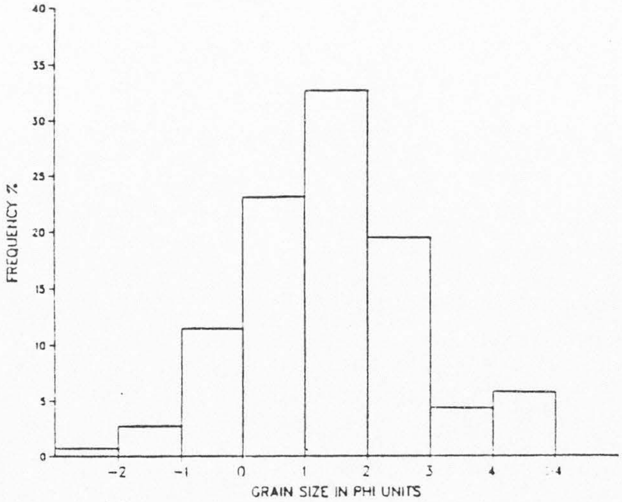
FORE REEF TERRACE 11m



FORE REEF TERRACE 14m



FORE REEF ESCARPMENT 24m



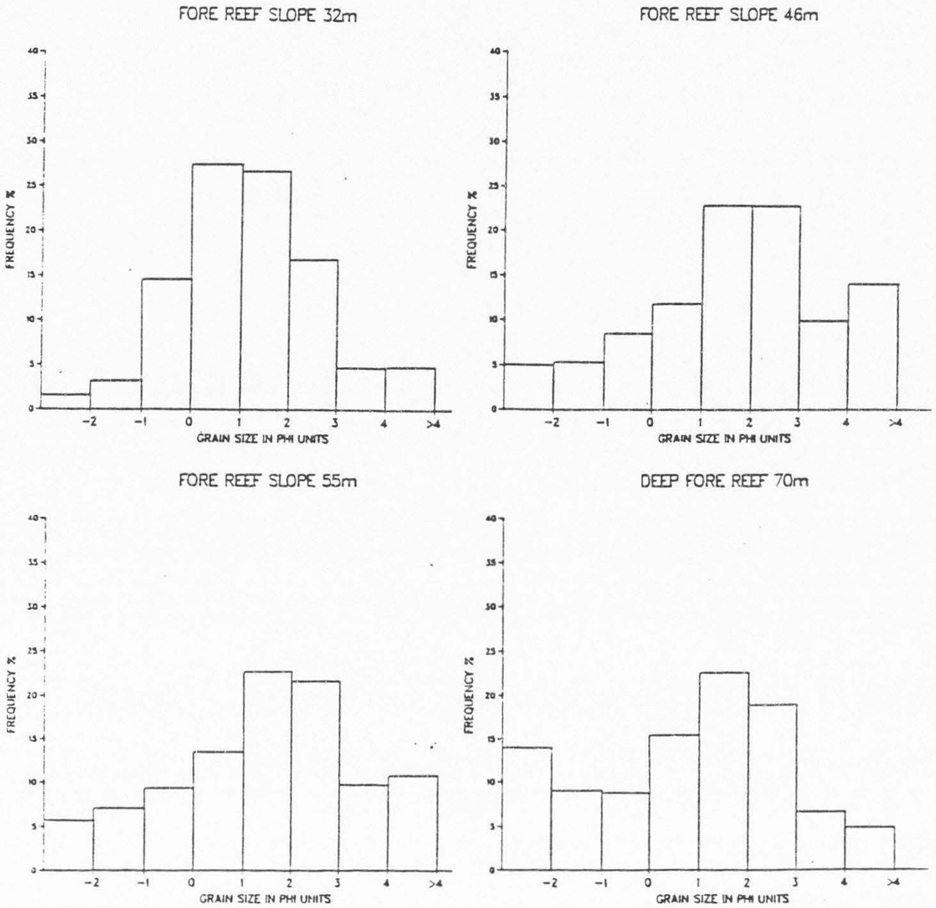


FIG. 6. Frequency histograms constructed from grain-size data (Tables 4-7) for comparison of gross textural features of reef sediments.

TABLE 4. Grain-size frequencies and mean grain size (Folk and Ward, 1957) for sediments collected in the back reef, Discovery Bay, Jamaica.

LOCATION		BACK REEF				
DEPTH*		SH	TH	CA	CR	All Sites
SAMPLE SIZE		3	4	6	5	18
BOTTOM TYPE**		S	S	S	S	S
GRAIN SIZE		MEAN % and 95 % CONFIDENCE INTERVAL				
φ	mm					
-2	4.000	0.24 ± 0.7	1.98 ± 5.4	4.52 ± 8.2	1.67 ± 2.1	2.10 ± 2.8
-1	2.000	7.78 ± 1.7	3.20 ± 3.0	4.49 ± 2.8	6.50 ± 2.6	5.49 ± 3.3
0	1.000	19.66 ± 3.4	14.09 ± 4.2	15.33 ± 5.4	27.80 ± 15.0	19.22 ± 9.8
1	0.500	25.60 ± 11.5	29.99 ± 14.7	22.51 ± 7.1	32.14 ± 5.5	27.56 ± 6.9
2	0.250	24.67 ± 4.5	28.36 ± 7.4	23.20 ± 5.6	19.50 ± 11.0	23.93 ± 5.8
3	0.125	14.12 ± 9.2	14.45 ± 10.3	18.36 ± 8.6	8.62 ± 7.5	13.89 ± 6.4
4	0.062	4.32 ± 3.8	3.98 ± 2.6	7.15 ± 4.4	2.42 ± 2.1	4.47 ± 3.2
>4	<0.062	3.32 ± 2.6	2.27 ± 2.1	4.30 ± 2.7	1.20 ± 0.9	2.77 ± 2.0
GRAPHIC MEASURES		MEAN and 95 % CONFIDENCE INTERVAL				
MEAN GRAIN SIZE (φ)		0.91 ± 0.3	1.08 ± 0.3	1.11 ± 0.7	0.55 ± 0.0	0.91 ± 0.4

*SH = BACK REEF, NEAR SHORE; TH = BACK REEF, *THALASSIA* BEDS; CA = BACK REEF, *CALLINASSA* MOUNDS; CR = BACK REEF, BEHIND REEF CREST.

**BOTTOM TYPE REFERS TO BOTTOM SUBSTRATE: R = REEF FRAMEWORK; S = UNSTABLE SAND.

TABLE 5. Grain-size frequencies and mean grain size (Folk and Ward, 1957) for sediments collected on the fore reef terrace, Discovery Bay, Jamaica.

LOCATION		FORE REEF TERRACE							
DEPTH		5m		8m		11m		14m	
SAMPLE SIZE (n)		6	-	6	6	6	8	6	6
BOTTOM TYPE*		R	S	R	S	R	S	R	S
GRAIN SIZE		MEAN % and 95 % CONFIDENCE INTERVAL							
φ	mm								
-2	4.000	0.11 ± 0.1	------	1.40 ± 3.5	0.21 ± 0.5	0.48 ± 0.8	0.20 ± 0.2	1.74 ± 4.3	0.75 ± 0.9
-1	2.000	1.20 ± 1.2	------	1.00 ± 0.9	0.97 ± 1.4	1.52 ± 1.2	0.71 ± 0.3	2.24 ± 1.9	1.59 ± 0.9
0	1.000	19.40 ± 16.6	------	14.10 ± 12.7	14.10 ± 17.1	16.84 ± 4.9	10.52 ± 3.4	21.11 ± 12.2	18.76 ± 8.1
1	0.500	34.7 ± 14.7	------	26.90 ± 19.4	28.20 ± 17.3	41.34 ± 9.4	38.20 ± 10.1	37.95 ± 12.2	40.80 ± 8.8
2	0.250	33.8 ± 22.0	------	40.70 ± 21.2	46.80 ± 29.8	27.78 ± 7.5	38.69 ± 7.6	25.02 ± 11.4	29.00 ± 11.7
3	0.125	9.56 ± 7.6	------	14.20 ± 11.9	8.82 ± 5.6	8.08 ± 5.1	10.30 ± 8.1	9.11 ± 7.3	7.70 ± 5.0
4	0.062	0.55 ± 0.3	------	0.80 ± 1.0	0.54 ± 0.3	1.61 ± 1.6	0.84 ± 0.6	2.26 ± 2.5	0.88 ± 1.1
>4	<0.062	0.49 ± 0.4	------	0.80 ± 0.7	0.44 ± 0.4	2.22 ± 3.1	0.48 ± 0.2	1.65 ± 2.2	0.55 ± 0.8
GRAPHIC MEASURES		MEAN and 95 % CONFIDENCE INTERVAL							
MEAN GRAIN SIZE (φ)		0.83 ± 0.6	------	1.07 ± 0.6	1.01 ± 0.6	0.87 ± 0.3	0.99 ± 0.2	0.72 ± 0.5	0.76 ± 0.3

*BOTTOM TYPE REFERS TO BOTTOM SUBSTRATE: R = REEF FRAMEWORK; S = UNSTABLE SAND.

TABLE 6. Grain-size frequencies and mean grain size (Folk and Ward, 1957) for sediments collected on the fore reef escarpment and fore reef slope, Discovery Bay, Jamaica.

LOCATION		FORE REEF ESCARPMENT		FORE REEF SLOPE					
DEPTH		24m		32m		46m		55m	
SAMPLE SIZE (n)		7	7	5	6	6	6	7	6
BOTTOM TYPE*		R	S	R	S	R	S	R	S
GRAIN SIZE		MEAN % and 95 % CONFIDENCE INTERVAL							
ϕ	mm								
-2	4.000	0.68 ± 0.7	2.47 ± 1.9	1.56 ± 2.2	0.46 ± 0.4	4.92 ± 2.6	2.99 ± 2.9	5.61 ± 3.2	5.03 ± 9.5
-1	2.000	2.57 ± 1.5	6.45 ± 2.6	3.17 ± 2.1	2.78 ± 1.1	5.34 ± 2.6	2.75 ± 1.3	7.03 ± 3.4	3.82 ± 1.8
0	1.000	11.42 ± 3.9	18.19 ± 5.6	14.64 ± 7.9	14.60 ± 2.5	8.45 ± 4.4	11.39 ± 3.1	9.20 ± 2.9	13.29 ± 3.1
1	0.500	23.07 ± 4.3	29.23 ± 9.1	27.50 ± 16.7	37.15 ± 2.8	11.74 ± 2.7	25.69 ± 6.0	13.39 ± 3.3	25.19 ± 5.2
2	0.250	32.65 ± 8.2	20.78 ± 8.5	26.73 ± 6.8	28.39 ± 3.5	22.81 ± 4.0	25.96 ± 2.2	22.66 ± 7.0	24.00 ± 6.1
3	0.125	19.43 ± 3.2	15.71 ± 5.5	16.82 ± 10.1	12.09 ± 3.5	22.71 ± 3.2	19.43 ± 5.6	21.52 ± 4.2	18.75 ± 3.3
4	0.062	4.28 ± 1.8	3.72 ± 1.8	4.65 ± 4.0	3.31 ± 1.2	9.76 ± 3.8	8.43 ± 5.5	9.60 ± 2.6	6.69 ± 1.8
>4	<0.062	5.71 ± 3.6	3.05 ± 3.1	4.75 ± 7.7	0.90 ± 0.2	14.05 ± 4.5	3.17 ± 1.3	10.73 ± 3.6	2.95 ± 0.7
GRAPHIC MEASURES		MEAN and 95 % CONFIDENCE INTERVAL							
MEAN GRAIN SIZE (ϕ)		1.38 ± 0.3	0.94 ± 0.3	1.22 ± 0.6	0.95 ± 0.2	1.77 ± 0.5	1.28 ± 0.4	1.51 ± 0.3	1.02 ± 0.4

*BOTTOM TYPE REFERS TO BOTTOM SUBSTRATE: R = REEF FRAMEWORK; S = UNSTABLE SAND.

TABLE 7. Grain-size frequencies and mean grain size (Folk and Ward, 1957) for sediments collected on the upper deep fore reef, Discovery Bay, Jamaica.

LOCATION	DEEP FORE REEF
DEPTH	70m
SAMPLE SIZE (n)	11
BOTTOM TYPE*	R

GRAIN SIZE		MEAN % and 95 % C.I.
ϕ	mm	
-2	4.000	14.00 ± 7.3
-1	2.000	8.96 ± 3.7
0	1.000	8.67 ± 1.7
1	0.500	15.37 ± 4.7
2	0.250	22.52 ± 5.5
3	0.125	18.84 ± 4.2
4	0.062	6.59 ± 1.9
>4	<0.062	4.75 ± 1.4

GRAPHIC MEASURES	MEAN and 95 % C.I.
MEAN GRAIN SIZE (ϕ)	0.85 ± 0.5

*BOTTOM TYPE REFERS TO BOTTOM SUBSTRATE: R = REEF FRAMEWORK; S = UNSTABLE SAND.

site were analyzed using the Euclidean metric distance measure. This was combined with the Unweighted Pair-Group Method with simple Arithmetic Averages (UPGMA) clustering method. These two options were chosen over others simply because of their broad applicability and familiarity to other researchers. The Euclidean metric measures the distance between the individuals *i* and *j* defined by:

$$d_{ij} = [\sum_{k=1}^{p} (X_{ik} - X_{jk})^2]^{1/2}$$

where d_{ij} is the Euclidean distance, X_{ik} is the kth variable for the ith object and X_{jk} is the kth variable for the jth object (Everitt, 1974). The UPGMA measures the average distance between all pairs of individuals (objects) in each of the clusters. Separate runs of the CLUSTAR program were conducted on constituent composition data, grain size data, and combined constituent and grain size data.

RESULTS

Constituent Particle Analysis

Thin-section study of these sediments indicates that major constituents include highly comminuted fragments of coral (27.1% ± 4.2 to 63.1% ± 6.8), plates of the calcareous green alga, *Halimeda* (0.4% ± 0.4 to 38.7% ± 17.3), coralline algae (4.7% ± 1.9 to 16.2% ± 14.3) and the encrusting Foraminifera, *Homotrema rubrum* (0.7% ± 0.6 to 9.5% ± 5.9), with lesser amounts of other taxonomic groups (molluscs, 1.4% ± 0.8 to 7.0% ± 6.0; echinoderms, 0.9% ± 0.4 to 5.0% ±

14.6; other Foraminifera, 1.3% ± 0.5 to 5.5% ± 2.0). Relative proportions of these constituents vary from site to site. Results of Chi-squared testing ($\alpha = 0.05$) indicate that the mean composition of sand channel sediments from 8m, 11m, 14m, 24m, 32m, 46m and 55m, is not significantly different from that of sediment trapped on and within reef framework at adjacent sample sites.

Grain Size Analysis

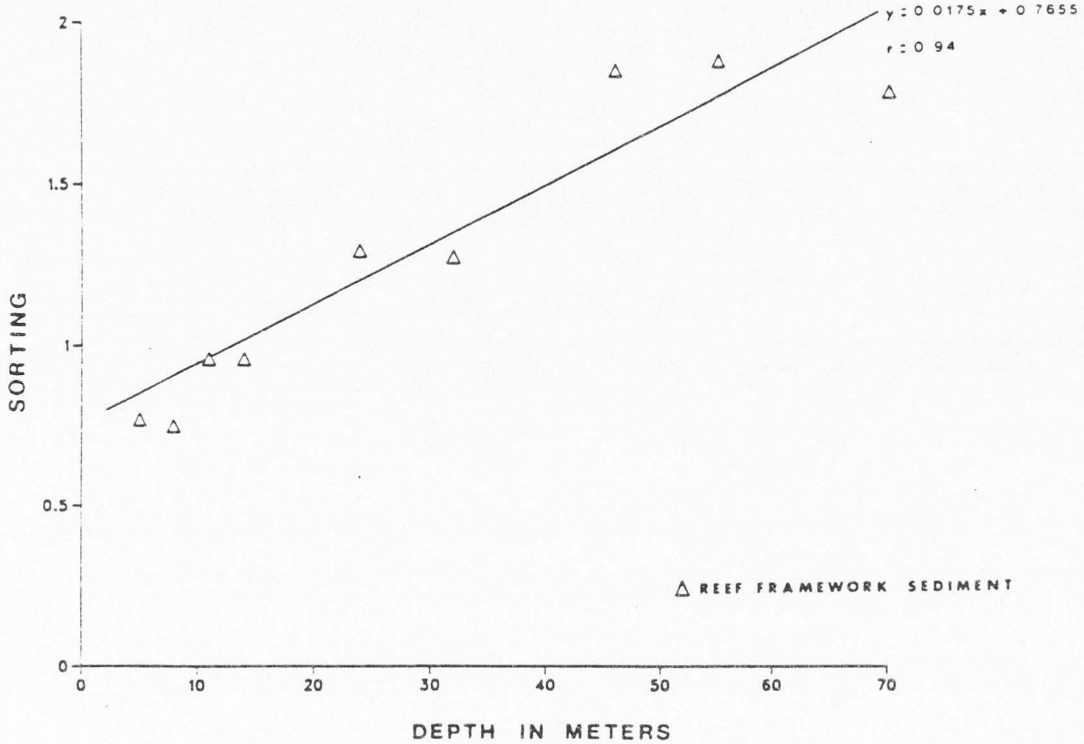
Sieve analysis of these sediments reveals that the mean grain size (M_z) for all sites approaches 0.5mm with no depth-related variation. Sorting, however, becomes progressively poorer with increasing depth (Fig. 7) from 5m to 70m for both sediment collected on reef framework and in adjacent sand channels (Pearson Product Moment Correlation Coefficient , r, = 0.94 and 0.91, respectively; significant at $p \leq 0.01$). Additionally, reef framework sediments tend to be slightly more poorly sorted at all depths when compared to sediment in adjacent sand channels (Tables 4 to 7).

