CARBONATE SEDIMENTATION ON THE INNER SHELF ISLA MAGUEYES, PUERTO RICO

by

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TABLE OF CONTENTS

LIST OF TABLES

ABSTRACT

Fifty-six sediment samples have been collected by diving and grab sampling from the inner shelf area extending from Magueyes Island to the first line of inner reefs. Several shallow inshore environments are separated from a deeper back-reef lagoon environment by a discontinuous line of submerged patch reefs. Fine grain, poorly sorted sediments characterize the back-reef lagoon, while very poorly sorted silty sand makes up the sediments in the inshore environments. Moderately sorted sands comprise the reef deposits. Varying amounts of *Halimeda*, coral and molluscan fragments form the bulk of the sediment. Abundant coral fragments (37-67%) in the reef deposits account for the high concentrations of arragonite encountered. Greater concentrations of high-magnesium calcite in samples from the back-reef lagoon reflect the larger numbers of foraminifera and echinoderms. Examination of the fine fraction with a scanning electron microscope indicates that it is composed of skeletal fragments, such as molluscan fragments, algal needles and coccoliths.

Based on compositional, textural and environmental criteria three facies have been distinguished, a lagoonal mud facies, a reef skeletal sand facies, and an inshore *Halimeda* facies.

CHAPTER I

INTRODUCTION

Limestones have received considerable attention due to their economic importance as stratigraphic traps for petroleum. Through investigation of modern shallow-water carbonate sediments, insights into the origin of ancient limestones can be obtained. On the basis of petrographic, textural and environmental criteria models of recent carbonate deposition have been developed and are used widely in paleoecological interpretations.

The Bahamas-Florida region has become a classic area of study of carbonate sedimentation. Studies in this region have recognized variations in environments of deposition as well as the relative importance of skeletal and nonskeletal material in determining sediment composition. The role of physio-chemical processes in the formation of carbonate sediments in that area was stressed by Illing (1954). In South Florida, Ginsburg (1956) described the changes in sedimentation over a reef tract, back-reef, and bay environments. He pointed out the significance of skeletal fragments as major constituents of recent carbonates.

These earlier studies in the Bahama-Florida region laid the foundations for additional investigations on shelf regions throughout the Gulf of Mexico and the Caribbean Sea.

A wide range of topics, including aspects of sediment formation and micritization, relationships of sediment types and biofacies, and structural controls of shelf sedimentation have been explored. Among these more recent studies are the investigation of lime-mud production in a lagoonal environment off British Honduras by Mathews (1966), studies on the Campeche Bank by Logan et al. (1971), and Kornicker and Boyd (1962), an investigation of the structure of the continental shelf and related sedimentation on the shelf off Venezuela by Morelock (in press), and a model of sedimentation on the Paria-Trinidad shelf by Koldewijn (1958).

Less information is available regarding carbonate sedimentation on the insular shelves of the Greater Antilles. Two major studies have been conducted. In the Gulf of Batabano, Cuba, Daetwyler and Kidwell (1959) described eight different sediment types based on grain-size patterns and compositional variations. In a more recent study Goreau and Burke (1966) have traced the development of Pleistocene and Holocene geology on the insular shelf of Jamaica. A preliminary sedimentary study of the insular shelf of Puerto Rico has been prepared by Saunders and Pilkey (in press). The investigation deals only with middle and outer areas of the insular shelf, as the inner shelf areas are inaccessible to research vessels. The purpose of this thesis is to provide a detailed sedimentation model of a portion of the inner shelf, based on textural and compositional perameters and on underwater observations of depositional environments. The area off La Parguera to the first line of reefs has been chosen for this purpose because of its proximity to research facilities and well documented local environment.

CHAPTER II

PREVIOUS WORKS

Almy and Carrion-Torres (1963) have described the distribution of reefs and the gross sand types associated with them on the south-western shelf of Puerto Rico. No studies, however, are available concerning sedimentation on the shelf off La Parguera.

CHAPTER III

SEDIMENTATION ON THE PUERTO RICO INSULAR SHELF

Puerto Rico is the smallest and easternmost of the four islands comprising the Greater Antilles. Puerto Rico lies 1000 miles southeast of Miami and nearly 500 miles north of Caracas, Venezuela (Fig. 1). The island is generally rectangular in shape, about 100 miles long and 35 miles wide. Puerto Rico faces the Atlantic Ocean to the north and the relatively calmer Caribbean Sea to the south. Together with the Virgin Islands, Puerto Rico forms a unit with a narrow insular shelf and a steep shelf slope that plunges sharply from depths of 25 to 40 m to depths of up to 4000 m. To the west Puerto Rico is separated from the island of Hispaniola by the deep Mona Passage.

The first study of sedimentation on the entire insular shelf of Puerto Rico has been prepared by Saunders and Pilkey (in press). Since this thesis is an outgrowth of that study, it is appropriate to describe it in some detail. Approximately 300 bottom grab samples were collected from accessible areas of the insular shelf. Seven lithofacies are described based on megascopic identification of constituents, relative percentage of sand, and calcium carbonate content. A preliminary map showing the distribution of these sedimentary types has been prepared and is shown in Figure 2.

Figure 1. Map of the Caribbean

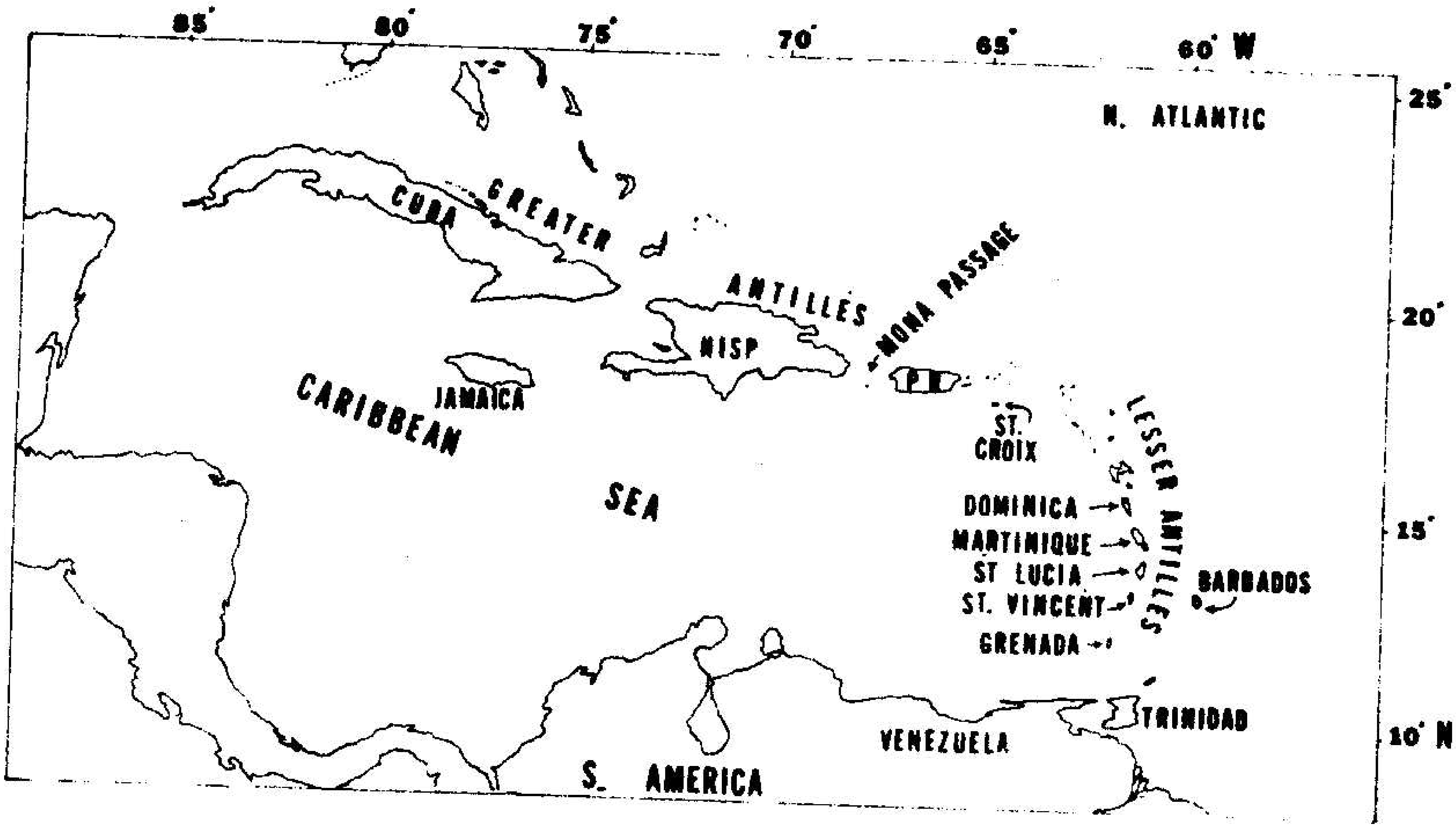
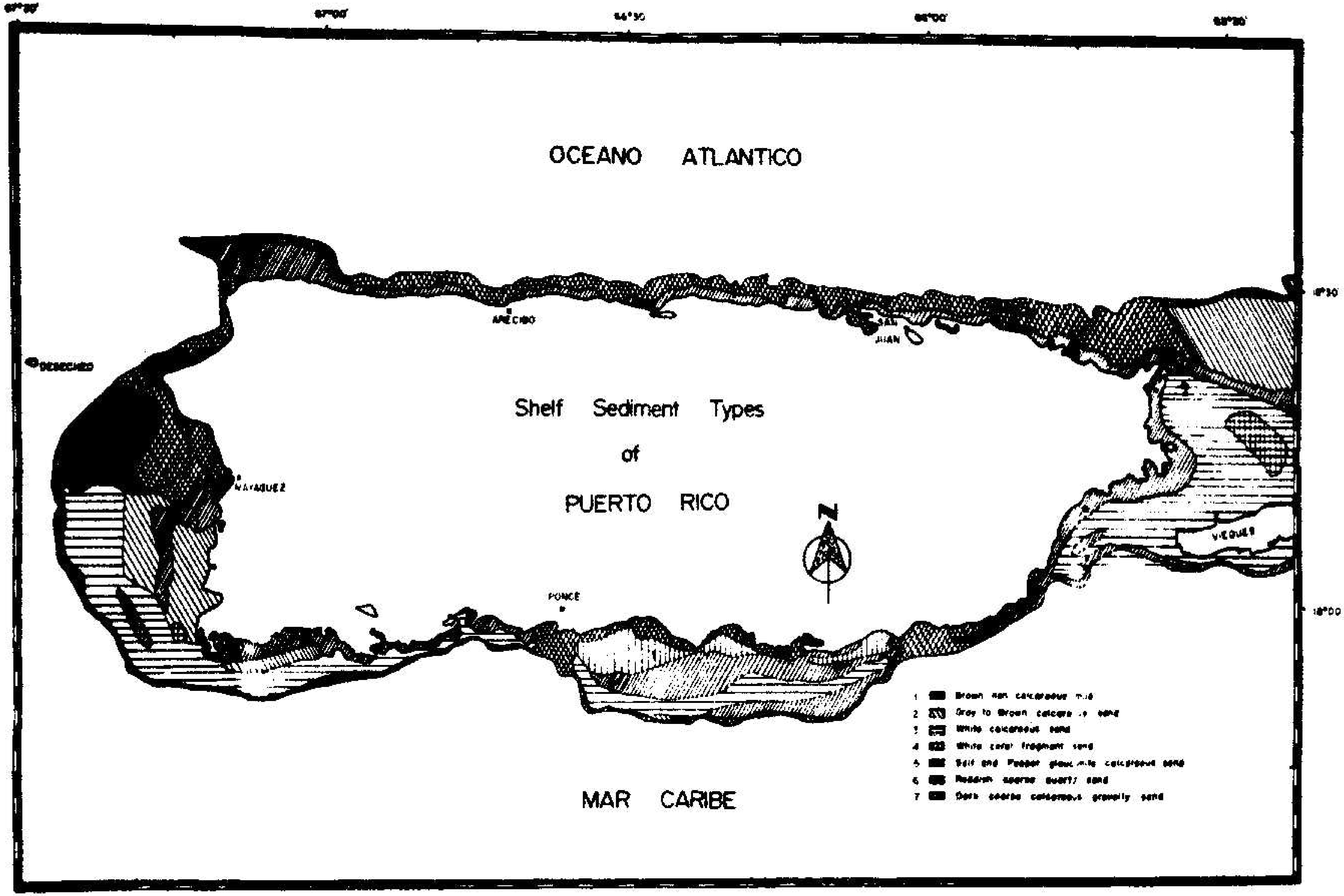

85°
80°
75°
70°
65°
60° W
25°
20°
15°
10° N
N. ATLANTIC
CUBA
GREATER
ANTILLES
HISP
MONA PASSAGE
P R
JAMAICA
CARIBBEAN
SEA
ST. CROIX
LESSER ANTILLES
DOMINICA
MARTINIQUE
ST LUCIA
ST. VINCENT
GRENADA
BARBADOS
TRINIDAD
VENEZUELA
S. AMERICA

Figure 2. Sediment type distribution map--Puerto Rico insular shelf



OCEANO ATLANTICO
Shelf Sediment Types
of
PUERTO RICO
MAR CARIBE
ARECIBO
SAN JUAN
MAYAGUEZ
PONCE
VIEQUES
DESECHEO
N
1 Brown non calcareous mud
2 Gray to Brown calcareous sand
3 White calcareous sand
4 White coral fragment sand
5 Salt and Pepper glauconite calcareous sand
6 Reddish coarse quartz sand
7 Dark coarse calcareous gravelly sand

A more detailed petrographic investigation is now in progress (Saunders, Schneidermann and Pilkey).

Two sharply contrasting sediment provinces are recognized, a north and northwestern terrigenous shelf and the remaining carbonate-dominated shelf. The large volume of discharge of river systems on the northern and northwestern coasts is responsible for a predominantly fine-grain, non-calcareous sediment cover on the adjacent shelf areas. Despite the high wave energy on the northern coast, rivers are apparently supplying mud at a faster rate than it is being removed. Most samples from these regions contain less than 30 per cent calcium carbonate. Samples from the outer shelf areas on these terrigenous shelves contain an abundance of bryozoans, foraminifera and molluscan fragments in the calcareous sand fractions. Coral fragments and other reef-associated constituents are virtually absent. The lack of coral fragments in these samples is probably a result of the inhibiting factors of high turbidity and lack of hard substrate due to the large outflow of terrigenous muds by local river systems.