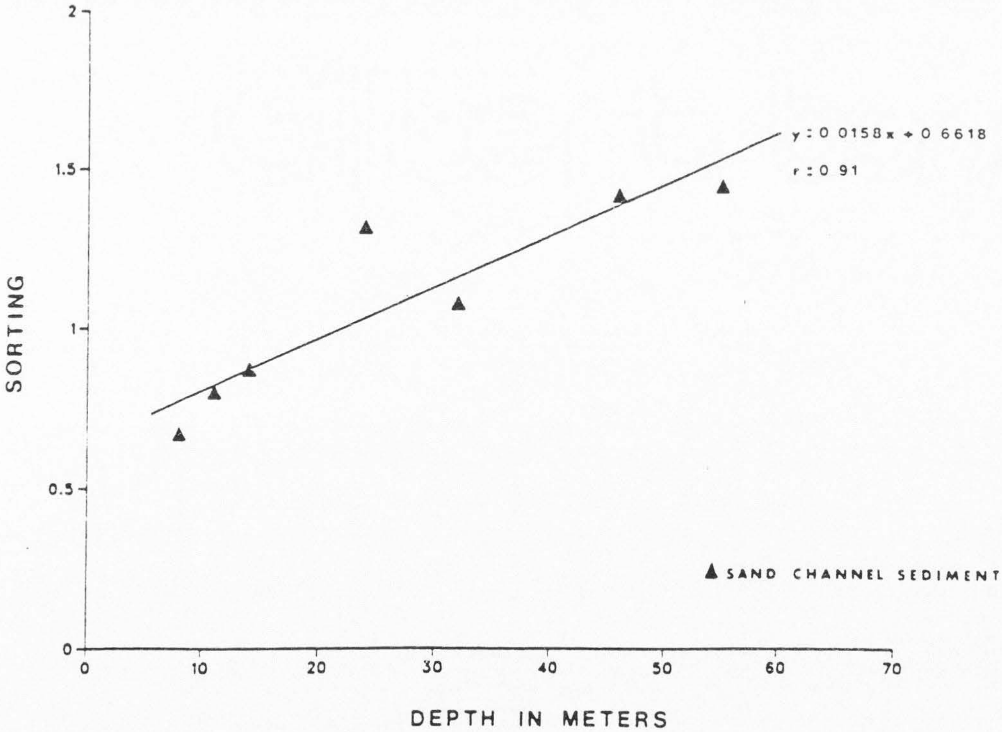
Cluster Analysis

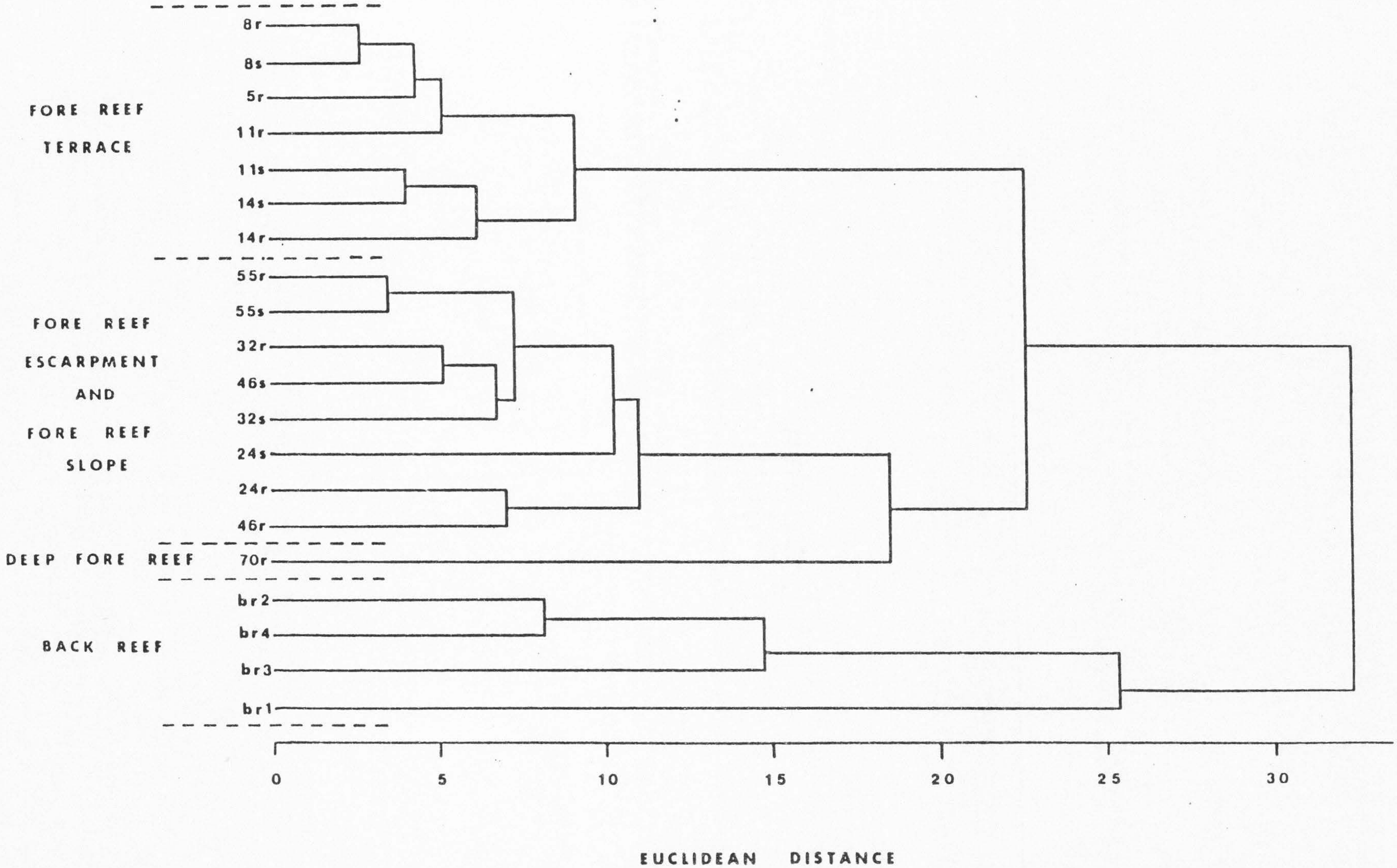
Q-mode analysis of constituent particle data produced the dendrogram illustrated in Figure 8. The four well-defined associations are formed from sediments of varying composition from the back reef, fore reef terrace, fore reef escarpment and fore reef slope, and deep fore reef.

Q-mode analysis using textural characteristics of the

SORTING VS DEPTH






FORE REEF TERRACE
FORE REEF ESCARPMENT AND FORE REEF SLOPE
DEEP FORE REEF
BACK REEF
8r
8s
5r
11r
11s
14s
14r
55r
55s
32r
46s
32s
24s
24r
46r
70r
br2
br4
br3
br1
0
5
10
15
20
25
30
EUCLIDEAN DISTANCE

same sediments failed to produce meaningful groupings, due to an absence of location-specific trends in the textures of the sediment.

Q-mode clustering of combined constituent and grain size information produced nearly the same groupings as analysis of constituent data alone. However, these clusters invariably joined at higher levels (i.e. greater Euclidean distances) than those based solely on constituent particle data. This reflects the influence of non-specific textural data on the calculation of Euclidean distance.

DISCUSSION

Constituent Particle Analysis

Averaged rarefaction curves derived from thin-section point-counts (Fig. 3) show that constituent particle diversity in these sediments is quite high. The steep slope of these curves below 600 counted points indicates that estimates based on fewer counted points may give spurious or misleading results.

Variation in the abundance of major sediment constituents is related to changes in the biotic composition of adjacent reef communities. For example, the abundance of coral-derived sand in the sediment corresponds favorably to percent living cover of corals at the sample sites (Ohlhorst, 1980; Liddel and Ohlhorst, 1981; Liddell, et al., 1984a; Liddell, et al., 1984b). Coral fragments represent a large proportion of the sediment on the fore reef terrace, and decrease with depth to 70m. Also, living colonies of Homotrema rubrum are most abundant in the shallow waters of the fore reef terrace (Mackenzie, et al., 1965). Sand-sized grains of Homotrema are also relatively abundant in sediment from the fore reef terrace, but are much reduced in sand from other reef zones (Boss and Liddell, 1983; Boss, et al, 1984). Additionally, the proportion of Halimeda in the sediment varies in relation to the proportion of Halimeda living on the reef. The living Halimeda are abundant in the back reef, much reduced in numbers on the fore reef terrace, and abundant again on the fore reef escarpment and deeper sites (Liddell, et al., 1984a and b).

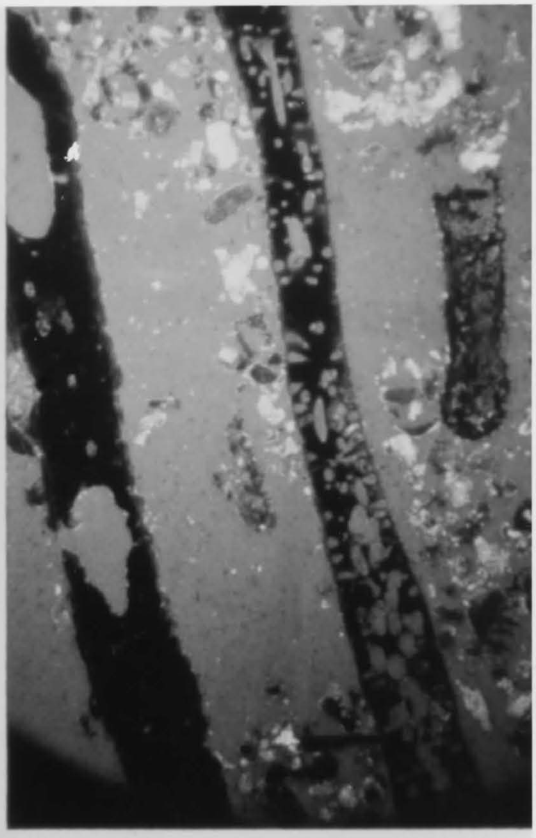
Goreau and Goreau (1973) have suggested that variation in the species composition of Halimeda with depth could serve as a useful environmental indicator. This method is encumbered by the fact that most researchers are not sufficiently well-versed in the systematics of the genus Halimeda to be able to identify disarticulated plates as to species, especially in thin-section! However, variation in the gross morphology of Halimeda plates is associated with changes in species distribution with depth (Goreau and Goreau, 1973). Observations from this study indicate that shallow-water species of Halimeda exhibit plates which are relatively thick and sturdy, related to the high energy conditions of the shallow-water environment. Also, the size of these plates is somewhat reduced when compared to plates of deep-water species of Halimeda. The deep-water Halimeda have plates which are much broader and thinner than their shallow-water counterparts. These two different plate morphologies are easily recognized in hand-specimen and thin-section (Fig. 9), and may be differentiated into a "shallow-water Halimeda suite" and a "deep-water Halimeda suite". Recognition of these two suites has proven invaluable in analyzing Recent sediments, and should prove useful in paleoenvironmental interpretations of Pleistocene or older reef limestones.

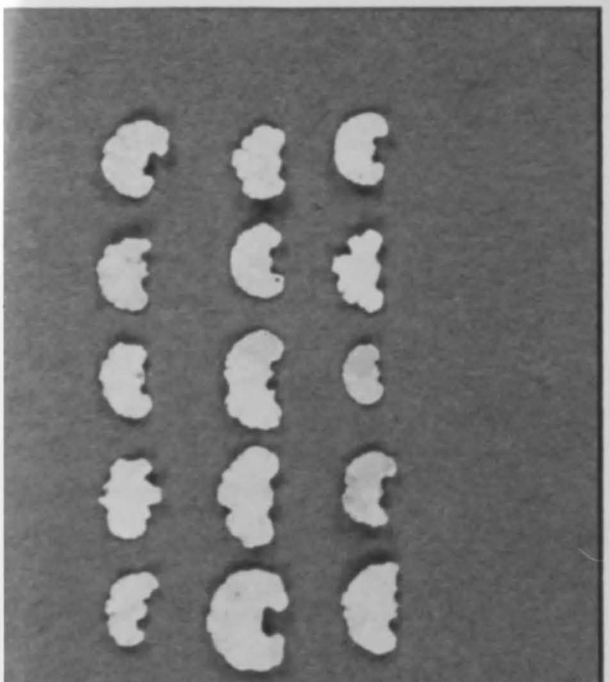
Grain Size Analysis

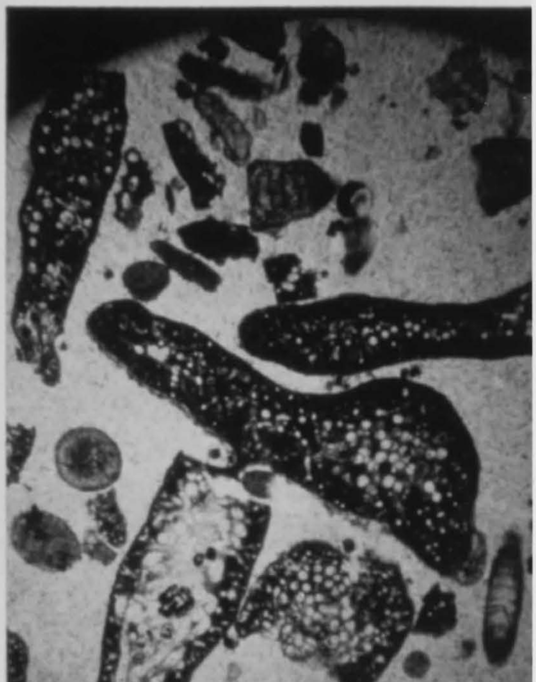
The grain size distributions of reef sediments (Tables 4 to 7) are modified by two factors. First, production of sediment over the entire spectrum of grain sizes is occurring at all depths on these reefs due to biological and mechanical erosion of the reef edifice. Second, texture-modifying phenomena such as wave turbulence and sediment resuspension diminish significantly with increasing depth under modal wind, wave, and tide conditions. Of these two factors, the former appears to be the more important in determining sediment textural characteristics. Localized sediment production from the continual disintegration of calcareous biota at all depths on these reefs introduces material over the entire spectrum of grain sizes. This aspect is most important where it affects the coarse and fine end-members of the grain size distribution.

An increase in the proportion of material coarser than

FIG 9. Photograph of typical Halimeda plates from shallow-water (lower left) and deep-water (upper left) environments and their appearance in thin-section (lower right = shallow-water; upper right = deep-water). Scale at top in centimeters. Field of view in bottom photos is 2mm.





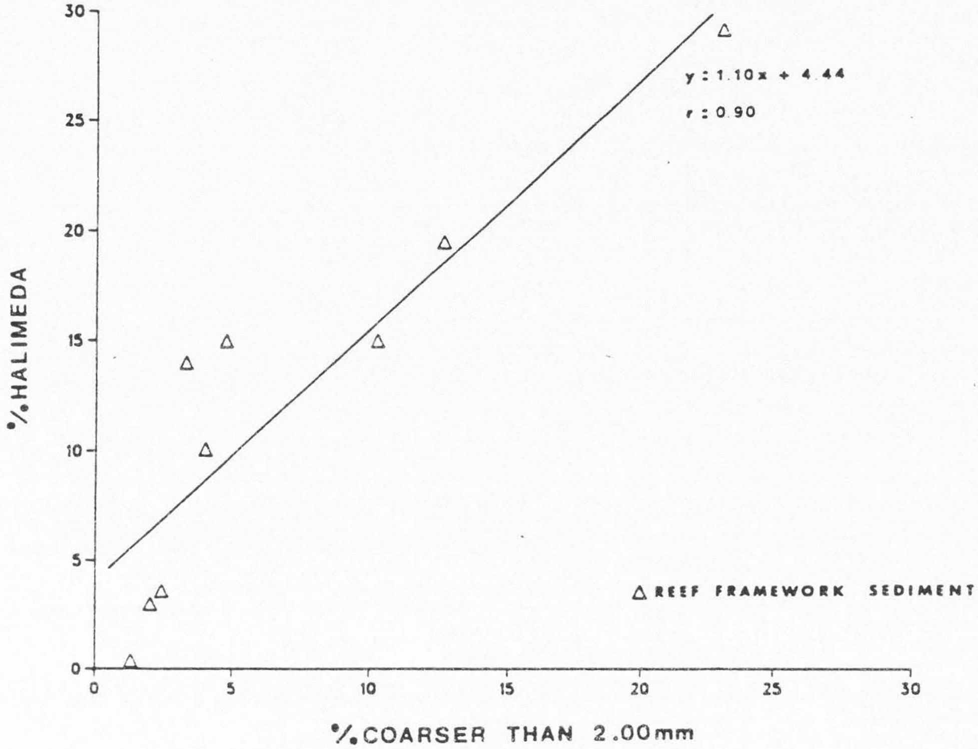


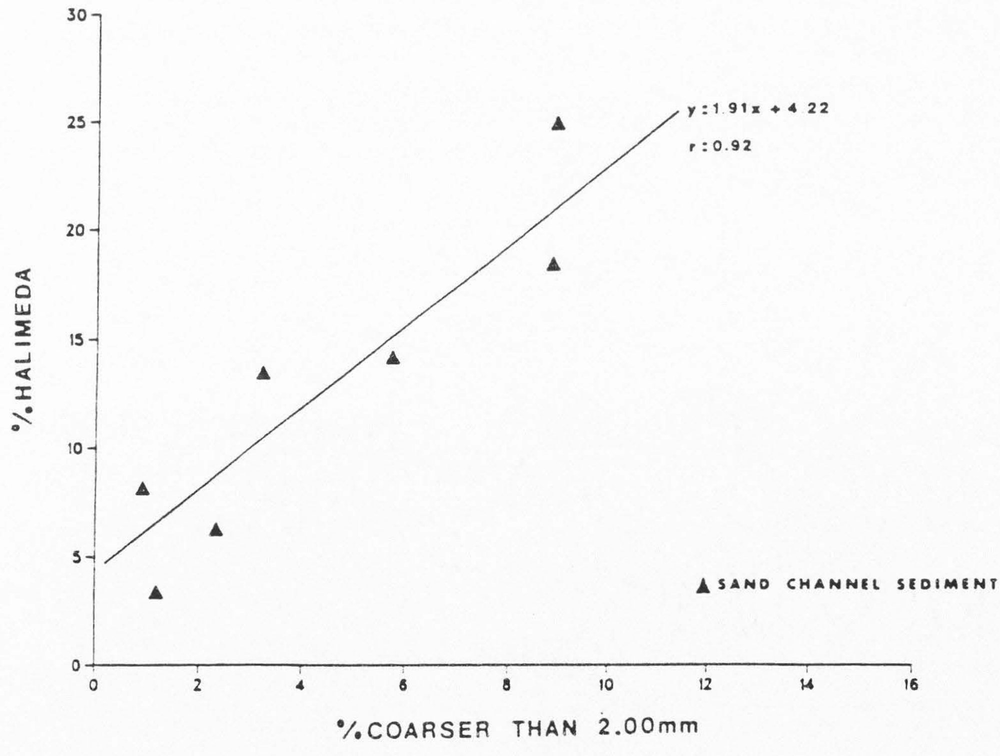
2.00mm is highly correlated with an increasing abundance of *Halimeda* in sediments from both sand channels (Pearson Product Moment Correlation Coefficient, r, = 0.92; significant at $p \leq 0.01$) and reef framework ($r = 0.90$; significant at $p \leq 0.01$) with increasing depth (Fig. 10). This relationship is substantiated by visual observations during the sieving process that *Halimeda* plates were the dominant component of detritus collected on the -1 ø and -2 ø sieves. A similar increase in the amount of fine-grained carbonate (<0.125mm) in sediments with increasing depth is associated with the decrease in wave turbulence and sediment resuspension in the deeper reef zones (Boss and Liddell, 1984a).