Carbonate sands are ubiquitous over the remaining shelf areas. These sands are entirely biogenic in origin. Skeletal sands, composed of varying amounts of coral, coralline algae, _Halimeda_, and molluscan fragments, foraminifera and numerous other minor constituents make up the bulk of sediments in these areas. The distribution of sediment types on these carbonate shelves is related to their position relative to reefs and to the energy of the environment of deposition. On shelf areas behind the inner reefs fine-grain greenish to grayish sands are found. In mid-shelf regions coarse, poorly sorted sands make up the sediment. These deposits are in the vicinity of reefs and are mostly composed of varying amounts of coral and *Halimeda* fragments. An extensive area of the outer shelf region is overlain by medium- to coarse-grain, moderately sorted sands. Towards the margin of the shelf, muds are deposited with sand fractions consisting of significant amounts of planktonic foraminifera and pteropods. Terrigenous components are present in sediments near river outlets and in the innermost shelf areas.

Two sediment types were identified from isolated positions on the insular shelf that are believed to represent relict sediments. Off Mayagüez Bay in depths of over 20 m sediment consisting of iron-stained sand and silt was found. Many samples from this area contain sand-size quartz grains which may represent river or beach deposits during a lower sea stand. Several samples contain algal balls that show evidence of neomorphism in the form of sparite crystals replacing the original texture. X-ray analysis of these grains shows a predominance of low-magnesium calcite, while similar modern algal representatives are composed of high-magnesium calcite. This diagenetic feature is believed to have been formed under subaerial conditions. Evidence of subaerial exposure of this shelf area is provided by bottom profiles which show notches at the shelf edge (80 m) and are assumed to be Pleistocene terraces (Lowman, et al., 1965).

On open areas of the western and eastern insular shelf sediments containing glauconitized grains are abundant. At present glauconitized grains have been reported to form on the Puerto Rico shelf in shallow-shelf environments under slightly anerobic conditions (Seiglie, 1971). Since the samples containing glauconitized grains are found today in well mixed open-shelf environments, these sediments probably represent relict Pleistocene sediments.

CHAPTER IV

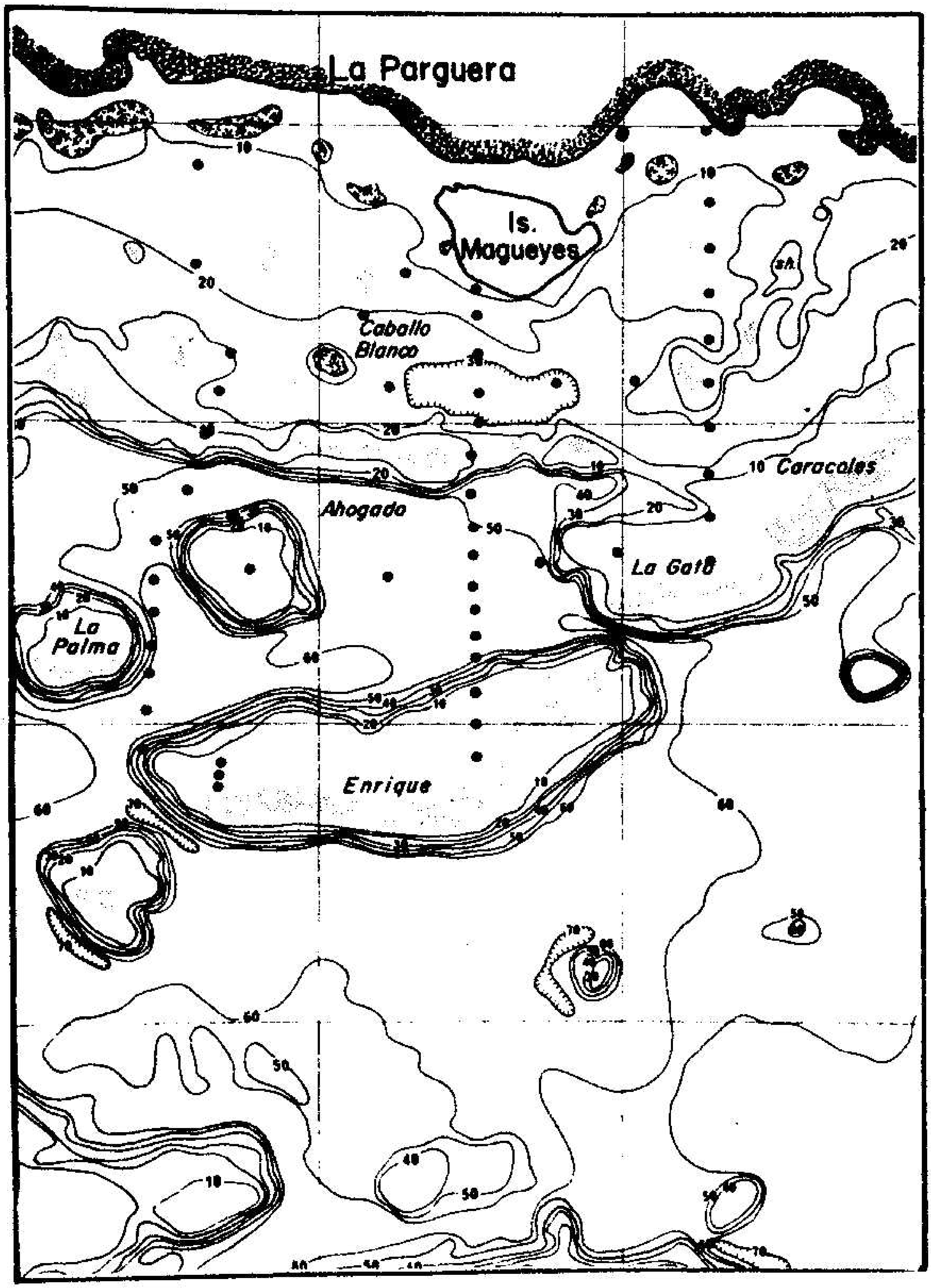
METHODS OF ANALYSIS

Field Methods

Samples were collected at 54 stations in the back-reef area in the vicinity of Magueyes Island (Fig. 3). They were collected approximately every 300 feet and put in plastic bags. Spacing of stations was held constant by driving the boat over a fixed time interval at a constant speed. The position of each station was established by sighting with a transit to known positions on land and near-by reefs.

Two methods were utilized in obtaining samples. An underwater transect was completed from Magueyes Island south to the shoreward edge of the reef flat of Enrique Reef utilizing SCUBA equipment. Along the transect samples were collected and bottom observations were recorded on an underwater slate. Bottom characteristics, such as depth, gross sediment type, presence of burrows and ripple marks, and bottom organisms were recorded. Underwater photographs of representative bottom environments were taken along the transect. The remainder of the sampling was carried out with a Peterson-type grab sampler. Approximately 200 g of sediment was collected and stored in plastic bags. A split of

Figure 3. Sample location map (map created by Gary Anderson, Department of Marine Sciences, 1971)



La Parguera
Is.
Magueyes
Caballo
Blanco
Ahogado
Caracoles
La Gata
La
Palma
Enrique

each sample has been saved for future reference at the Department of Marine Sciences sedimentation laboratory.

Grain Size Analysis

Analysis of grain size was carried out according to methods described by Folk (1968). A split of each sample is divided into a sand fraction (greater than 62 microns) and a fine fraction by wet sieving. In order to minimize the error due to organic aggregation the sample is first dispersed in a 20% solution of H_2O_2. After 24 hours the resulting slurry is stirred and poured into a 62 micron (230 mesh) screen. A 1000 ml beaker is placed under the screen in order to catch the fine material. Water is run through the screen, while the sediment is gently stirred with a fine bristle brush. This procedure is continued until the water passing through the screen is clear. During wet sieving many samples needed more than 1000 ml of water to remove the fine material, thus requiring another beaker to collect the fines. Since only 1000 ml of suspended fine material is used in pipette analysis, the fine material in both beakers was allowed to settle, the supernate was poured off and the contents of the two beakers were combined.

The sand fraction retained in the sieve is allowed to dry in an oven at 100°C and is weighed. It is then dry sieved using a magnetic shaker in a set of sieves ranging from -1 to 4 phi. Each sieve fraction is separately weighed.

The portion of fine material left in the catch pan is weighed and added to the fine fraction suspension.

Splits of representative sand fractions and several silt and clay fractions were sent to Duke University for X-ray analysis of carbonate minerals.

The size distribution of the fine fraction was determined using the pipette method. The suspension of fine material is poured into a 1000 ml volumetric flask, 1 g of calgon water softener is added, and the mixture is shaken for several minutes. It is then poured into a 1000 ml graduated cylinder and stirred for several minutes to insure homogeneity. Twenty ml alliquots are drawn off at appropriate depths and time intervals according to a schedule devised by Folk (1968, p. 40). The time of extraction is the time needed for a whole phi unit fraction to settle below the depth of extraction. The 20 ml of suspension is filtered through a pre-weighed millipore filter, and is dried and weighed. A correction is made for the amount of calgon in solution by subtracting the proportional weight contained in each 20 ml alliquot.

Separate fine fractions from samples along the transect were digested in diluted HCl to determine the percentage of noncarbonate material.

Thin-Section Studies

Epon-imbedded thin sections of selected samples were prepared commercially. Counts of 200 grains were made from each thin section with a petrographic microscope. Identification of grain character was made according to descriptions by Bathurst (1971) and comparison with known fragments in prepared thin sections. All the grains in each field of view were counted. Counting was made on successive fields of view until 200 grains were counted. To check the accuracy of the counting procedure, several thin sections were recounted. It was found that the average deviation of counts was 9% with a maximum deviation of 14%.

CHAPTER V

INNER SHELF OFF LA PARGUERA

The area of study lies off the southwest coast of Puerto Rico near the town of La Parguera (Fig. 4). The shelf is nearly 8 km wide and is divided into outer, middle, and inner shelf areas by a line of inner and outer reefs. The study area consists of the back-reef area shoreward of Enrique Reef and is approximately 1.5 km wide. Situated mid-way between the inner reefs and shore is a line of discontinuous submerged reefs, called Ahogado Reef (Fig. 5). Several sand shoals, some of which are overgrown by mangroves, rise within a few feet of the surface. Magueyes Island, the site of the Department of Marine Sciences, University of Puerto Rico, is located 75 m offshore in the northern section of the study area. The coastline in the vicinity of La Parguera is pitted by small bays and inlets which are bordered by dense growths of mangroves. A tidal flat lies inland of the coastline.

Local Geology

Low-lying hills line the coastal area of southwestern Puerto Rico consisting of southward dipping limestones of Cretaceous age (Almy, 1965). The area northwest of these hills is underlain by serpentinized peridotite of Early to

Figure 4. Map of Southwestern Puerto Rico

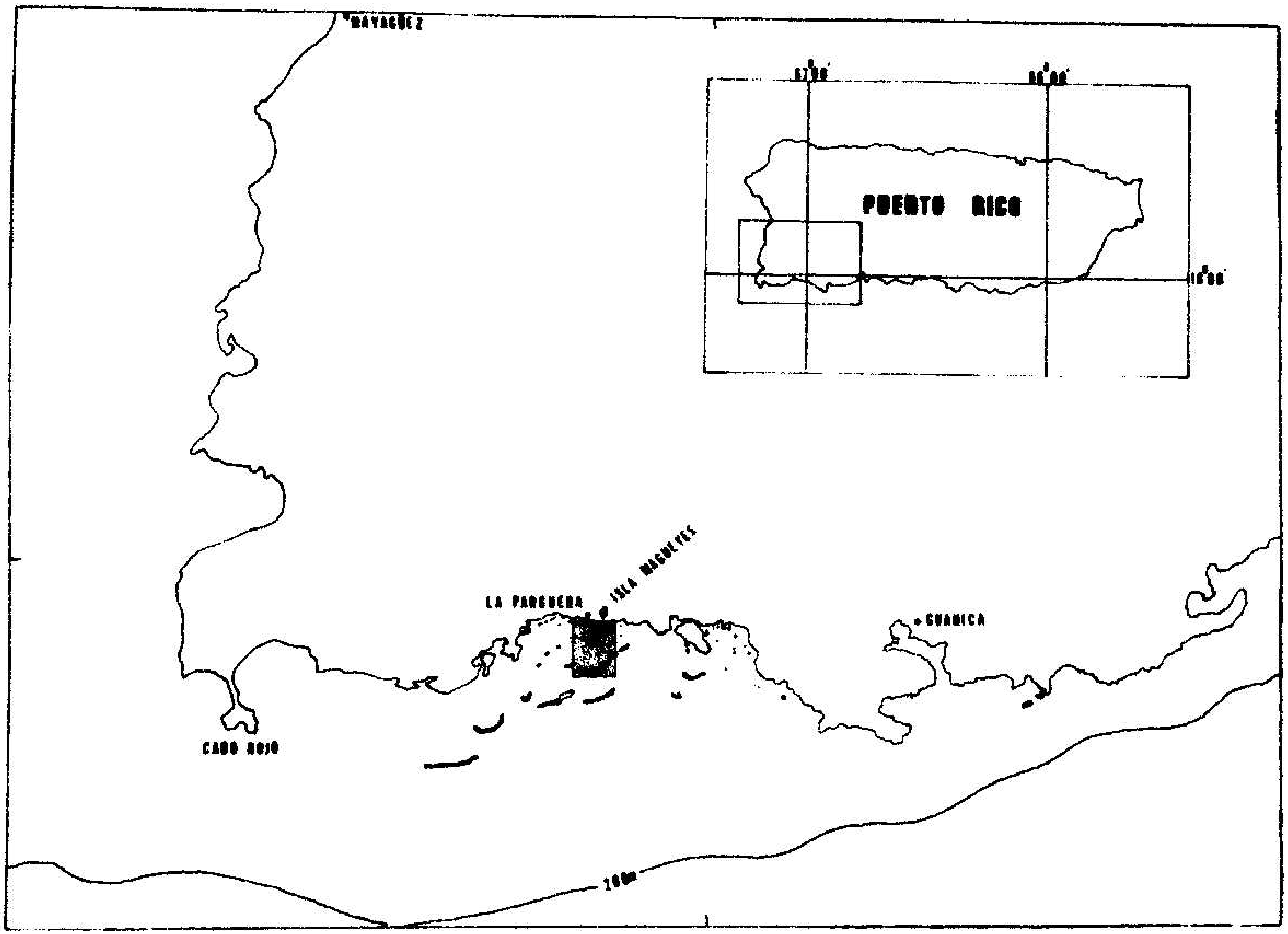

MAYAGUEZ
PUERTO RICO
LA PARGUERA
ISLA MAGUEYES
GUANICA
CABO ROJO
200m

Figure 5. Aerial photograph of the inner shelf (Department of Commerce color aerial photograph)

early Late Cretaceous age. The coastal lowland area near La Parguera is covered by Quaternary alluvial sand and silt and tidal and swamp deposits of silt and clay (Kaye, 1959).