The compositional similarity of sediment collected on reef framework and in adjacent sand channels (below 8m depth) attests to the absence of sufficiently competent sand-transport mechanisms under modal wind, wave and tide conditions. This conclusion is contrary to the concept of Goreau and Land (1974), Moore, *et al.*, (1976), and Moore and Shedd (1977) that sand channels act as "sediment conveyor belts" continually transporting reef detritus from shallow reef zones into the deep ocean basin. It is more likely that significant sediment transport of sand-sized material occurs only on steep slopes (such as the fore reef escarpment and lower fore reef slope) and during isolated disturbances such as major storms and hurricanes (Meany, 1973; Boss and Liddell, in preparation).

Turbulence created by waves impinging on these reefs

%HALIMEDA VS. %COARSER THAN 2.00MM





must have some effect in modifying the grain size distributions of sediments on the shallow (5-14m) fore reef terrace. Moore and Shedd (1977) have suggested that turbulence created by these waves transports silt-sized carbonate (produced by the boring of clionid sponges) in suspension from shallow reef zones into deeper water. Indeed, Boss, et al. (in preparation) have shown that sediment resuspension in shallow water (5m or less) results in measured summer sedimentation rates which are 2.7 times greater than net sediment accretion and that up to 63.5% of the sediment trapped from suspension on the fore reef terrace is derived from clionid bioerosion (Boss and Liddell, 1984a). However, most of this material is settling from suspension with only minimal off-reef transport into deeper water (Moore and Shedd, 1977; Boss, et al., in preparation).

Modification of grain-size distributions due to the winnowing action of wave-surge appears to be more prevalent in sand channels than on reef spurs (Tables 5-6). An examination of sediment sorting from both sites shows that sediments collected from reef framework were slightly more poorly sorted at all depths than sediments collected from sand channels nearby. Apparently, the open network of interlocking corals composing the reef frame modifies circulation patterns through frictional attenuation of wave energy and provides sheltered pockets in which fine-grained carbonate accumulates.

Cluster Analysis

Initial attempts at Q-mode analysis were frustrated by the apparent compositional similarity of back reef and deep reef sediments. However, a re-evaluation of constituent data led to the differentiation of shallow- and deep-water *Halimeda* suites. Modification of the data to account for the occurrence of each of these distinctive suites produced the dendrogram illustrated in Figure 8. As can be seen, the back reef, fore reef terrace, fore reef escarpment and fore reef slope, and deep fore reef are readily distinguished using this method.

SUMMARY

Constituent particle analysis of Recent Jamaican fringing reef sediments has shown that these sands display variability in biotic composition related to the community structure of different reef zones. Q-mode cluster analysis has demonstrated that sediment composition is a reliable indicator of specific reef environment (Fig. 8) and can be used efficiently to resolve facies relationships on these reefs.

Sediment sorting becomes progressively poorer with increasing depth due to local sediment production at all depths and the decreasing competence of sorting mechanisms with increasing depth. The similarity of the composition of sediment from both reef framework and sand channels to the composition of adjacent reef communities provides compelling evidence that these sands are truly autochthonous deposits.

The results of this study should provide a useful data base for future research. The application of standard petrographic techniques and multivariate statistical procedures in the analysis of these Recent deposits demonstrates the utility of using such methods with respect to microfacies analysis of Pleistocene and older reef limestones.

CHAPTER III

ENVIRONMENTAL SIGNIFICANCE OF MINERALOGY IN FRINGING REEF SEDIMENTS FROM NORTH JAMAICA

INTRODUCTION

Few attempts have been made to assess the impact of reef community structure on the mineralogy of Recent carbonate sediments. Disarticulation and disintegration of the skeletons of marine organisms in a heterogeneous community will produce sediments whose grain constituents reflect the distribution of biotic constituents within that community (Ginsburg, 1956; Newell, et al., 1959; Purdy, 1963a and b; Wantland and Pusey, 1975; Boss and Liddell, 1983). If the organisms in the community display different skeletal mineralogies, then the gross sediment mineralogy should also reflect antecedent zonal patterns. Fringing reefs of the Jamaican north coast exhibit a striking biological zonation related to the environmental tolerances of sessile and frame-building invertebrates and algae (Goreau, 1959; Goreau and Goreau, 1973; Kinzie, 1973). The present study examines the mineralogy of some fringing reef sediments from north Jamaica to determine whether or not observed fluctuations in biotic components have an important and recognizable effect upon gross mineralogic characteristics of the resulting sediments.

PREVIOUS WORK

Many workers (most notably Chave, 1954a and Lowenstam,

1954) have shown that skeletonized invertebrates in the modern oceans secrete primarily aragonite, high-Mg calcite, and low-Mg calcite. Variations in skeletal mineralogy are related to biological and physical/environmental factors such as taxonomic group (Chave, 1954a), growth stage of the organism (Dodd, 1963; Stenzel, 1963; Lowenstam, 1954) and temperature (Lowenstam, 1954).

Analyses of the mineralogy of Recent carbonate sediments are well documented (Chave, 1954b and 1962; Stehli and Hower, 1961; Friedman, 1964; Land, 1967; Milliman, 1967; Land, 1973; Nair and Hashimi, 1981; Hashimi, et al., 1982). These analyses indicate that for tropical, shallow marine environments, the metastable phases aragonite and high-Mg calcite predominate over low-Mg calcite. In modern carbonate accumulations, low-Mg calcite appears to become an important mineralogic constituent only in sediments from the deep ocean basins (due to contributions from planktonic Foraminifera and calcareous nannoplankton; Stehli and Hower, 1961) and at high latitudes (due to lower ocean-surface temperatures; Chave, 1954a and b). Aside from these generalizations, few attempts have been made to assess the impact of community structure on overall sediment mineralogy.

Chave (1962) analyzed the mineralogy of carbonate sediments from Bermuda and Campeche Bank. His results revealed that lagoonal areas contained the highest proportion of aragonite, whereas the highest levels of high-Mg calcite were encountered in "reef and near-reef" settings. He attributed differences in sediment mineralogy to the abundance of calcareous green algae (Halimeda) in the back reef lagoons and to relatively high concentrations of coralline algae (Lithothamnium and Lithophyllum) and encrusting Foraminifera (Homotrema rubrum) in reef environments.

Nair and Hashimi (1981) and Hashimi, et al. (1982) examined the mineralogy of carbonate sediments on the continental shelf of India. Here, aragonite-rich sediments were associated with mollusc-dominated communities. High-Mg calcite became more prevalent in areas where benthic foraminifera were abundant sediment constituents.

The only previous documentation regarding the mineralogy of Recent Jamaican carbonates is given by Land (1973) for seven unconsolidated reef-sediment samples. Data for the percent aragonite in each sample were presented, but no attempt was made to relate sediment mineralogy to the composition of the reef community at each site.

Boss and Liddell (1983) have shown that sediment constituent composition is correlated with reef community structure. Because sediment mineralogy is inherited from the mineralogic constitution of bioclasts which compose the sediment, sediment mineralogy should be related to community structure as well.

LOCATION OF STUDY

Field work for this project was conducted during August and September of 1982 from the Discovery Bay Marine Laboratory of the University of the West Indies. This facility is located on the Jamaican north coast at Discovery Bay (lat. 18° 30' N, long. 77° 20' W), and provides easy access to the modern fringing reef. Samples were collected through a depth range of 1 to 70m on LTS reef (Fig. 11; A-A'). Following this period of field work, all samples were transported to Utah State University for detailed analysis.

METHODS

Sampling and Preparation

51 samples of Recent fringing reef sands were obtained from shallow cores (15cm long x 5cm diameter) collected by SCUBA divers. Each core contained approximately 200g of sediment. The sampling interval was chosen to coincide with five geomorphic zones which have been described for Jamaican reefs (Fig. 12). These zones were the back reef, fore reef terrace, fore reef escarpment, fore reef slope, and upper deep fore reef (Goreau, 1959; Goreau and Goreau, 1973; Goreau and Land, 1974; Moore, *et al.*, 1976;). In the fore reef zones, replicate shallow cores were collected from sediment accumulations in sand channels (grooves) as well as sand ponded in shallow depressions within the reef framework (spurs). Back reef sediments were collected on sandy bottom from four distinct community environments: 1) the shore zone; 2) a *Thalassia testudinum* community (80m from shore and 160m behind the reef crest); 3) a *Callianassa* community

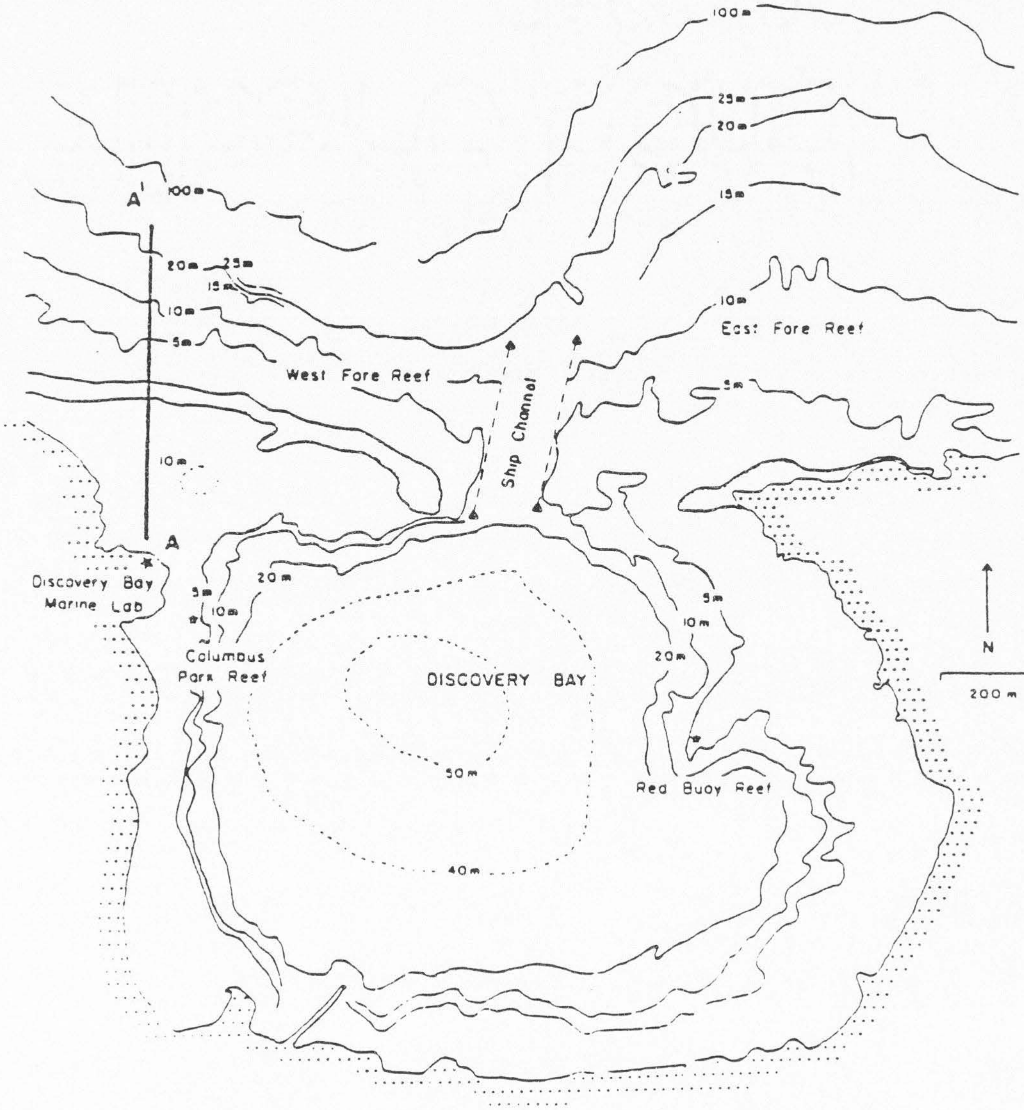
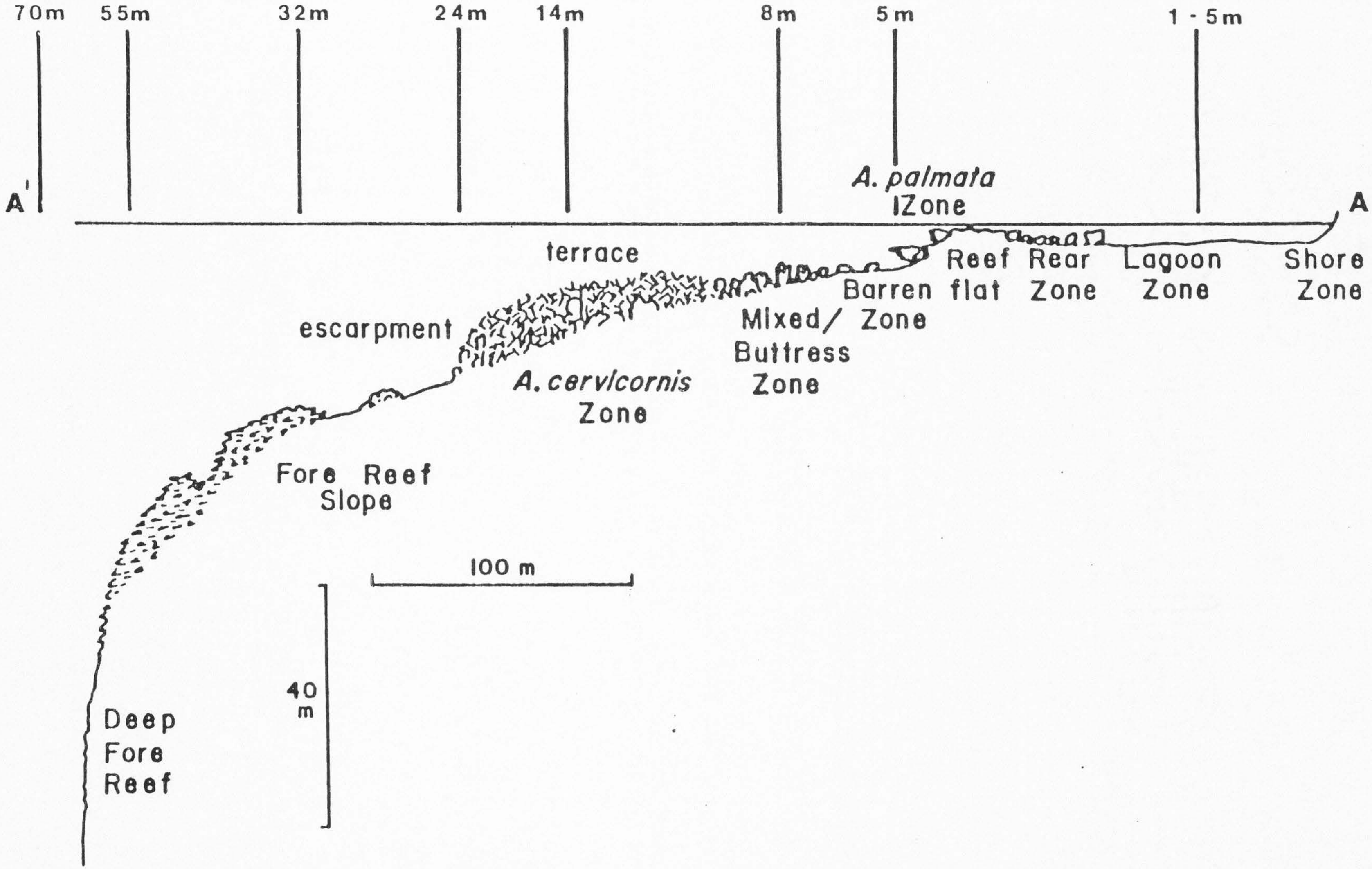


FIG. 11. Bathymetric map of Discovery Bay, Jamaica showing location of transect A - A'(modified from Liddell and Ohlhorst, 1981).


70m
55m
32m
24m
14m
8m
5m
1 - 5m
A'
A
A. palmata
Zone
terrace
Reef flat
Rear Zone
Lagoon Zone
Shore Zone
Barren Zone
escarpment
Mixed/ Buttress Zone
A. cervicornis Zone
Fore Reef Slope
100 m
40 m
Deep Fore Reef

(160m from shore and 80m behind the reef crest); and 4) the rear zone (an area immediately behind the reef crest).