Local Climate

The climate of the La Parguera area is semi-arid with an average annual rainfall of 75 cm (Coker and González, 1960). Winds are usually southeasterly and normally reach their peak by noon. During September through October periods of torrential rainfall have been recorded. Most of this rain falls during during a period of several weeks and only for short durations (Guinones, 1953). Thus, runoff is very significant due to the intensity of the rains. During rain storms dense flows of mud washed from the soil cover are seen diffusing offshore and are densest adjacent to the tidal flats. Flows are also observed coming off Magueyes Island. Runoff is the only local source of terrigenous sediment, since no rivers are present in the area.

Although the southwest coast of Puerto Rico is supposedly out of the path of major hurricanes, several hurricanes have struck the area, the last being Hurricane Edith in September, 1963. Winds of over 55 mph generated seas causing extensive destruction of coral growth on the outer reefs and some of the inner reefs (Glynn, Almodovar and Gonzales, 1964).

...graphic location map (Fig. 3). The back-reef area of the inner shelf is subdivided by a line of patch reefs into two physiographic units termed in this study the inshore and back-reef lagoons. From shore to the patch reefs the bottom slopes gradually to a maximum depth of 10 m. Seaward of the line of patch reefs there is a uniform depth of 18 m. The inner reefs have back-reef aprons of sand that range from .5 to 3 m in depth. The seaward side of the reef flats are often exposed due to boulder buildup during storms (Almy and Carrion-Torres, 1963). Most of the shelf area seaward of the inner reefs has depths between 20 and 25 m. At the shelf break the bottom descends rapidly from a depth of approximately 22 m to oceanic depths.

Hydrography

Tides: The tides on the southwest coast are diurnal. The mean tidal range is normally under .2 m. May has the widest recorded range of .25 m. Tidal currents are relatively weak (Coker and Gonzales, 1960).

Currents: Currents move westward paralleling the coast off La Parguera (Colon, 1971). July is generally the month of strongest winds and consequently surface waters are roughest during this period. Bottom currents observed during diving appear to vary in speed, usually not exceeding 1/2 knot.

Salinity: Normally, salinity values vary less than 2.3 ppt annually in this region. Salinity data collected by Jorge Rivera on the western side of Magueyes Island indicate a maximum of 36.9 ppt and a minimum of 34.6 ppt over the period between June 1971 and November 1972. These salinity values are similar to those from samples collected by the R. V. Medusa and the R. V. Crawford at the hydrographic station some 17 km south of Magueyes Island (Phillip Froelich, personal communication). Thus, circulation in the inner shelf region is adequate to maintain open sea salinity conditions.

Turbidity: A significant variation in transparency was observed among the back-reef region of Enrique Reef, the outer reefs, and the shelf edge. While diving during the period between January 1972 to March 1973 I have observed water clarity in these regions as follows: In the back-reef lagoon of Enrique Reef the clarity seldom exceeds 3 m and may be as low as 1 m. In the outer reef area, such as Laurel Reef, clarity usually exceeds 5 m and sometimes may exceed 25 m. Visibility at the shelf edge is usually excellent, often exceeding 30 m.

Water Temperature: Annual variations in surface water temperatures are generally less than 2.5°C in the waters off La Parguera. A minimum of about 25°C in February and a maximum of about 30°C in September were recorded (Coker and González, 1960).

versity of depositional environments, and is characterized by a wide variation in sediment types. Based on underwater observations conducted during the course of this study and descriptions of local marine environments in works by Almy and Carrion-Torres (1963) and Mathews (1967), several depositional zones are recognized. Using physiographic position, gross sediment type and characteristic bottom communities as a basis for classification the following six environments are distinguished:

(1) Tidal flat

(2) Mangrove channel

(3) Grass-covered shallow lagoon

(4) Patch reef

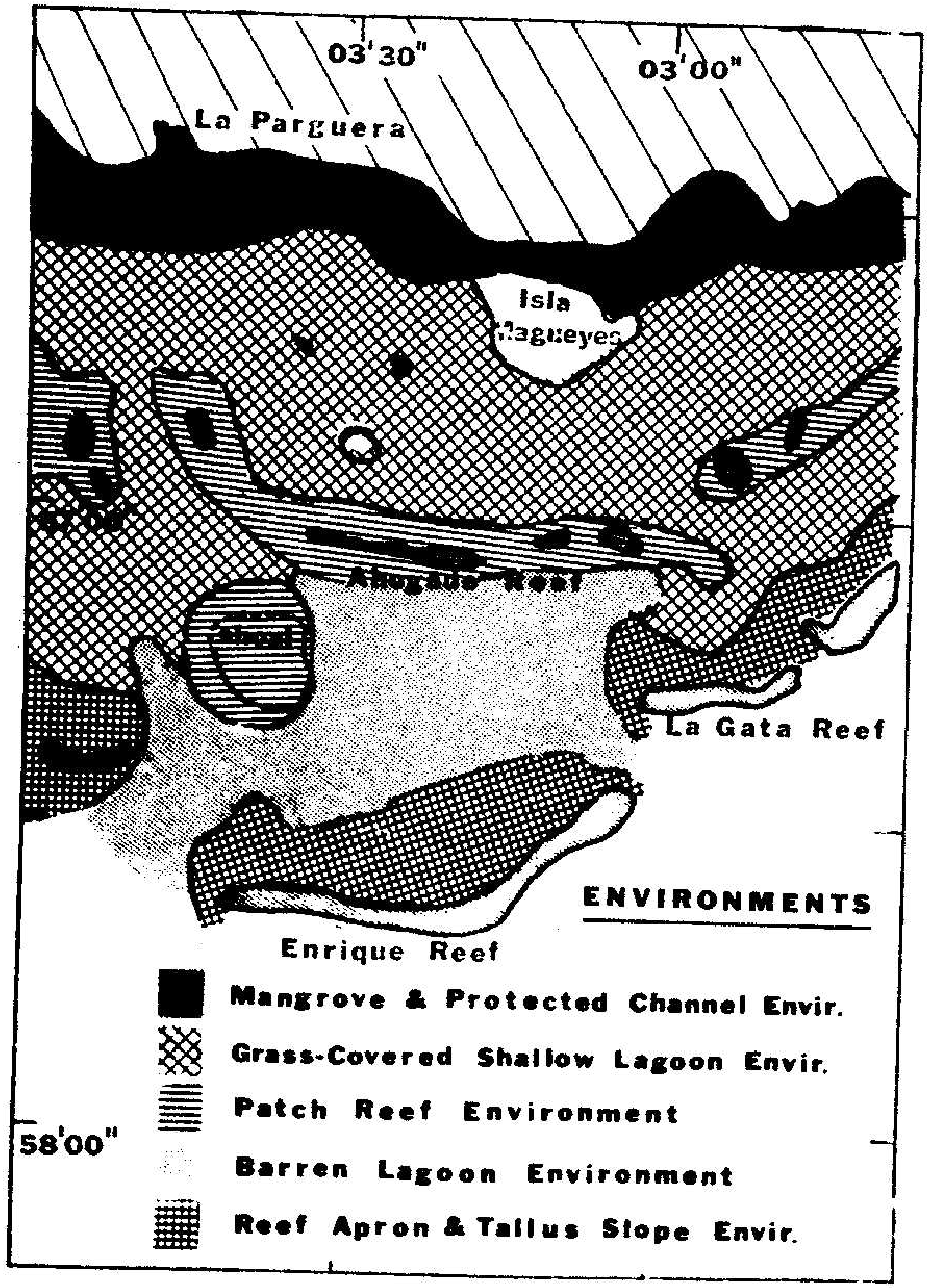
(5) Barren lagoon

(6) Reef apron and talus slope

The boundaries between the various depositional environments (Fig. 6) are usually gradational. However, a submerged zone of patch reefs, termed locally Ahogado Reef, represents a sharp boundary between the shallower inshore environments and the deeper back-reef lagoon.

Short descriptions of the major benthic organisms and bottom characteristics of the above environments are given below.

Figure 6. Areal distribution of depositional environments


03'30"
03'00"
La Parguera
Isla
La Gata Reef
Enrique Reef
58'00"
ENVIRONMENTS
Mangrove & Protected Channel Envir.
Grass-Covered Shallow Lagoon Envir.
Patch Reef Environment
Barren Lagoon Environment
Reef Apron & Tallus Slope Envir.

Tidal flat environment.--A tidal flat extends about 150 m inland of the mangrove-lined coast in the vicinity of La Parguera. Its present boundaries are limited in some areas by local road and housing construction. Much of the tidal flat area is occupied by mangroves which provide a habitat for a variety of flora and fauna. The tidal flat floods completely only during spring tides at which time algal growth covers part of the substrate. The sediment deposited on the tidal flat consists primarily of silt and clay.

Mangrove Channel environment.--Mangroves dominate the coastline in the study area. They are established in the subtidal and intertidal zones of the shore area and offshore islets. The species growing closest to shore, *Rhizophora Mangle*, has long, branching prop roots, which in association with algal communities act to reduce the energy of the depositional environment. In the mangrove-lined channels a significant proportion of the sediment is composed of mangrove peat (Golley, Odum, and Wilson, 1962). The establishment of mangroves on the coast and the subsequent accumulation of peat and skeletal sand and silt are causing the slow progradation of the land seaward (Mathews, 1967).

Grass-covered shallow lagoon environment.--In the shallow areas less than 10 m deep *Thalassia testudinum* blankets the bottom. The dense growth of grass provides a habitat for diverse communities of benthic organisms. Encrusting forms of foraminifera, molluscs, and red and filamentous algae attach to the surfaces of *Thalassia* blades. The heavily calcified codiacein algae *Halimeda* is prevalent, but *Penicillus capitatus* and *Udotea flabellum* also thrive and become more abundant as *Thalassia* becomes less dense seaward. Benthic animals, such as *Oreaster reticulatus*, *Tripneustes esculentus*, *Strombus gigas* and a variety of sponges dwell in this environment.

From Magueyes Island the bottom slopes gradually seaward to a depth of 10 m. *Thalassia* becomes progressively less dense until at a depth of 10 m only patches are observed on a silty-sand bottom. Numerous mounds are seen which are similar in size and shape to those described in South Florida by Shinn (1968) and are attributed to the burrowing shrimp *Callinassia*. The mounds are conical with a small opening at the apex and a smaller hole at the periphery. The size and frequency of mounds increase seaward until at a depth of 10 m they overlap and reach heights of more than .5 m. Burrowing by Callinassid shrimp in the Bahamas was observed to result in the vertical mixing of sediment to a meter or deeper (Bathurst, 1971). Leeward of Ahogado Reef the bottom, which consists of fine sand and silt, is relatively flat. Only several heads of *Manicina areolata* are present.

Patch reef environment.--Some 800 m from Magueyes Island the bottom rises abruptly to a series of linear, discontinuous reefs called Ahogado Reef which are totally submerged, except during periods of very low tides. They are recognized herein as patch reefs by the conspicuous absence of reef flat, abrupt relief on the lagoonal floor and discontinuity in linear extent. The zonation of coral growth is less apparent here than on the more developed outer reefs, probably as a result of the reduction of current strength in this back-reef area (Almy and Carrion-Torres, 1963). On the reef front Monastrea annularis and Acropora palmata are the dominant species of coral (Fig. 7d). In deeper water Acropora cervicornis and Porites porites were observed. Diadema sp., Savellastarte magnifica, holothurians, gorgonians and several sponges thrive among the corals and pockets of sand. The fore-reef drops abruptly to a platform at 10 m of depth consisting of dead coral that is totally encrusted by coralline algae. From this area the bottom again descends sharply seaward to the lagoon floor at depths of nearly 20 m.

Barren lagoon environment.--A lagoonal mud bottom stretches approximately 900 m between the line of patch reefs and the talus slope of Enrique Reef. The sediments in this environment consist of fine-grain silt and clay. To the east behind the back-reef slope of Lagata and Carricoles Reefs, where depths do not exceed 10 m, fine sediment is less abundant. Crustacean mounds cover the entire traversed lagoonal floor. The bottom is marked by trails of gastropods which feed on the organic matter in the surface sediments.