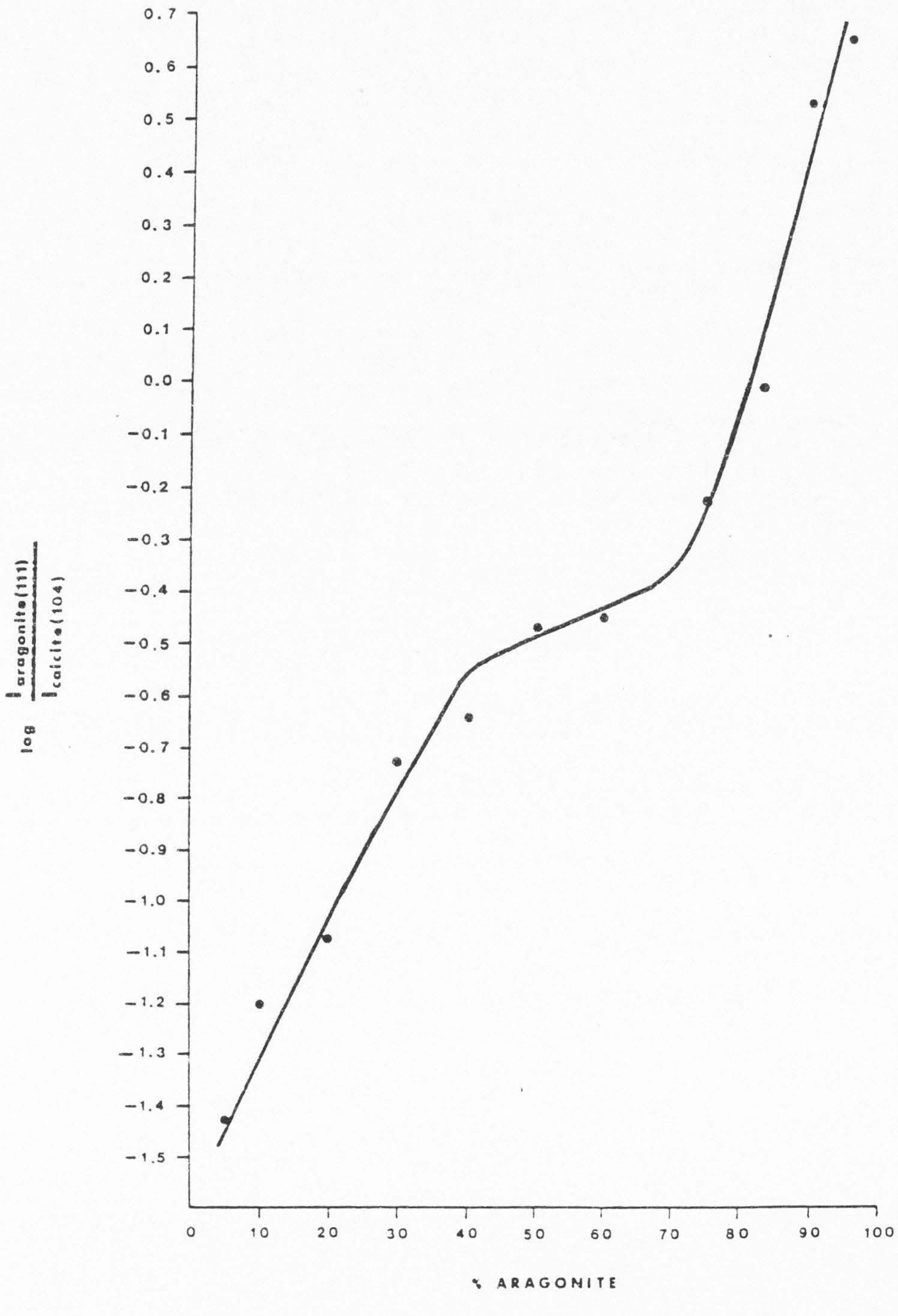
Following collection, all sediments were placed into a 1000ml graduated cylinder and washed with distilled water. The sediment was then allowed to settle for 6 hours in order to limit the loss of fine-grained constituents. After this period of settling, the water was removed from the cylinder using a siphon, and the sediment was washed again with distilled water. The supernatant from each wash was passed through a Buchner Funnel and pre-weighed Whatman's #1 Filter Paper to capture any remaining suspended sediment. This process was repeated three times for each sample, after which the sediments were removed from the cylinder and oven dried at 105oC. The filters were also dried and weighed to determine the amount of fine-grained sediment which was lost from the bulk sample. In all cases, this was found to be a negligible amount (averaging a few tenths of a gram for each 200g sample). Following the drying period, each sample was placed in a plastic bag and sealed for shipment to Utah State University. There, subsamples for X-ray analysis were pulverized and passed through a 115 (3ø) mesh sieve onto Vaseline-coated glass plates.

X-ray and Insoluble-Residue Analysis

Mineralogical analyses of the 51 sediment samples were made using a Siemens X-ray Diffractometer. Operating conditions for the diffractometry unit were 35kV and 16mA. The sample was bombarded with nickel-filtered copper K_α radiation (1.54Å) and the specimen rotated at 2^o 2θ per minute.

Initially, 13 samples (four from the back reef and one each from the sample sites at 5m, 8m, 11m, 14m, 24m, 32m, 46m, 55m, and 70m on LTS reef) were scanned over 45^o 2θ (4^o to 49^o 2θ). Only aragonite, high-Mg calcite, and low-Mg calcite were present. The 38 remaining samples were assumed to be relatively pure carbonate as well and were only scanned from 22^o to 31^o 2θ.

Quantitative determinations for aragonite, high-Mg calcite, and low-Mg calcite were accomplished using the method of Stehli and Hower (1961). A working curve for the determination of aragonite percent was prepared by combining various known weight fractions of pure aragonite and calcite. First, the peak heights of the aragonite (111) reflection (26.2^o 2θ) and the calcite (104) reflection (29.4^o 2θ) were measured from the x-ray diffractograms. The ratio of these intensities (peak heights) was then plotted against percent aragonite to construct the curve shown (Fig.13). This curve shows good agreement with that of Chave (1954a). The next step in this process was to determine the composition of the remaining carbonate with respect to high-Mg calcite ($MgCO_3 > 4$ mol%) and low-Mg calcite ($MgCO_3 \leq 4$ mol%). For purposes of this study, it was assumed that the presence of $MgCO_3$ in the calcite did not significantly affect the mass absorption coefficient (and thus, reflected X-ray intensity) of that phase. The reported error for this


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3
-1.4
-1.5
log I aragonite(111) / I calcite(104)
0 10 20 30 40 50 60 70 80 90 100
% ARAGONITE

assumption is rather large, being 5-18% (Stehli and Hower, 1961; Chave,1962; Runnells, 1970). However, it makes possible the direct comparison of peak heights as a measure of the concentrations of high-Mg calcite and low-Mg calcite. The ratio of the peak heights of the (104) reflections for these two phases were measured and the percent of each mineral proportioned according to the percent carbonate remaining (100 minus % aragonite) for each sample.

For all samples, the mole % Mg in solid solution within the lattice of high-Mg calcite was determined using the method of Goldsmith, et al. (1955). Their data indicate a linear relationship between the change in the d(104) dimensions and mol % $MgCO_3$ up to 21 mol % $MgCO_3$ in the system $CaCO_3$-$MgCO_3$. This change in the d(104) dimension results in a shift of the (104) spacing to lower d-values. The d(104) in high-Mg calcite can be calculated directly from the angular position of the (104) reflection on the diffractogram using the Bragg equation. Once the d-spacing of the Mg-rich calcite is known, the mol % $MgCO_3$ in the system can be found using the formula:

$$[(3.035 - d_s) \div 0.261] \times 100 = \text{mol \% } MgCO_3$$

where d_s is the d(104) spacing calculated for the sample from the diffractogram. Table 8 shows the results of these analyses and the mineralogical composition of the 51 samples. Figure14 is a ternary plot of the mineralogical data.

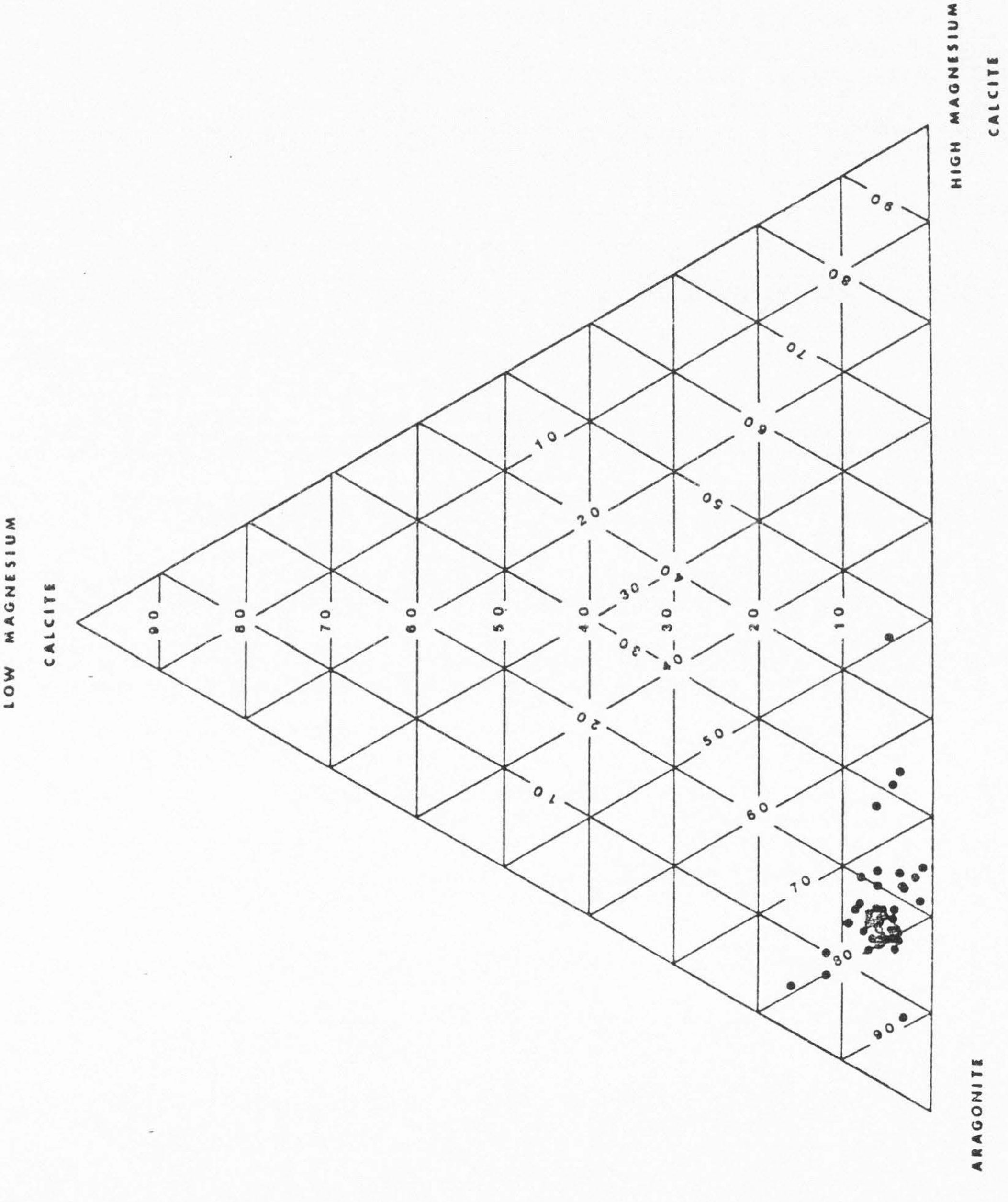
The non-carbonate fraction in each of the 51 samples was

TABLE 8. Mineralogical composition of LTS Reef sediments, Discovery Bay, Jamaica.

LOCATION	SAMPLE #	% ARAGONITE	% LOW-Mg CALCITE	% HIGH-Mg CALCITE	MOL % MgCO3 in high-Mg CALCITE
Back Reef					
BRns 1ms	JA 048	78	12	10	15
BRth 3ms	JA 015	80	5	15	12
	JA 016	80	4	16	19
BRca 5ms	JA 013	80	6	14	15
	JA 014	78	6	16	12
BRcr 2ms	JA 045	77	2	21	23
	JA 071	89	3	8	15
	JA 073	82	4	14	12
MEAN and 95% C.I.		81 ± 3.2	5 ± 2.6	14 ± 3.4	15 ± 2.9
MEDIAN and 95% C.I.		80 ± 2.0	4.5 ± 1.5	14.5 ± 4.5	15 ± 4.0
Fore Reef Terrace					
5mr	JA 144	62	4	34	19
	JA 147	76	3	21	15
8mr	JA 141	67	5	28	15
	JA 142	49	5	46	23
8ms	JA 138	75	3	22	15
	JA 143	74	6	20	15
11mr	JA 140	74	4	22	19
	JA 145	79	4	17	12
11ms	JA 137	75	4	21	15
	JA 139	75	4	21	12
14mr	JA 146	80	4	16	19
	JA 149	78	5	17	19
14ms	JA 150	80	4	16	15
	JA 151	77	6	17	15
MEAN and 95% C.I.		73 ± 4.9	4 ± 0.6	23 ± 4.8	16 ± 1.5
MEDIAN and 95% C.I.		75 ± 3.0	4 ± 1.0	21 ± 4.0	15 ± 4.0
Fore Reef Escarpment					
24mr	JA 113	78	5	17	12
	JA 134	77	9	14	12
	JA 135	76	8	16	12
	JA 009	78	4	18	15
	JA 148	77	5	18	17
24ms	JA 110	79	5	16	12
	JA 111	79	4	17	15
	JA 011	77	6	17	15
	JA 096	80	6	14	15
MEAN and 95% C.I.		78 ± 1.0	6 ± 1.3	16 ± 1.1	14 ± 1.7
MEDIAN and 95% C.I.		78 ± 1.0	5 ± 1.0	17 ± 1.0	15 ± 3.0
Fore Reef Slope					
32mr	JA 116	80	6	14	15
	JA 120	79	5	16	8
32ms	JA 105	78	6	16	23
	JA 108	78	6	16	19
46mr	JA 106	80	7	13	15
	JA 107	79	7	14	15
46ms	JA 109	78	5	17	15
	JA 114	73	6	21	15
55mr	JA 115	77	7	16	12
	JA 117	80	12	8	12
55ms	JA 112	78	6	16	15
	JA 118	78	7	15	19
MEAN and 95% C.I.		78 ± 1.3	7 ± 1.2	15 ± 1.9	15 ± 2.2
MEDIAN and 95% C.I.		78 ± 1.0	6 ± 1.0	16 ± 2.0	15 ± 0.0
Deep Fore Reef					
70mr	JA 061	78	5	17	15
	JA 062	78	5	17	19
	JA 065	76	7	17	15
	JA 066	77	6	17	23
	JA 067	79	6	15	15
	JA 068	78	6	16	23
	JA 129	78	7	15	19
	JA 130	78	6	16	19
MEAN and 95% C.I.		78 ± 0.8	6 ± 0.6	16 ± 0.8	19 ± 3.3
MEDIAN and 95% C.I.		78 ± 1.0	6 ± 1.0	16.5 ± 1.5	19 ± 4.0

Sample codes:
- BRns = back reef, near shore
- BRth = back reef, *Thalassia* beds
- BRca = back reef, *Callianassa* mounds
- BRcr = back reef, behind reef crest

8mr = sample depth (in meters), bottom type at sample locality
(r = reef framework; s = sand channel)


LOW MAGNESIUM CALCITE
HIGH MAGNESIUM CALCITE
ARAGONITE

determined by immersing each sample in 20% HCl solution until all carbonate had been dissolved. Following acid treatment, the insoluble residue was thoroughly rinsed with distilled water, dried in an oven at 60° C, and weighed. The results of this analysis are presented in Table 9. X-ray diffraction analysis of five of these insoluble fractions (one from each reef zone) was conducted to determine their mineralogy.

RESULTS

The various polymorphs of calcium carbonate usually comprise greater than 95% by weight of these sediments with acid-insoluble residues constituting the remaining weight fraction. X-ray analysis of 5 of these residues (one from each reef zone) failed to produce any reflections through a 45° range of 2θ (4° to 49° 2θ). Ohlhorst (1980) showed that these residues are composed entirely of amorphous siliceous sponge spicules and organic matter. There were no discernable trends in the variation of insoluble material with depth or reef zone.

X-ray analyses of the carbonate fraction of the 51 sediment samples for this study reveal that they are dominated by aragonite (49-89%), followed by high-Mg calcite (8-46%) and low-Mg calcite (2-12%). Back reef sediments exhibit the highest aragonite content ($\bar{X}$=81% $\pm$ 3.2%), whereas sands of the fore reef terrace contain the most high-Mg calcite ($\bar{X}$=23% $\pm$ 4.8%).

TABLE 9. Weight percent insoluble fraction and total $CaCO_3$ in LTS Reef sediments.

LOCATION	SAMPLE #	% INSOLUBLE	% $CaCO_3$
Back reef			
BRns 1ms	JA 048	1.1	98.9
BRth 3ms	JA 015	0.9	99.1
	JA 016	0.3	99.7
BRca 5ms	JA 013	4.8	95.2
	JA 014	6.2	93.8
BRcr 2ms	JA 045	1.3	98.7
	JA 071	1.3	98.7
	JA 073	1.2	98.8
MEAN and 95% C.I.		2.1 ± 1.8	97.9 ± 1.8
MEDIAN and 95% C.I.		1.3 ± 3.6	98.8 ± 3.6
Fore Reef Terrace			
5mr	JA 144	1.3	98.7
	JA 147	1.4	98.6
8mr	JA 141	0.8	99.2
	JA 142	7.0	93.0
8ms	JA 138	0.4	99.6
	JA 143	1.9	98.1
11mr	JA 140	1.6	98.4
	JA 145	1.7	98.3
11ms	JA 137	2.4	97.6
	JA 139	2.2	97.8
14mr	JA 146	1.4	98.6
	JA 149	2.0	98.0
14ms	JA 150	4.7	95.3
	JA 151	0.7	99.3
MEAN and 95% C.I.		2.1 ± 1.0	97.9 ± 1.0
MEDIAN and 95% C.I.		1.7 ± 0.6	98.4 ± 0.6
Fore Reef Escarpment			
24mr	JA 009	1.7	98.3
	JA 148	2.1	97.9
	JA 113	2.4	97.6
	JA 134	2.3	97.7
	JA 135	1.1	98.9
24ms	JA 011	1.9	98.1
	JA 096	1.9	98.1
	JA 110	2.8	97.2
	JA 111	1.0	99.0
MEAN and 95% C.I.		1.9 ± 0.5	98.1 ± 0.5
MEDIAN and 95% C.I.		1.9 ± 0.4	98.1 ± 0.4
Fore Reef Slope			
32mr	JA 116	1.1	98.9
	JA 120	0.9	99.1
32ms	JA 105	1.0	99.0
	JA 108	1.0	99.0
46mr	JA 106	2.3	97.7
	JA 107	1.5	98.5
46ms	JA 109	0.7	99.3
	JA 114	1.2	98.8
55mr	JA 115	2.0	98.0
	JA 117	4.4	95.6
55ms	JA 112	1.7	98.3
	JA 118	2.3	97.7
MEAN and 95% C.I.		1.7 ± 0.6	98.3 ± 0.6
MEDIAN and 95% C.I.		1.4 ± 0.7	98.7 ± 0.7
Deep Fore Reef			
70mr	JA 061	1.6	98.4
	JA 062	1.8	98.2
	JA 065	1.3	98.7
	JA 066	1.5	98.5
	JA 067	2.0	98.0
	JA 068	1.7	98.3
	JA 129	1.7	98.3
	JA 130	1.7	98.3
MEAN and 95% C.I.		1.7 ± 0.2	98.3 ± 0.2
MEDIAN and 95% C.I.		1.7 ± 0.2	98.3 ± 0.2

To test the significance of the observed variability in mineralogy between sites, the Mann-Whitney U statistic was employed (Johnson, 1976). This statistic assumes that two samples are the same (H_0: $S_1 = S_2$). The value for U is calculated from the sample data and compared to a standard table for the critical values of U ($\alpha = 0.05$). If the calculated U is greater than this critical value, the null hypothesis (H_0) is rejected and the alternate hypothesis (H_a: $S_1 \neq S_2$) is accepted. The results of this analysis are presented in Table 10. A significant difference between the mineralogy of fore reef terrace sediment and sediment from other reef zones is evident. This indicates that shallow reef sediments may be distinguished from their lagoonal and deep-water counterparts on the basis of mineralogy alone.

DISCUSSION

The observed differences in mineralogy between fore reef terrace sediments and sediments from other reef zones are almost certainly the result of variable sediment contribution by different taxonomic groups in these reef zones. Sedimentologic data from Discovery Bay reefs indicate that the green alga, Halimeda, contributes significant quantities of aragonitic skeletal debris to back reef and deep reef sediments (up to 52%; Boss and Liddell, 1983). Additionally, other green algae such as Penicillus, Rhipocephalus, and Udotea contribute fine (<62 m) aragonite mud to reef sediments (Lowenstam and Epstein, 1957; Stockman, et al., 1967;

TABLE 10. Results of Mann-Whitney U tests* using mineralogical data from each sample site on LTS Reef.

ARAGONITE

	Back Reef	Fore Reef Terrace	Fore Reef Escarpment	Fore Reef Slope	Deep Fore Reef
Back Reef	----				
Fore Reef Terrace	x	----			
Fore Reef Escarpment	----	----	----		
Fore Reef Slope	----	x	----	----	
Deep Fore Reef	----	----	----	----	----

LOW-MAGNESIUM CALCITE

	Back Reef	Fore Reef Terrace	Fore Reef Escarpment	Fore Reef Slope	Deep Fore Reef
Back Reef	----				
Fore Reef Terrace	----	----			
Fore Reef Escarpmet	----	x	----		
Fore Reef Slope	x	x	----	----	
Deep Fore Reef	----	x	----	----	----

HIGH-MAGNESIUM CALCITE

	Back Reef	Fore Reef Terrace	Fore Reef Escarpment	Fore Reef Slope	Deep Fore Reef
Back Reef	----				
Fore Reef Terrace	x	----			
Fore Reef Escarpment	----	x	----		
Fore Reef Slope	----	x	----	----	
Deep Fore Reef	----	x	----	----	----

* $H_0: S_1 = S_2$

$H_a: S_1 \neq S_2$

x = H_0 rejected at $\alpha = 0.05$

---- = cannot reject H_0 at $\alpha = 0.05$

Neumann and Land, 1975). On the fore reef terrace, coralline algae and the Foraminiferan, Homotrema rubrum, provide the major sources of high-Mg calcite (5.8-13.5% and 6.4-9.5%, respectively; Boss and Liddell, 1983), with lesser amounts contributed by other benthic Foraminifera (1.8-3.3%) and echinoderms (1.7-3.6%).

Variations in the mineralogic composition of carbonate sediments may have a profound influence on post-depositional diagenetic phenomena. Maxwell, et al. (1963) suggested that sediments initially rich in high-Mg calcite would be more susceptible to dolomitization than sediments with minor amounts of high-Mg calcite. Schlanger (1957) has shown that coralline algae are particularly susceptible to dolomitization. In borings from Funafuti Atoll, the coralline algae in Eocene carbonates display recrystallization to dolomite. Gross (1965) provides similar data from drilling records in carbonates on Plantagenet Bank, Bermuda where poorly ordered dolomite (43 mol% $MgCO_3$) was detected in a core from 20m below the sediment-water interface. Thin section study of these sediments revealed that the dolomite occurred as cement binding red-algal bioclasts. Additionally, Land and Epstein (1970) found poorly ordered dolomite (41-44 mol% $MgCO_3$) in coralline algae from Pleistocene reef carbonates near Discovery Bay, Jamaica. The limestones in which these dolomitized algae occur have faunal and sedimentological features comparable to Recent, shallow fore reef environments (Boss and Liddell, 1984b) and are presumed to have had similar original mineralogies. This indicates that fore reef terrace sediments (relatively enriched in high-Mg calcite) may be more susceptible to dolomitization than back reef or deep-reef sediments. Further, magnesium may be selectively leached from high-Mg calcites (Stehli and Hower, 1961; Friedman, 1964; Gavish and Friedman, 1969). Through this process, substantial quantities of magnesium may be added to pore fluids. Increasing the Mg/Ca ratio in this manner may further influence dolomitization of carbonate deposits.

Matthews (1968) speculated that abundant calcitic grains dispersed throughout carbonate sediments would hasten solution of aragonite and precipitation of low-Mg calcite cements by providing nucleation sites for calcite crystal growth. In Pleistocene reef deposits of Barbados, he noted that some fossil coral heads still exhibited their original aragonitic mineralogy while associated reef sediments showed extensive alteration to low-Mg calcite.

Certainly, factors other than original sediment mineralogy will affect diagenetic processes in carbonate sediments. Sediment textural properties such as porosity and permeability may be limiting factors in the movement of water and concomitant dissolution/precipitation kinetics (Matthews, 1968). Also, tectonic history and position of these deposits with respect to the freshwater vadose zone, freshwater phreatic zone, or marine phreatic zone will affect the outcome of diagenetic processes (Friedman, 1964;

Gavish and Friedman, 1969; Land, 1973; Land and Epstein, 1970; Longman, 1980). Presently, there are insufficient data to determine the contribution of these factors to the diagenetic history of Pleistocene reef limestones of Jamaica. However, future studies of carbonate diagenesis should consider the possible role of original sediment mineralogy in the diagenetic history of limestones.

CHAPTER IV

DEPOSITIONAL ENVIRONMENTS OF THE FALMOUTH FORMATION: BACK REEF AND FORE REEF ANALOGS IN THE PLEISTOCENE OF NORTH JAMAICA

INTRODUCTION

Holocene fringing reefs of the Jamaican north coast are among the most intensively studied coral reefs in the world. Numerous studies of reef community structure (Goreau, 1959; Goreau and Goreau, 1973; Kinzie, 1973; Bonem and Stanley, 1977; Ohlhorst, 1980; Liddell and Ohlhorst, 1981; Liddell, *et al.*, 1984a; Liddell, *et al.*, 1984b) and sedimentology (Land, 1970; Land and Goreau, 1970; Land, 1973; Goreau and Goreau, 1973; Aller and Dodge, 1974; Goreau and Land, 1974; Boss and Liddell, 1983; Boss and Liddell, 1984a and in preparation; Boss, *et al.*, 1984 and in preparation) have been made.

In sharp contrast to the wealth of knowledge concerning the community structure and depositional environments of these fringing reefs, no detailed paleontologic or sedimentologic studies of the Pleistocene reef systems have been conducted, although several diagenetic studies have been performed (Land and Epstein, 1970; Land, 1973). The 120,000 y.b.p. (Sangamonian) Falmouth Formation (Land, 1973) represents an emergent fringing reef complex exposed along the north coast of Jamaica. During Sangamon time, Falmouth Fm. reefs were constructed upon a submerged erosional surface at an approximately +5m sea level (Cant, 1973; Land, 1973).

Lowering of sea level after this interval resulted in truncation of the Falmouth Fm. and the formation of a number of terraces, some of which are now submerged and mantled by Holocene reef growth (Liddell and Ohlhorst, 1981). At Discovery Bay, the Falmouth Fm. is typically exposed at the present shore and in an eroded terrace surface located a few meters above sea level.

The close juxtaposition of this Pleistocene reef limestone and Recent fringing reef environments provides an excellent opportunity for the application of uniformitarian principles in comparative sedimentology and microfacies analysis. Boss and Liddell (1983) and Boss, et al., (1984) have developed a model for microfacies analysis of Holocene reef deposits using constituent composition of associated sediments. This paper presents the results of a study conducted on selected outcrops of the Falmouth Formation to test the utility of this model with respect to the analysis of fossil reef limestones.

PREVIOUS WORK

In general, the Pleistocene reefs exposed throughout the Caribbean region have not been extensively examined. However, several comparative studies relating Late Pleistocene reef facies to equivalent Holocene reef environments have been conducted. Most notable of these studies are those of Stanley (1966) on the paleoecology of the Key Largo Limestone of Florida, Mesolella, et al. (1970) and James, et al.

(1977) on the Pleistocene reefs of Barbados, and Tebbutt's (1975) analysis of the Pleistocene carbonates of Ambergris Cay, Belize.

Stanley (1966) analyzed the preserved faunal and sedimentological characteristics of the Key Largo Limestone and compared these attributes with faunal and sedimentological aspects of modern carbonate accumulations on the Florida shelf. Based primarily upon consideration of the ecology of the preserved coral fauna, he was able to describe the Key Largo Limestone as a series of coalescing patch reefs developed in water 6.5 - 13 meters deep.

Mesolella, et al. (1970) and James, et al. (1977) conducted extensive surveys of the Pleistocene reefs of Barbados. Again, making their interpretations primarily upon a consideration of the ecology of preserved scleractinian faunas, they were able to define a number of distinctive facies within these Pleistocene reefs. Also, they described all of the major zones which have been described from modern West Indian coral reefs. This fossil zonation included environments equivalent to back reef, reef crest, shallow fore reef and deep fore reef.

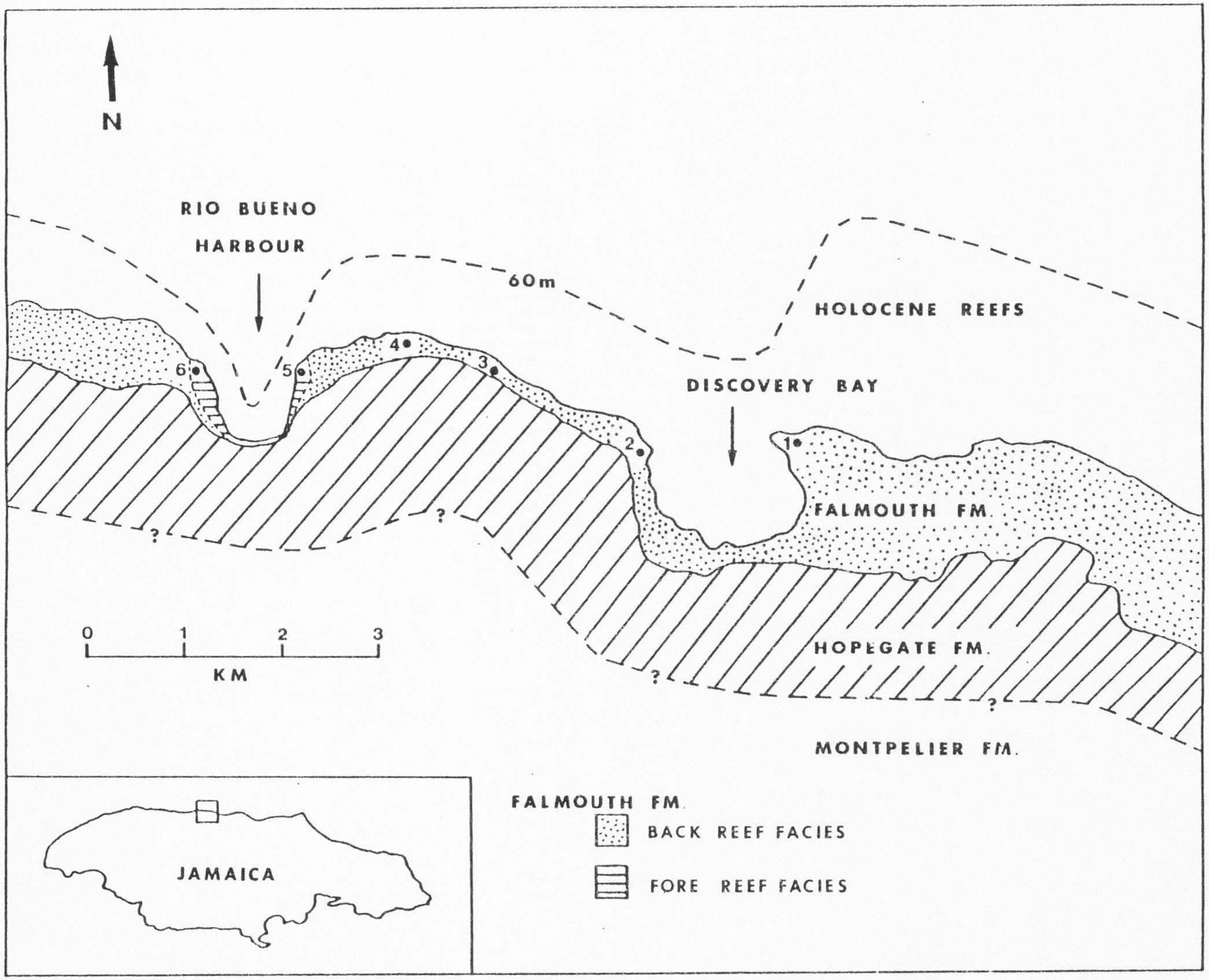
Using the same criteria as the above-mentioned studies, Tebbutt (1975) was able to delineate reef crest, back reef, shelf lagoon, and mud bank facies in the Pleistocene of Ambergris Cay, Belize. In addition, Tebbutt recognized variability in the extent of diagenetic alteration which he attributed to variation in porosity and permeability as well as primary mineralogy of skeletal components in these limestones.

In Jamaica, the depositional setting of the Falmouth Formation has been briefly described in several publications. Cant (1973) provides a brief description of generalized facies geometries within the Falmouth Formation near Oracabessa on the Jamaican north coast. Here, he illustrates the areal distribution of reef framework and sandy back reef deposits upon an exposed low terrace of the Falmouth Formation 4km east of Oracabessa. In addition, Land and Epstein (1970) examined diagenetic phenomena within Falmouth limestones near Discovery Bay. They concluded from petrographic and isotopic studies that the observed post-depositional alteration of these reef carbonates resulted from the interaction of these deposits with meteoric waters in the vadose zone associated with subaerial exposure during the Wisconsin glaciation.

Each of these studies utilized analyses of preserved macrofauna within the Falmouth Formation to define facies relationships. In this paper, it will be shown that the analysis of associated sediments can be used with equal effectiveness to delineate the various facies of this fossil reef accumulation.

LOCATION OF STUDY

Measurement and sampling of Falmouth limestones was made at 6 locations along the Jamaican north coast in the vicini-


N
RIO BUENO
HARBOUR
60m
HOLOCENE REEFS
6
5
4
3
2
1
DISCOVERY BAY
FALMOUTH FM.
?
?
?
?
HOPEGATE FM.
MONTPELIER FM.
0
1
2
3
KM
JAMAICA
FALMOUTH FM.
BACK REEF FACIES
FORE REEF FACIES

ty of Discovery Bay (lat. 18o 30' N, long. 77o 20' W)(Fig. 15). Outcrops were sampled at approximately 0.5km intervals between Rio Bueno Harbour on the west and Discovery Bay on the east. Analyses of Falmouth Formation rocks were conducted at Utah State University.

METHODS

Sampling

Line Transects

The excellent preservational quality of the Falmouth Formation enabled the utilization of line transecting techniques to make quantitative estimates of the Pleistocene reef community composition. At each outcrop, the point intercept method of transecting was used (c.f. Liddell, et al., 1984a). Here, a 10m length of cord marked at 20cm intervals was stretched across the outcrop. At each marked point, a hammer was used to break through the weathered calcareous crust, thus exposing a fresh surface of the limestone for examination. The nature of the substrate (whether lithified sediment or reef frame) and faunal components occurring beneath each marked point were noted. After all points on the line were counted, the cord was moved 1m parallel to the first transect. A second transect was then made in the same manner described above. This process was repeated until a minimum of 150 points were recorded for each site. The results of transecting are presented in Table 11.

TABLE 11. Faunal composition of the Falmouth Formation in the Discovery Bay area. Expressed as percentage of transect points (approximately 150 per site). (from Liddel, *et al.*, 1984c).

LOCALITY (from Fig. 15)	1	2	3	5
Category				
Corals				
Acropora cervicornis	6		1	5
Agaricia agaricites				10
Diploria strigosa	3	4		
Montastrea annularis	19	13		5
Montastrea cavernosa	1			4
Porites astreoides		1		4
Porites furcata	32	28	9	47
Gastropods	7	10	7	
Bivalves	1	10	14	
Unidentified molluscs	1	10	40	
Sediment only	31	24	30	25

Constituent Particle Analysis

Hand specimens of Falmouth limestones were collected at each outcrop. A total of 64 samples were collected from the 6 measured outcrops. 32 of these samples were selected as representatives to be sectioned for petrographic analysis of constituent particle composition. Standard point-counting techniques were utilized and rarefaction analysis (Hurlbert, 1971; Heck, et. al., 1975) used to determine the adequacy of thin-section samples. Using this method, a curve is constructed which shows the number of "species" (grain types) present in the sample per unit measure (points counted). These curves rise rapidly at first, but soon begin to level off and at some point become asymptotic (Fig.16). After this point is reached, the curve can be expected to rise only slightly and at long intervals due to the addition of exceedingly rare constituents. No significant changes in constituent proportions are expected beyond the asymptotic point and one may be confident that the sample is an adequate representation of constituent diversity. For this study it was found that a count of 600 points was needed to accurately describe the constituent composition of each sediment sample. Results of constituent particle analysis are presented in Table 12.