Figure 7. Underwater photographs

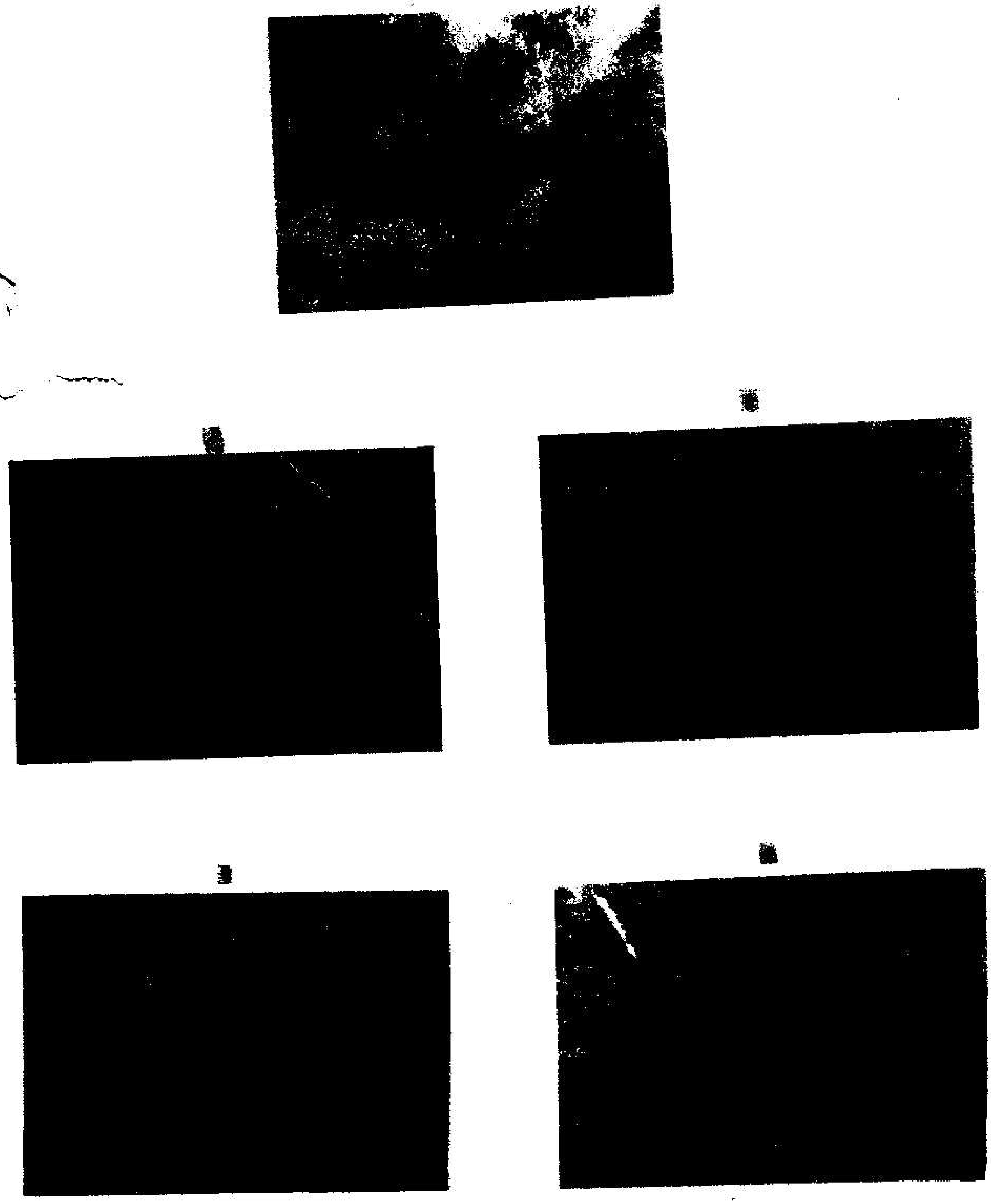
a. _Porites_ zone

b. _Porites_ with _Halimeda_

c. _Thalassia_ zone

d. _Acropora palmata_ growing on Patch Reef

e. _Callinassia_ mound in the background



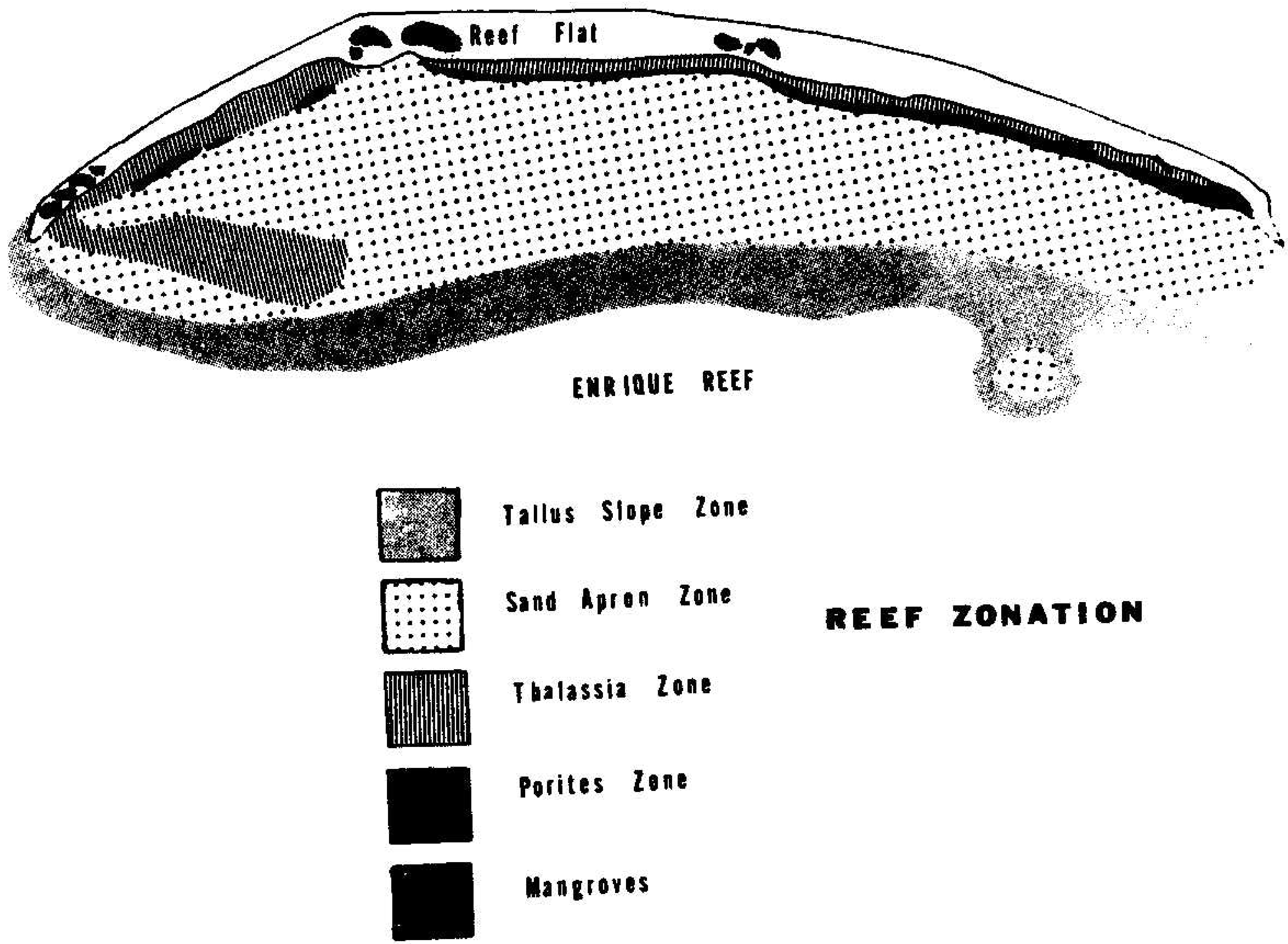
Numerous faecal pellets are deposited along these trails and on the sides of mounds. In several areas the fighting conch Strombus pugilus, sea urchins, such as Astropectins sp. and Diadema sp., along with assorted sponges are present.

A thin mucous film overlies the bottom sediment on the lagoon floor. The dominant constituent of this organic film has been identified as the filamentous cyanophyte, Schizothrix calcicola (Dr. Almodóvar, Department of Marine Sciences, personal communication, 1973). Schizothrix has been observed in algal mats in several intertidal and subtidal carbonate environments in the Bahamas (Month, 1965) and in Bermuda (Gebelein, 1969). In these areas they appear to play an important role in the formation of recent stromatolites. The Schizothrix algal mat in this location, however, appears to serve only as a stabilizer for the underlying muds.

Reef apron and talus slope environment.--Enrique Reef, the longest of the inner reefs, extends nearly 800 m in length. Preliminary investigations of the shallow back-reef area show some general trends in the distribution of bottom types and benthic communities. Lateral variations in bottom character are common. A generalized scheme of bottom zones has been devised and is illustrated in Figure 8. These zones include a back-reef talus slope, a sand apron, a Porites, and a Thalassia zone.

A back-reef slope of approximately 20° rises from the lagoonal floor, and is composed of medium- to coarse-grain

Figure 8. Zonation of Enrique Reef



REEF ZONATION

sands. Much of the slope is barren, although in some areas large heads of Diplora labyrinthiformis and Siderastrea siderea, and large branched sponges were observed. Leeward of the western end of the reef a smaller submerged reef rises to within 5 m of the water surface.