Cluster Analysis

A computer-based program of hierarchical cluster analysis (CLUSTAR) was utilized (Romesburg, 1984; Romesburg and

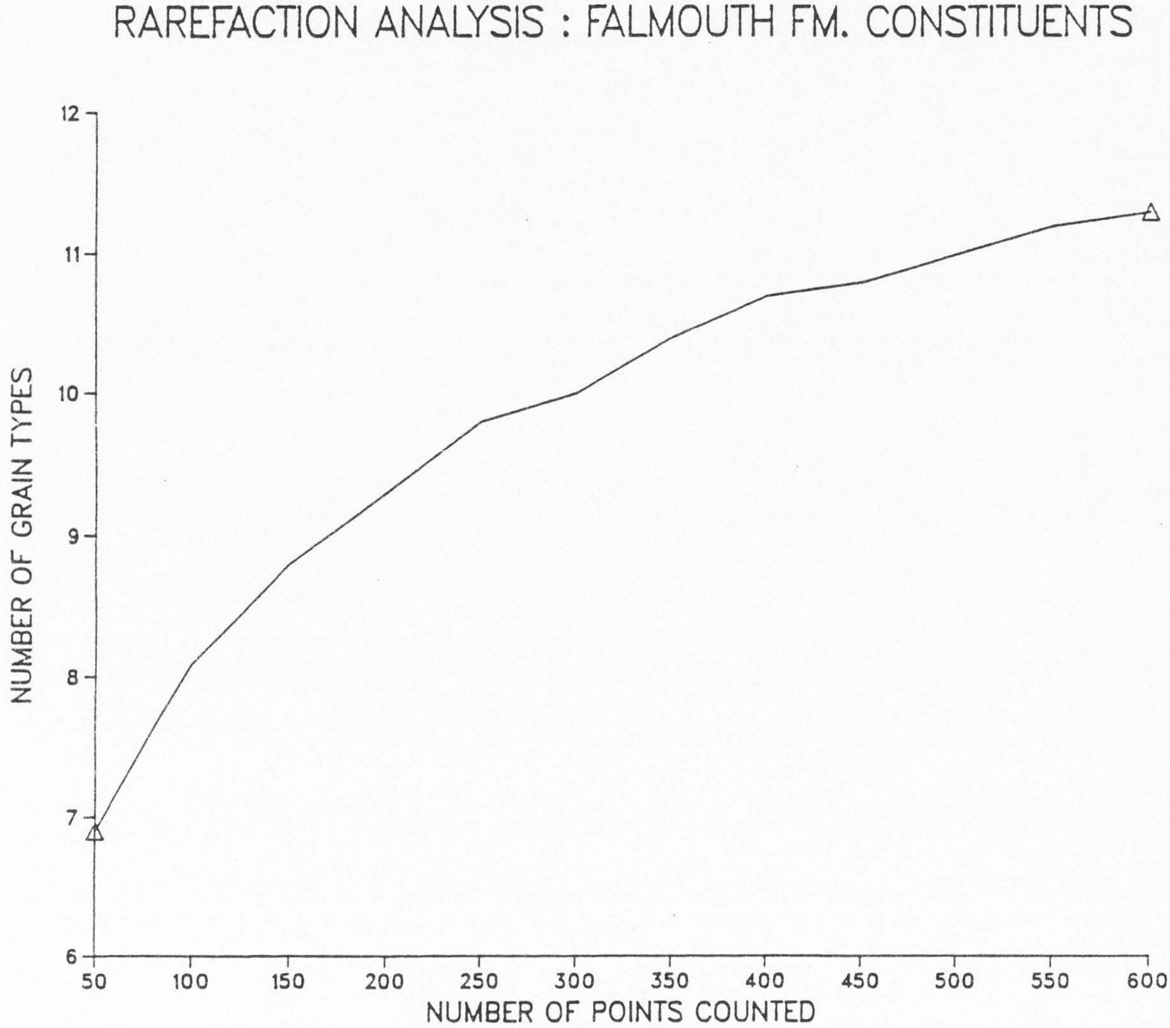


FIG. 16. Rarefaction curve derived from thin-section point-counts of Falmouth Fm. limestones. Curve represents average of counts from 32 samples.

TABLE 12. Comparison of constituent composition of Falmouth Formation facies and Recent back reef and shallow fore reef sediments, Discovery Bay, Jamaica (in % with 95% confidence interval).

CONSTITUENT (%)	FALMOUTH PACKSTONE FACIES	RECENT BACK REEF* SEDIMENTS	FALMOUTH GRAINSTONE FACIES	RECENT FORE REEF* SEDIMENTS
Coral	32.6 ± 3.7	41.3 ± 6.8	57.0 ± 6.3	61.5 ± 7.0
Halimeda	22.8 ± 3.1	24.0 ± 9.6	1.1 ± 0.9	2.5 ± 2.3
Coralline Algae	24.9 ± 3.7	13.2 ± 1.9	23.7 ± 5.3	12.9 ± 9.5
Homotrema	1.8 ± 0.8	3.5 ± 3.5	4.4 ± 2.7	8.6 ± 5.1
Other Foraminifera	2.8 ± 0.5	2.1 ± 0.7	0.3 ± 0.5	1.5 ± 1.2
Molluscs	11.0 ± 2.7	3.5 ± 1.0	10.7 ± 4.2	2.3 ± 1.5
Echinoderms	1.5 ± 0.5	2.8 ± 1.4	2.8 ± 1.3	1.9 ± 1.5
Cryptocrystalline	1.1 ± 0.8	7.5 ± 1.8	0.0 ± 0.0	6.1 ± 3.3
Composite	0.0 ± 0.0	1.2 ± 0.6	4.0 ± 3.4	1.9 ± 1.9
Unidentified	0.0 ± 0.0	0.7 ± 0.5	0.8 ± 0.7	0.3 ± 0.6
Other	0.4 ± 0.2	0.4 ± 0.2	0.3 ± 0.4	0.4 ± 0.4

*Composition of Recent sediments from Boss and Liddell (1983).

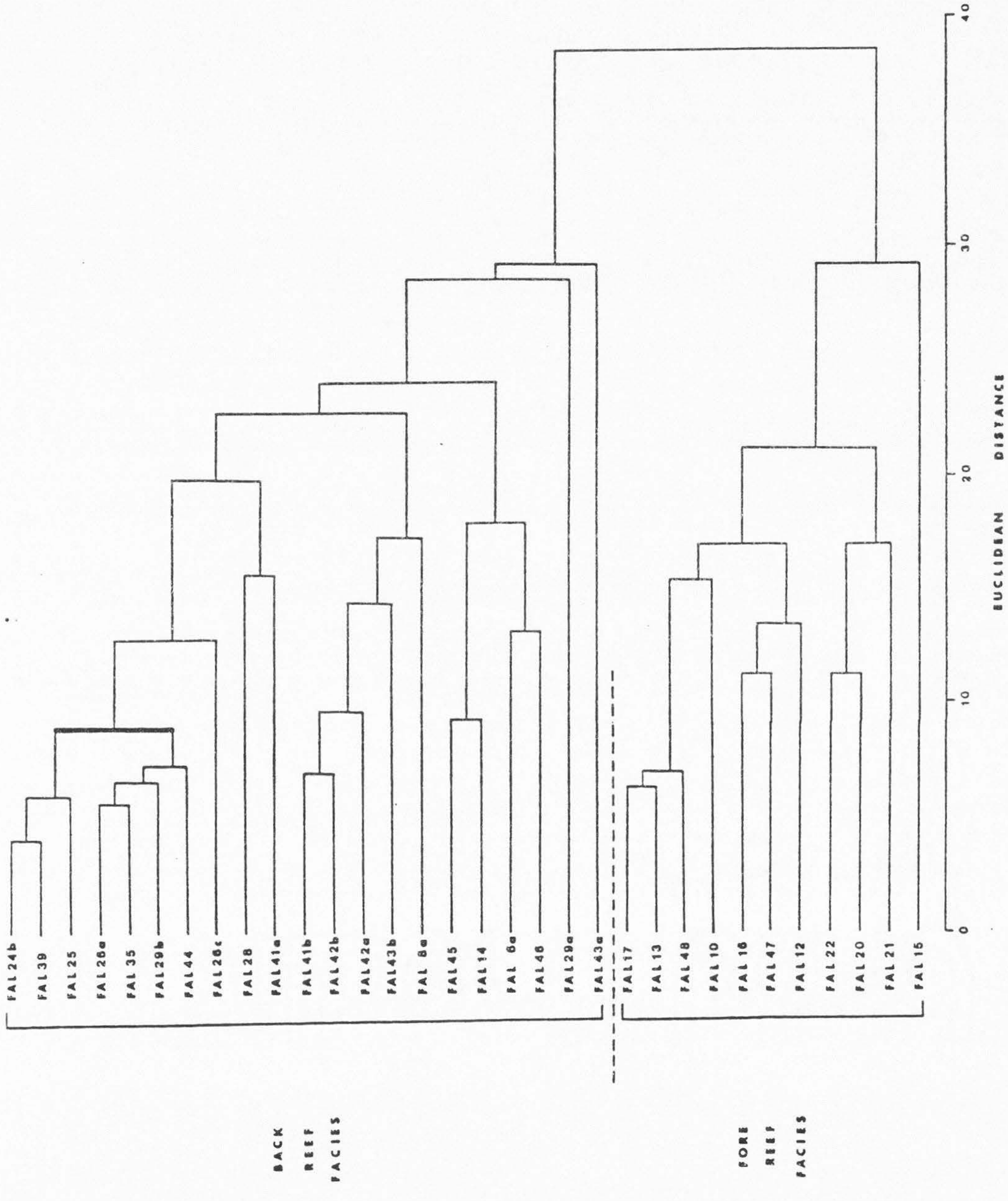
Marshall, 1984) to compare sediment constituent characteristics. It was believed that Q-mode analysis of multivariate sediment constituent data would assist in delineating patterns of association which could not be resolved using simpler statistical methods. For this study, values for the constituent proportions of each sample were analyzed using the Euclidean metric distance measure. This was combined with the Unweighted Pair-Group Method with simple Arithmetic Averages (UPGMA) clustering method. These two options were chosen over the others simply because of their broad application and familiarity to other researchers. The Euclidean metric measures the distance between the individuals i and j defined by:

$$d_{ij} = [\sum_{k=1}^{p} (X_{ik} - X_{jk})^2]^{1/2}$$

where d_{ij} is the euclidean distance, X_{ik} is the kth variable for the ith object and X_{jk} is the kth variable for the jth object (Everitt, 1974). The UPGMA measures the average distance between all pairs of individuals (objects) in each of the clusters. The dendrogram produced from this analysis is illustrated in Figure 17. To test the significance of derived clusters, the Chi-squared test ($\alpha = 0.05$) was used.

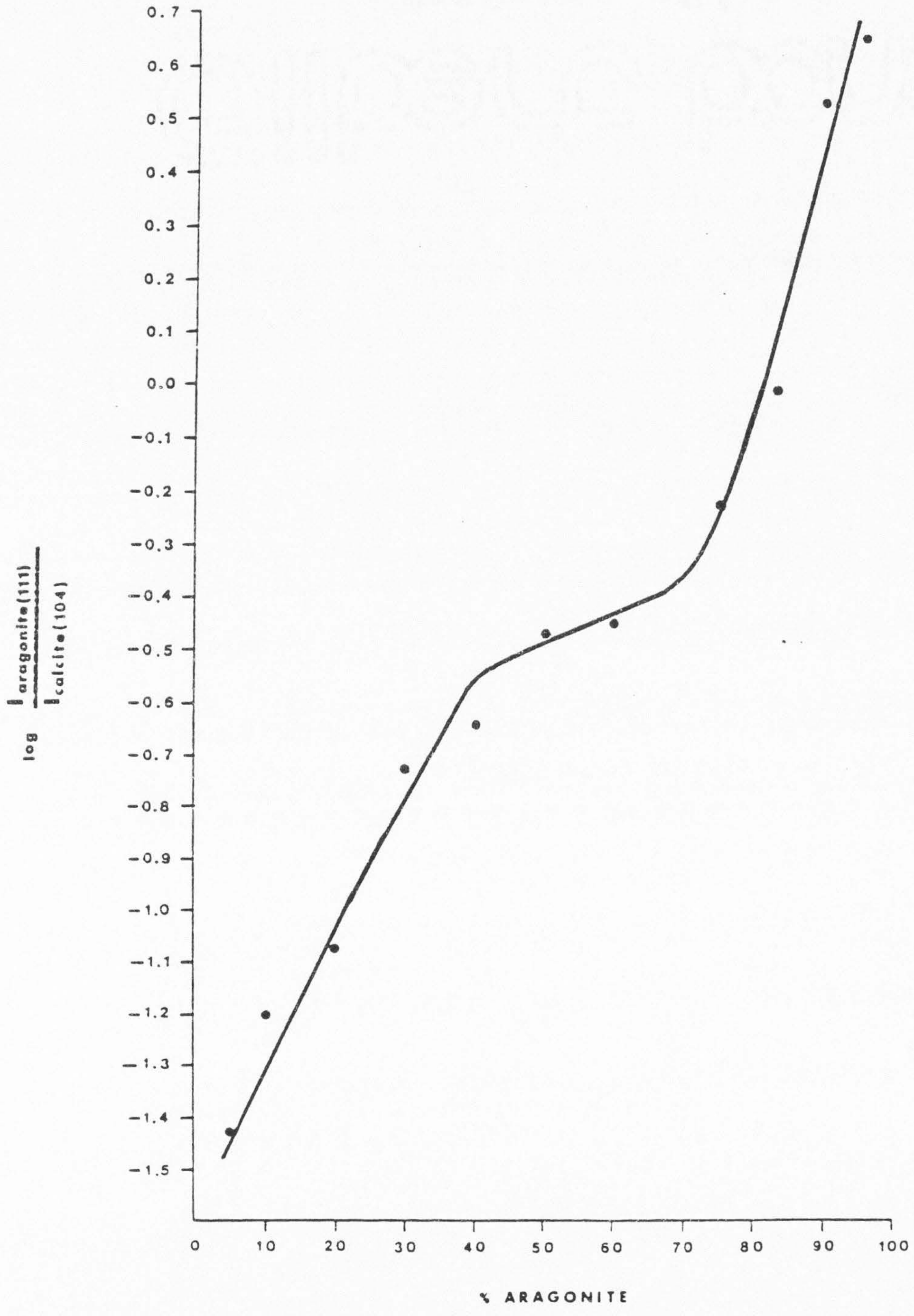
X-ray Analysis of Mineralogy

Mineralogical analyses of 64 limestone samples were made using a Siemens X-ray Diffractometer. Operating conditions for the diffractometry unit were 35kV and 16mA. The sample


FAL 24b
FAL 39
FAL 25
FAL 26a
FAL 35
FAL 29b
FAL 44
FAL 26c
FAL 28
FAL 41a
FAL 41b
FAL 42b
FAL 42a
FAL 43b
FAL 8a
FAL 45
FAL 14
FAL 6a
FAL 46
FAL 29a
FAL 43a
FAL 17
FAL 13
FAL 48
FAL 10
FAL 16
FAL 47
FAL 12
FAL 22
FAL 20
FAL 21
FAL 15
0
10
20
30
40
EUCLIDEAN DISTANCE
BACK REEF FACIES
FORE REEF FACIES

was bombarded with nickel-filtered copper K_α radiation (1.54Å) and the specimen rotated at 2° 2θ per minute.

Quantitative determinations for aragonite, high-Mg calcite, and low-Mg calcite were accomplished using the method of Stehli and Hower (1961). A working curve for the determination of aragonite percent was prepared by combining various known weight fractions of pure aragonite and calcite. First, the peak heights of the aragonite (111) reflection (26.2° 2θ) and the calcite (104) reflection (29.4° 2θ) were measured from the x-ray diffractograms. The ratio of these intensities (peak heights) was then plotted against percent aragonite to construct the curve shown (Fig.18). This curve shows good agreement with that of Chave (1954a). The next step in this process was to determine the composition of the remaining carbonate with respect to high-Mg calcite ($MgCO_3$ > 4 mol%) and low-Mg calcite ($MgCO_3 \leq 4$ mol%). For purposes of this study, it was assumed that the presence of $MgCO_3$ in the calcite did not significantly affect the mass absorption coefficient (and thus, reflected x-ray intensity) of that phase. Although the reported error for this assumption is rather large, being 5-18% (Stehli and Hower, 1961; Chave, 1962; Runnells, 1970), it makes possible the direct comparison of peak heights as a measure of the concentrations of high-Mg calcite and low-Mg calcite. The ratio of the peak heights of the (104) reflections for these two phases were measured and the percent of each mineral proportioned according to the percent carbonate remaining


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3
-1.4
-1.5
log I aragonite(111) / I calcite(104)
0
10
20
30
40
50
60
70
80
90
100
% ARAGONITE

(100 minus % aragonite) for each sample.

For all samples, the mole % Mg in solid solution within the lattice of high-Mg calcite was determined using the method of Goldsmith, et al. (1955). Their data indicate a linear relationship between the change in the d(104) dimensions and mol % $MgCO_3$ up to 21 mol % $MgCO_3$ in the system $CaCO_3$-$MgCO_3$. This change in the d(104) dimension results in a shift of the (104) spacing to lower d-values. The d(104) in high-Mg calcite can be calculated directly from the angular position of the (104) reflection on the diffractogram using the Bragg equation. Once the d-spacing of the Mg-calcite is known, the mol % $MgCO_3$ in the system can be found using the formula:

$$[(3.035 - d_s) \div 0.261] \times 100 = \text{mol } \% \ MgCO_3$$

where d_s is the d(104) spacing calculated for the sample from the diffractogram. Tables 13 and 14 show the mineralogical composition of the 64 samples. Figure 19 is a ternary plot of the mineralogical data.

RESULTS

Line Transects

Table 11 illustrates the faunal composition of Falmouth limestones as determined from transect data for four of the six localities studied along the Jamaican north coast. This table clearly depicts the differences in observed coral abundance and community composition of sampled localities. Note in particular the increase in abundance of corals at

TABLE 13. Mineralogical composition of Falmouth Formation back reef facies limestones, Jamaica.

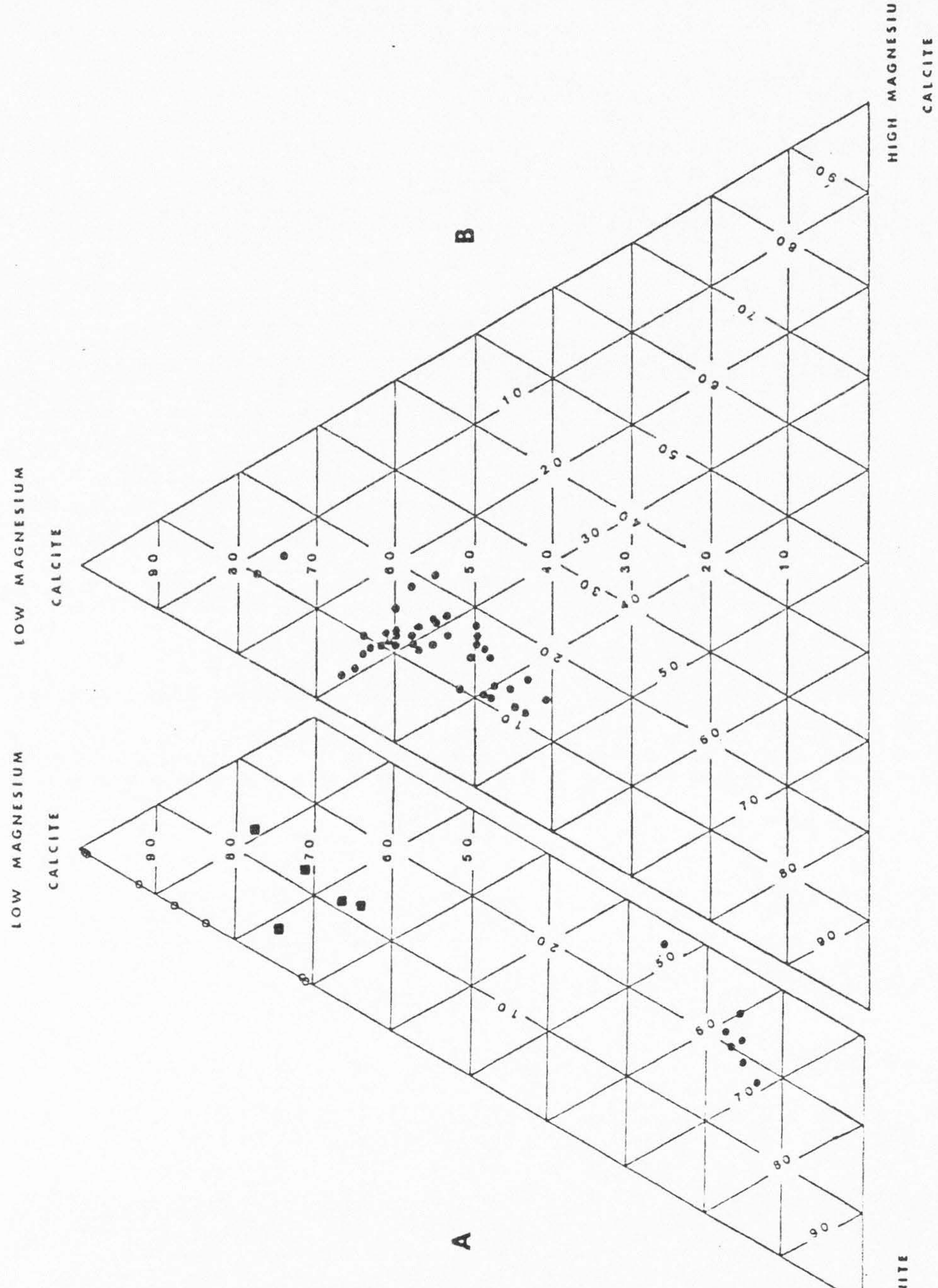
LOCATION (Fig. 15)	SAMPLE #	% ARAGONITE	LOW-Mg % CALCITE	HIGH-Mg % CALCITE	% $MgCO_3$ in HIGH-Mg CALCITE
	FAL 8a	12	74	14	14
	FAL 8b	29	55	16	12
	FAL 9b	41	43	16	12
	FAL 4	41	45	14	8
1	FAL 5a	36	48	16	12
	FAL 5b	41	48	11	8
	FAL 6a	44	45	11	17
	FAL 6b	45	41	14	14
	FAL 6c	43	44	13	12
MEAN and 95% C.I.		36 ± 7.3	50 ± 7.3	14 ± 1.6	12 ± 2.1
	FAL41a	28	64	8	16
	FAL41b	29	65	6	15
	FAL41c	33	50	17	16
	FAL42a	28	60	12	14
	FAL42b	29	58	13	12
	FAL43a	28	62	10	12
	FAL43b	30	57	13	14
2	FAL43c	29	54	17	4
	FAL44	26	64	10	16
	FAL45	38	52	10	17
	FAL46a	27	61	12	4
	FAL46b	27	62	11	4
	FAL46c	29	60	11	16
MEAN and 95% C.I.		29 ± 1.9	59 ± 2.9	12 ± 1.8	12 ± 3.1
	FAL24a	35	51	14	16
	FAL24b	40	47	13	14
	FAL24c	24	58	18	14
	FAL25	24	55	21	8
	FAL26a	34	50	16	14
	FAL26b	32	50	18	12
	FAL26c	29	67	4	12
3	FAL27a	31	53	16	12
	FAL27b	35	49	16	15
	FAL27c	31	56	13	16
	FAL28	29	55	16	14
	FAL29a	25	60	15	17
	FAL29b	31	57	12	16
MEAN and 95% C.I.		31 ± 2.9	55 ± 3.3	15 ± 2.5	14 ± 1.6
	FAL34	63	28	9	16
	FAL35	28	60	12	12
4	FAL38	12	78	10	4
	FAL39	40	49	11	16
	FAL40	28	57	15	14
MEAN and 95% C.I.		34 ± 23.5	54 ± 22.6	11 ± 2.9	12 ± 6.2

TABLE 14. Mineralogical composition of Falmouth Formation fore reef faices limestones, Jamaica.

LOCATION (Fig. 15)	SAMPLE #	% ARAGONITE	LOW-Mg % CALCITE	HIGH-Mg % CALCITE	% $MgCO_3$ in HIGH-Mg CALCITE
	FAL11	13	87	0	---
5a*	FAL18	16	84	0	---
	FAL23	1	99	0	---
MEAN and 95% C.I.		10 ± 19.7	90 ± 19.7	0 ± 0.0	---
	FAL10	21	75	4	10
	FAL12	22	67	11	12
5b	FAL15	9	78	13	16
	FAL21	24	64	12	16
	FAL22	17	71	12	10
MEAN and 95% C.I.		19 ± 7.4	71 ± 7.1	10 ± 4.5	13 ± 3.8
	FAL13	60	24	16	8
	FAL16	63	17	20	16
	FAL48	69	14	17	12
5c	FAL14	61	21	18	14
	FAL17	67	14	19	12
	FAL19	63	15	22	12
	FAL20	48	27	25	17
MEAN and 95% C.I.		62 ± 6.3	19 ± 4.9	20 ± 2.9	13 ± 2.8
	FAL 1	29	71	0	---
	FAL 2	29	71	0	---
6a	FAL 3	7	93	0	---
	FAL 4	1	99	0	---
MEAN and 95% C.I.		17 ± 23.3	84 ± 23.3	0 ± 0.0	---
	FAL 1b	60	26	14	10
6b	FAL 2b	68	21	11	12
	FAL 3b	44	31	25	14
MEAN and 95% C.I.		57 ± 30.3	26 ± 12.4	17 ± 17.7	12 ± 7.0

* Location subscripts refer to position of samples on vertical face of exposed Falmouth limestones:

a = top of section
b = middle of section
c = base of section


A
B
LOW MAGNESIUM CALCITE
LOW MAGNESIUM CALCITE
ARAGONITE
HIGH MAGNESIUM CALCITE

the Rio Bueno Harbour site and the high proportion of molluscs at the other localities.

Field examination of Falmouth limestones revealed the presence of two distinctive lithologies within the study area. The most common lithology in the Discovery Bay area is a dense, well-lithified, muddy limestone which contains abundant molluscs (Fig. 20) and occasional isolated coral heads, principally *Montastrea annularis* (Fig. 21) and *Porites furcata* (Table 11). These deposits are encountered at localities 1 - 4 of Figure 15.

The second lithotype exposed in the study area is poorly lithified and contains an abundance of frame-building corals (Table 12). A vertical section through these deposits is illustrated (Fig. 22) from the margin of Rio Bueno Harbour (locality 5, Fig. 15). Here, the branching coral, *Acropora cervicornis* is shown in growth position at the base of the section with large fronds of *Acropora palmata* occurring immediately above the *A. cervicornis* horizon. The upper 1m of this section (not pictured) has been extensively altered by diagenetic processes to form a dense but friable caliche cap (Land 1973).

Constituent Particle Analysis

Thin-section study of Falmouth limestones reveals variability in the biotic composition of the sediment which results from the influence of reef community composition upon sediment composition (Boss and Liddell, 1983; Boss, *et* *al*., 1984). Two distinctive lithologies are again recognized from the study area (Figs. 23 and 24).

The most common lithology is represented by specimens from localities 1 - 4 (Fig. 15). This skeletal packstone contains abundant plates of the calcareous green alga, *Halimeda* ($\bar{X}$ = 22.8% ± 3.1), as well as comminuted coral ($\bar{X}$ = 32.6% ± 3.7), coralline algae ($\bar{X}$ = 24.9% ± 3.7) and molluscs ($\bar{X}$ = 11.0% ± 2.7), with lesser amounts of Foraminifera ($\bar{X}$ = 4.5% ± 1.3) and echinoderms ($\bar{X}$ = 1.5% ± 0.5).

The second lithology is exposed around the margins of Rio Bueno Harbour (localities 5 and 6, Fig. 15). These skeletal grainstones are poorly lithified with constituent composition dominated by sand-sized coral ($\bar{X}$ = 57.0% ± 6.3) and coralline algae ($\bar{X}$ = 23.7% ± 5.3), with only minor amounts of *Halimeda* ($\bar{X}$ = 1.1% ± 0.9).

Cluster Analysis

Q-mode cluster analysis (CLUSTAR) using constituent data from all 32 sectioned-samples of Falmouth Formation limestones illustrates the distinctive nature of the previously mentioned lithologies. The dendrogram produced from this analysis (Fig. 17) shows two prominent groupings. The upper cluster is represented by the packstones collected from localities 1 - 4 (Fig. 15). The lower cluster is formed by the grainstones which occur within the Falmouth Formation at localities 5 and 6 (Fig. 15).

Chi-squared tests (α = 0.05) between individual pair

FIG. 20. Hand specimen of Falmouth Fm. back reef facies showing abundant molluscs. Sample collected from surface exposure of the Falmouth Fm. at location 2 (Fig. 15). Bar scale = 5cm.

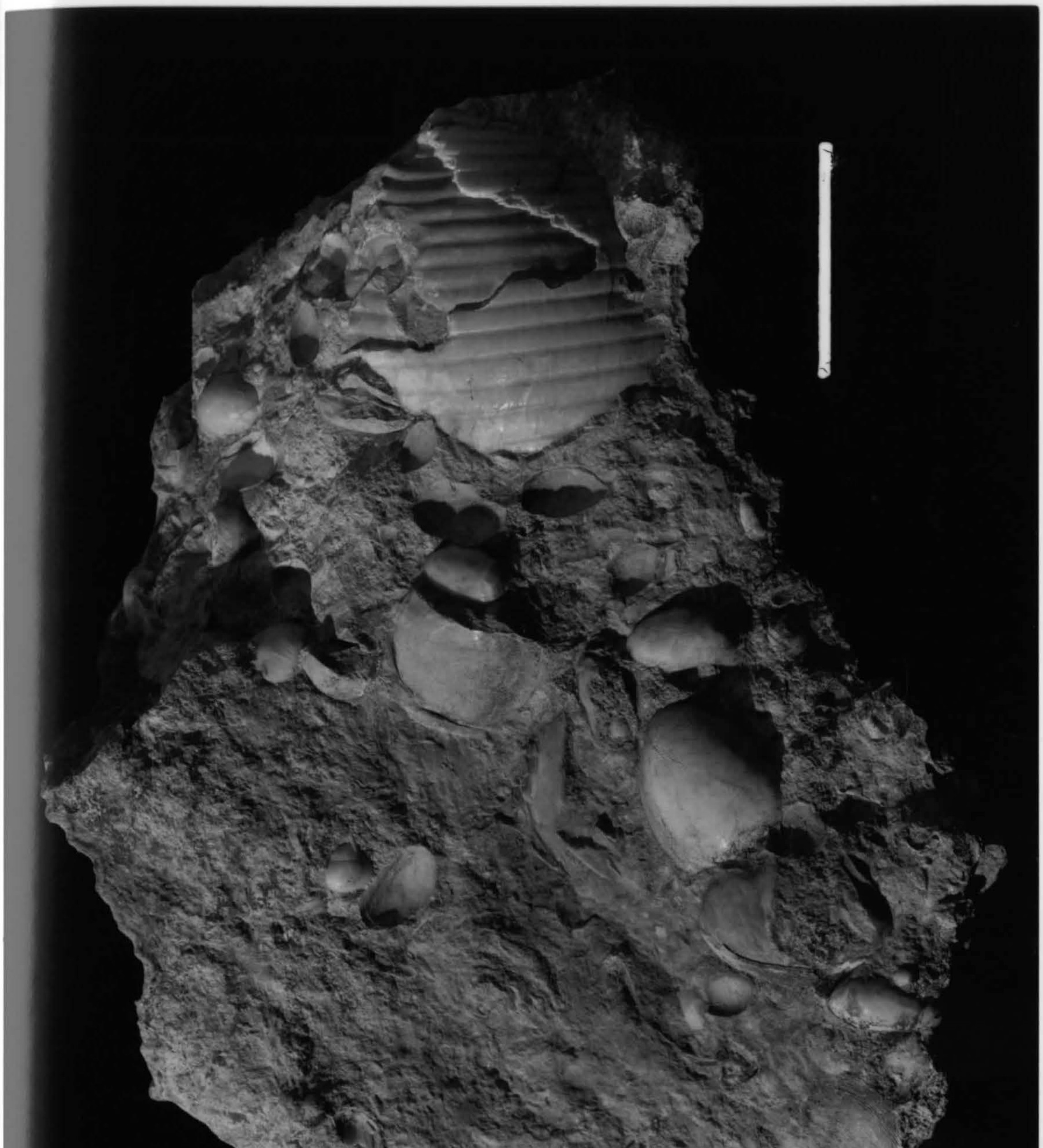


FIG. 21. Photograph of Falmouth Fm. outcrop of the back reef facies showing an individual coral (*Montastrea annularis*) enclosed in muddy, calcarenaceous matrix at location 2 (Fig.15). 35mm film cannister for scale.

FIG. 22. Vertical exposure of Falmouth Fm. fore reef facies along eastern margin of Rio Bueno Harbour. Note the abundance of frame building corals, including *Acropora cervicornis* (AC) and *A. palmata* (AP).(From Liddell, *et al*., 1984c).


Ap
Ap
Ap
Ac
Ac

groups within each cluster showed that variation in the constituent composition of samples within the cluster were not significant. However, a X^2 test using the mean constituent composition of the two major clusters showed them to be significantly different, supporting the contention that these two lithologies represent different sedimentary facies of the Falmouth Fm.

X-ray Analysis of Mineralogy

X-ray analysis of the mineralogy of Falmouth limestones shows that low-Mg calcite is the dominant $CaCO_3$ phase ($\overline{X}$ = 53.9% $\pm$ 3.8) in the packstone facies, occurring primarily as void filling cement and micrite. Aragonite is the next most abundant mineral ($\overline{X}$ = 32.0% $\pm$ 2.7) followed by high-Mg calcite ($\overline{X}$ = 13.0% $\pm$ 1.0)(Table 13).

The grainstone facies displays a continuum of mineralogies from little-altered sediments ($\overline{X}$ aragonite = 61.6% $\pm$ 6.3; $\overline{X}$ high-Mg calcite = 19.6% $\pm$ 2.9; $\overline{X}$ low-Mg calcite = 18.9% $\pm$ 4.9) exposed at the base of the outcrop to nearly complete conversion of sediments to low-Mg calcite ($\overline{X}$ aragonite = 10.0% $\pm$ 19.7; $\overline{X}$ high-Mg calcite = 0.0%; $\overline{X}$ low-Mg calcite = 90.0% $\pm$ 19.7) which is associated with the development of a 1m thick caliche cap at the top of the section (Table 14).

DISCUSSION

Comparison of the distribution of Falmouth Formation

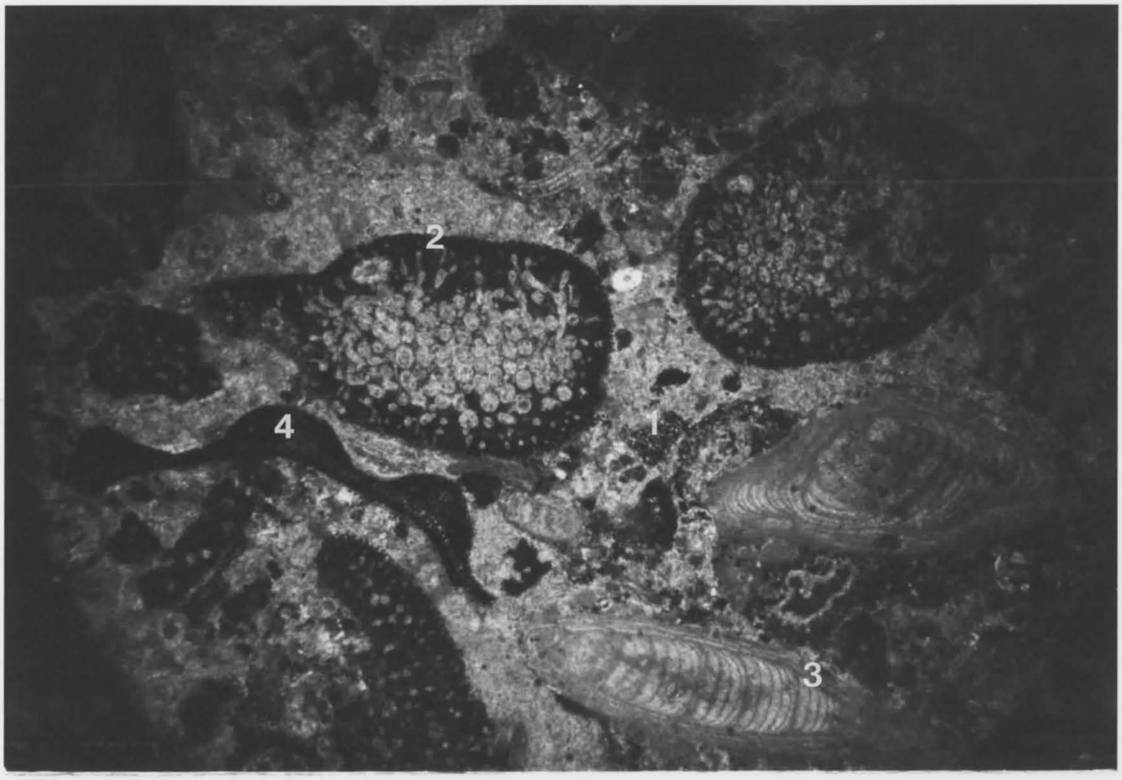
FIG. 23. Thin-section photomicrograph for comparison of Pleistocene and Recent back reef sediments.

A) Falmouth Fm.

B) Recent sediments from Discovery Bay.

1 = coral
2 = *Halimeda* spp.
3 = coralline algae
4 = molluscs
5 = echinoderms

Note the abundance of *Halimeda* in both photomicrographs (Field width = 2mm in both photos).



A

B

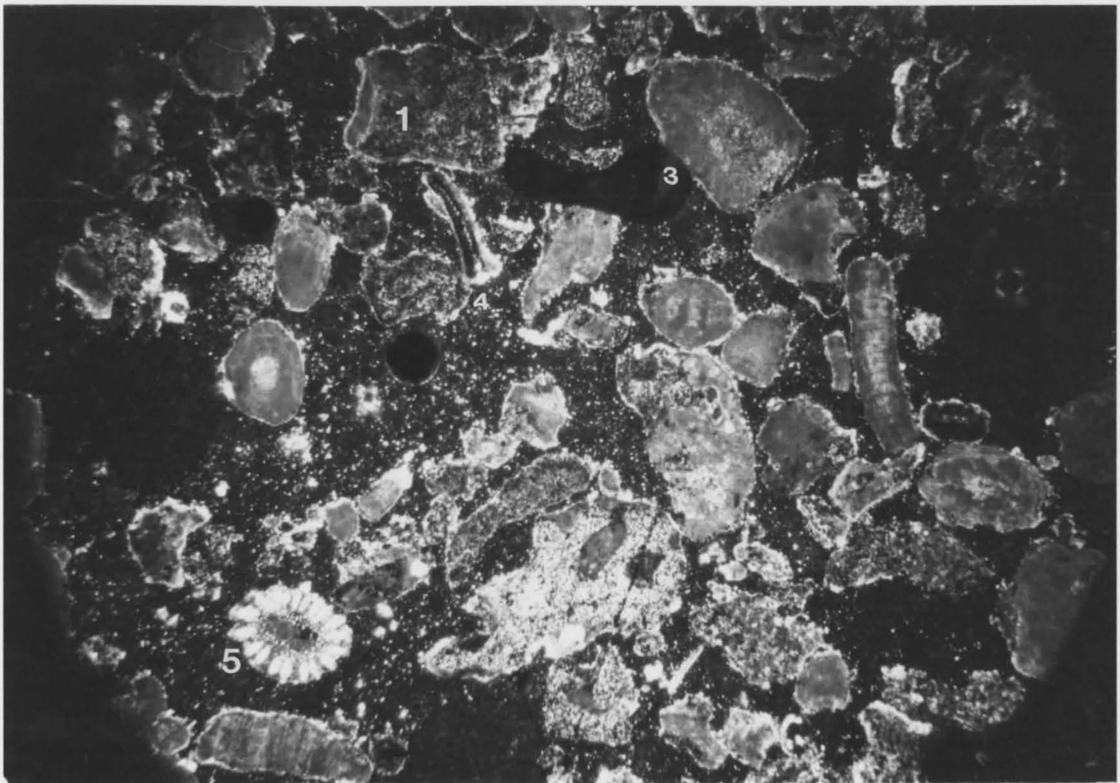
IG. 24. Thin-section photomicrographs for comparison of Pleistocene and Recent shallow (5 - 8m) fore reef deposits.

A) Falmouth Fm.

B) Recent sediments from Discovery Bay reefs.

1 = coral
2 = *Halimeda spp.*
3 = coralline algae
4 = molluscs
5 = echinoderms

Note the abundance of coral and coralline algal fragments and the absence of *Halimeda* in these sediments (Field width = 2mm in both photos).



A

B

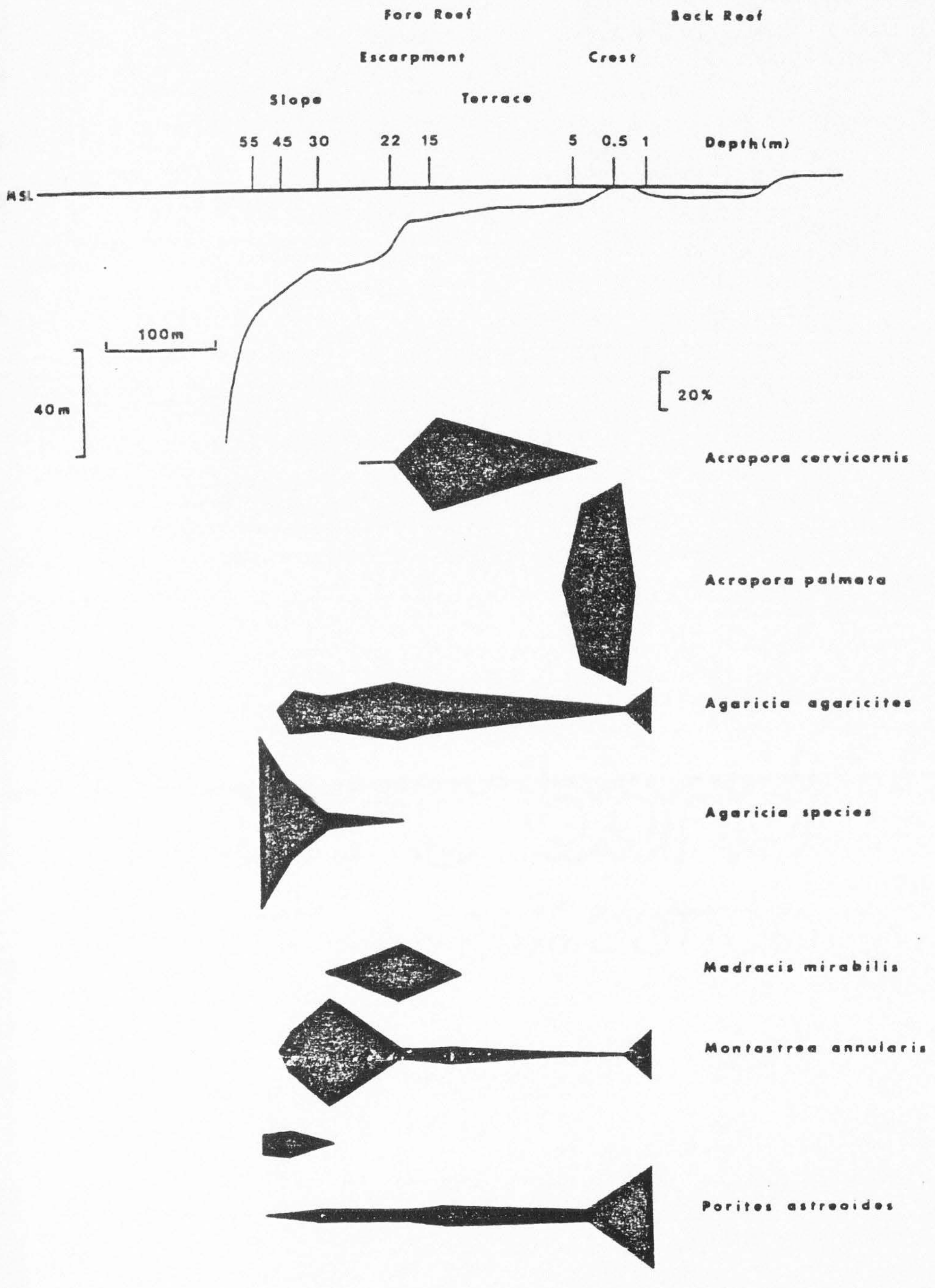


FIG 25. Spindle diagram showing the bathymetric distribution of common coral species within the modern fringing reef system, north Jamaica (From Liddell and Ohlhorst, in preparation). Note in particular restricted range of _Acropora palmata_ and _A. cervicornis_.

corals with the distribution of the same species within the modern fringing reef system (Liddell and Ohlhorst, 1981 and in prep.; Liddell, et al., 1984a; Fig. 25) provides interesting insights into the depositional environments of the Falmouth Fm.

On Holocene fringing reefs, Acropora cervicornis is shown to occur in abundance only in the shallow waters of the fore reef terrace, especially between 8 - 15m depths. A. palmata is shown to be restricted to a narrow band along the reef crest between 0.5 - 5m depths. Montastrea annularis, on the other hand, is shown to have a much broader bathymetric range than either of the acroporid species. Therefore, based principally upon the occurrence of Acropora cervicornis and A. palmata around the margins of Rio Bueno Harbour, the Falmouth Formation here is interpreted to represent a shallow (5 - 8m deep) fore reef environment.

The muddy character, reduced coral species diversity, and numerous molluscs of the remaining Falmouth Formation sites (localities 1 - 4, Fig. 15) are suggestive of the modern back reef environment at Discovery Bay.

These tentative interpretations based upon analysis of preserved macrofauna are supported by the constituent particle data acquired from thin-section study of Falmouth rocks and by the results of Q-mode cluster analysis using constituent data. The high proportions of Halimeda and carbonate mud in the packstone facies (Fig. 23) are consistent with the observed frequency of Halimeda and mud in

Recent Jamaican back reef sediments (Boss and Liddell, 1983, 1984b, and in prep.; Table 12). High values for Halimeda content are also reported for back reef sediments from south Florida (Ginsburg, 1956) and Belize (Pusey, 1975).

Notable characteristics of Falmouth grainstones from the Rio Bueno Harbour locations (Fig. 24) are the high proportions of coral (57.0% ± 6.3) and coralline algae (23.7% ± 5.3) and the conspicuous reduction in the amount of Halimeda (1.1% ± 0.9). Each of these features is consistent with the composition of sediments collected from the Recent shallow (5 - 8m) fore reef where coral and coralline algae are abundant (62% - 55% and 12% - 21%, respectively), and Halimeda comprises only 0.4% - 3.6% of the sediment (Boss and Liddell, 1983; 1984b, and in prep.; Table 12).

These comparisons show conclusively that paleoenvironmental interpretations using the composition of sediments within the Falmouth Formation agree favorably with paleoenvironmental interpretations based upon analyses of preserved macrofauna. Additionally, it has been demonstrated that Q-mode cluster analysis using sediment constituent composition can be used effectively to delineate distinctive facies within the Falmouth Formation.

The mineralogy of Falmouth limestones suggests that original sediment texture plays an important role in controlling the extent of diagenetic alteration. Examination of Figure 19 shows that fore reef deposits exposed at the top of the Rio Bueno Harbour sections show near complete conversion to low-Mg calcite. This is associated with the development of a 1m thick caliche cap at the top of these exposures. By contrast, subaerially exposed back reef deposits retain much of their original aragonite and high-Mg calcite, and contain low-Mg calcite primarily as void filling cement and micrite.

Variability in the extent of diagenetic alteration exhibited by these two facies almost certainly results from variations in permeability of these deposits related to characteristics of original sediment texture. Grain size analysis of Recent back reef and shallow fore reef deposits (Boss and LIddell, 1983, 1984b, and in prep.) indicates that back reef sediments are generally more poorly sorted and contain greater quantities of fine-grained carbonate than shallow fore reef sediments. These factors combine to reduce the permeability of back reef sediments, thus enhancing their preservation potential. Conversely, the better sorting of shallow fore reef deposits increases their permeability and susceptibility to alteration by percolating fluids.

Several authors provide data in support of this permeability-preservability hypothesis. Matthews (1968) reports that Pleistocene reef sediments of Barbados often display conversion to low-Mg calcite, whereas less-porous coral heads in the same deposits retain their primary aragonitic mineralogy. Additionally, Tebbutt (1975) describes Pleistocene outcrops from Ambergris Cay, Belize where corals with relatively high permeabilities are preferentially dissolved while less permeable corals weather in relief from the surrounding low-Mg calcite limestone matrix.

In conclusion, this study demonstrates that detailed analyses of biotic and physical parameters of Recent reef deposits can provide information pertinent to the analysis of depositional environments of Pleistocene reefs. These observations may then be combined to develop greater insight into and understanding of the dynamics of more ancient reef systems.

CHAPTER V

SUMMARY

Recent carbonate sediments from Jamaican north coast fringing reefs were collected along three parallel transects in the vicinity of Discovery Bay. Each transect extended from near shore across the back reef (1-5m), fore reef terrace (5-14m), fore reef escarpment (14-24m), fore reef slope (24-55m) and upper deep fore reef (70m). Sediment samples display variation in constituent composition and texture (sorting) which is correlated with their location on the reef.

The sediment is dominated by highly comminuted coral fragments (27.1% $\pm$ 4.2 to 63.1% $\pm$ 6.8), plates of the calcareous green alga, *Halimeda* (0.4% $\pm$ 0.4 to 38.7% $\pm$ 17.3), coralline algae (4.7% $\pm$ 1.9 to 16.2% $\pm$ 14.3) and the encrusting Foraminifera, *Homotrema rubrum* (0.7% $\pm$ 0.6 to 9.5% $\pm$ 5.9), with lesser amounts of other taxonomic groups (Foraminifera, 1.3% $\pm$ 0.5 to 5.5% $\pm$ 2.0; molluscs, 1.4% $\pm$ 0.8 to 7.0% $\pm$ 6.0; echinoderms, 0.9% $\pm$ 0.4 to 5.0% $\pm$ 14.6). Relative abundances of the biotic constituents vary between sites, reflecting general patterns of reef community composition.

Sieve analyses of these sediments reveal that mean grain size (M_z) approaches 0.5mm at most sites, with little depth-related variation. Sorting, however, becomes progressively poorer with increasing depth for sediments from both sand channels ($r = 0.91$; significant at $p \leq 0.01$) and sand trapped by reef framework ($r = 0.94$; significant at $p \leq 0.01$). This relationship results primarily from the influence of local sediment production combined with decreasing competence of sorting mechanisms (wave turbulence) with increasing depth.

Q-mode cluster analysis using sediment constituent data demonstrates that sediments from the back reef (1-5m), fore reef terrace (5-14m), fore reef escarpment (14-24m) and fore reef slope (24-55m), and deep fore reef (70m) are readily distinguished. Application of these techniques to the analysis of ancient reef limestones should permit the delineation of similar microfacies.

X-ray diffraction and insoluble-residue analyses were conducted on 51 Recent fringing reef sediments from north Jamaica. Samples were collected across the back reef and fore reef (0.5m to 70m). These analyses indicate that total $CaCO_3$ in these sediments is generally greater than 95% by weight. Amorphous siliceous sponge spicules and organic matter comprise the remaining non-carbonate fraction of these sands. Aragonite is the most abundant carbonate phase (49-89%), followed by high-Mg calcite (8-46%) and low-Mg calcite (2-12%). Significant differences in the proportion of aragonite and high-Mg calcite between fore reef terrace sediments and sediments from other reef zones is attributed to the influence of reef community composition on sediment mineralogy. Specifically, this difference results from the contribution of high-Mg calcite to shallow reef sediments by coralline algae, Foraminifera (principally _Homotrema_) and echinoderms, which flourish in the clear, agitated waters of the fore reef terrace. These organisms are relatively less abundant sediment constituents elsewhere on the reef. Primary sediment mineralogy may influence solution/precipitation kinetics and can play an important role in initiating specific post-depostional processes in carbonate sediments.

The 120,000 y.b.p. (Sangamonian) Falmouth Formation represents an emergent Pleistocene fringing reef complex exposed along the north coast of Jamaica. Line transects were conducted on selected outcrops to quantitatively determine macrofaunal components of the fossil reef community. Thin-sections of rock samples were made and the constituent compositions determined using standard point-counting methods. Q-mode cluster analysis using constituent data reveals two distinctive lithologies which display variability in sedimentological and faunal components analogous to back reef and shallow (5 - 8m deep) fore reef environments of the Holocene Jamaican fringing reef system. The most common lithology of the Falmouth Fm. in the Discovery Bay area is a skeletal packstone containing abundant plates of the calcareous green alga, *Halimeda* ($\bar{X} = 22.8\% \pm 3.1$), as well as comminuted coral ($\bar{X} = 32.6\% \pm 3.7$), coralline algae ($\bar{X} = 24.9\% \pm 3.7$) and molluscs ($\bar{X} = 11.0\% \pm 2.7$), with lesser amounts of Foraminifera ($\bar{X} = 4.5\% \pm 1.3$) and echinoderms ($\bar{X} = 1.5\% \pm 0.5$). A back reef interpretation for these packstones is supported by observed low coral diversity (dominated by *Porites furcata* and *Montastrea annularis*) and abundant molluscs. The second lithotype is located in the vicinity of Rio Bueno Harbour. These skeletal grainstones are poorly lithified, with constituent composition indicating a shallow (5 - 8m deep) fore reef environment. Sediments here are dominated by sand-sized coral fragments ($\overline{X}$ = 57.0% $\pm$ 6.3) and coralline algae ($\overline{X}$ = 23.7% $\pm$ 5.3), with only minor amounts of Halimeda ($\overline{X}$ = 1.1% $\pm$ 0.9). This is consistent with the composition of sediments collected from the Recent shallow fore reef environment where coral and coralline algae are abundant and Halimeda comprises only 0.4 - 3.6% of the sediment. Higher coral diversity and the presence of corals such as Acropora palmata and A. cervicornis also indicates a shallow fore reef setting for this locality.

X-ray analysis of the mineralogy of Falmouth limestones reveals that fore reef grainstones exhibit greater diagenetic alteration than back reef packstones. This suggests variability in the extent of diagenetic alteration which is related to characteristics of original sediment texture.

The results of this study demonstrate the utility of various quantitative methods in the interpretation of Holocene and Pleistocene reef carbonates. Application of the same techniques may assist in the interpretation of more ancient limestones.

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