The apron of sand surrounding the back-reef reaches a maximum width of 200 m and ranges from .3 to 3 m in depth. The sand apron zone extends reefward to the Porites zone and consists of sand that is being thoroughly reworked by burrowing organisms (Fig. 7e). Some of the topographic lows between burrows are filled with coral rubble and whole shells, while in others silt is exposed. Algae, such as Dictyota, Halodule and Hypnea, generally decrease in abundance towards the reef flat. Several species of echinoderms, Diadema sp., Tripnuestes ventricosus, Lytechinus, and Oreaster reticulatus are found in the reef apron zone.

The porites zone consists of dense colonies of Porites porites and adjacent areas of coral rubble (Fig. 7a). This zone is discontinuous across the length of the reef with the most prolific colonies situated on the western end of the reef. Halimeda grows abundantly amongst the living coral (Fig. 7b) and is deposited as fragments in the surrounding sediments. Diadema, Tripneustes, ophuroids, zoanthids and sabellid worms are also present.

Progressing towards the reef flat an area of coarse sand overlain by Thalassia is seen (Fig. 7c). The shallow bottom is well stabilized by the grass beds and by clusters of Zoanthus socialis. Sea urchins, such as Tripneustes esculentus, Lytechinus variegatus, Diadema antillarus and Eucidaris tribuloides are very abundant. The sea anenome, Stoichactis heliathus, many sponges and small gastropods also dwell in this zone.

There are several thickets of the red mangrove Rhizophora mangle on the reef flat. The reef flat has very little relief as compared to the outer reefs where boulders have been piled up to heights of 2 m during storms. The absence of relief and the establishment of mangroves have been attributed to the partial blocking of heavy seas by the outer reefs (Almy and Carrion-Torres, 1963). At the western end of the reef flat reef growth is progressing shoreward resulting in a curved edge. Hydrographic conditions appear to be optimal here for a wide diversity of coral organisms.

CHAPTER VI

SEDIMENT PROPERTIES

Texture

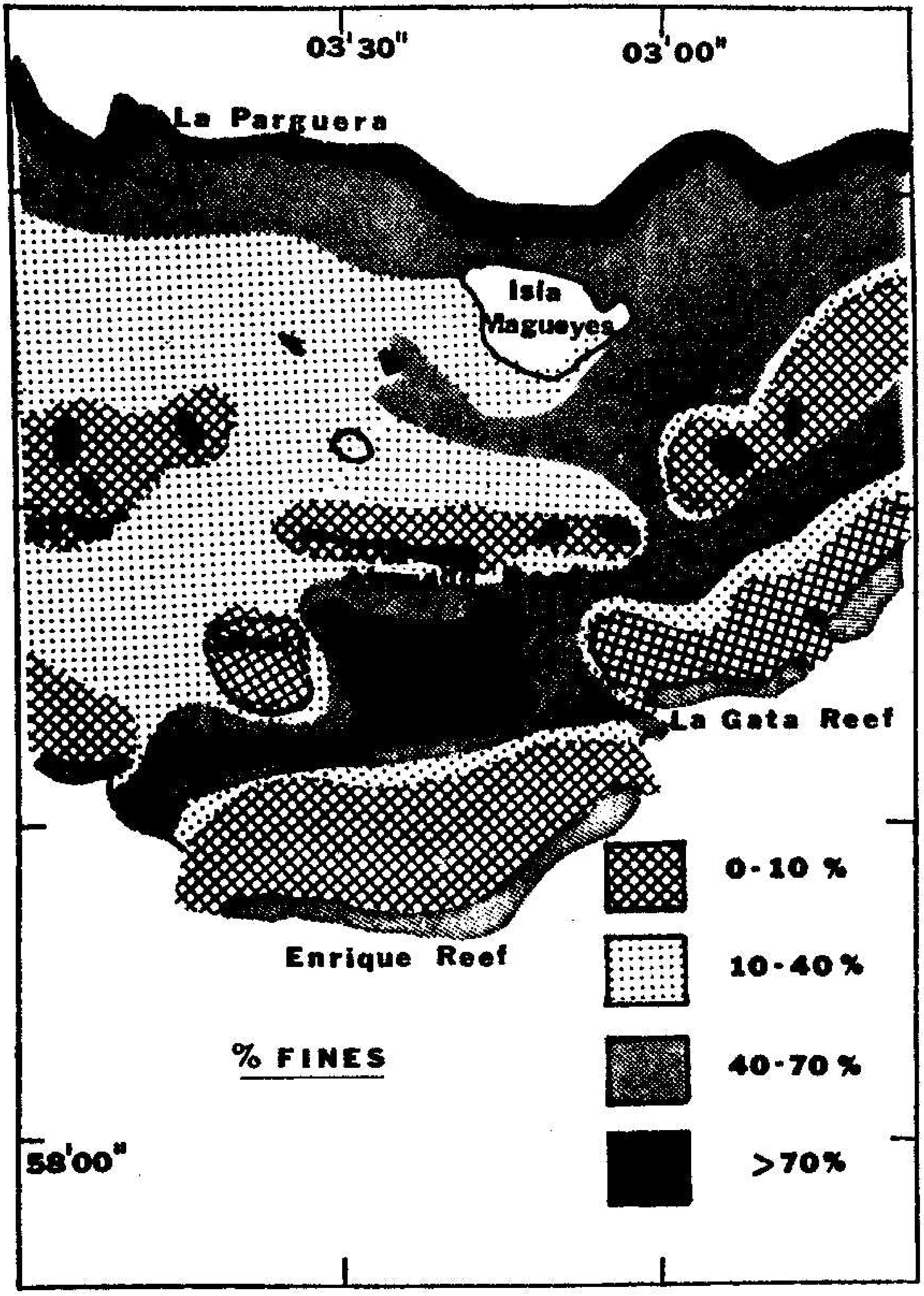
The grain-size distribution of clastic terrigenous sediments is believed to reflect the hydrodynamic aspects of the transporting medium and the environment of deposition. Consequently, the application of textural criteria to ancient clastic terrigenous rocks is useful in geological interpretations. The understanding of parameters of size distributions in carbonate sediments, however, is exceedingly more complicated.

The application of standard mechanical size analysis techniques to carbonate sediments is problematic. Many of the grain sizes measured during mechanical analysis do not represent actual sizes in the natural environment. Composite particles, such as faecal pellets are broken into their fine-grain components by conventional wet sieving methods. Many pellet aggregates recognized in thin section do not appear in the sand fraction of the same samples after size analysis. For verification purposes, one sample was taken directly into the laboratory after collection and examined with a binocular microscope. Numerous pellets of fine sand size were recognized and upon agitation these grains quickly disaggregated.

The problems of interpreting grain-size distribution in carbonate sediments are even more pronounced due to the nature of in situ production of carbonate particles. Skeletal particles, for example, are produced with inherent variations in grain size. Their initial size ranges from pebble-size coral rubble to silt-size foraminifera tests and clay-size coccoliths. Furthermore, skeletal grains are not only susceptible to mechanical abrasion, but also to degradation as a result of a wide range of biodestructive processes. Thus, the interpretation of grain size may be unrelated to local energy conditions, but may instead reflect the original skeletal architecture, as well as the feeding habits of endemic benthic organisms. The application of statistical parameters of grain-size distributions to carbonate sediments must then be made with caution. Nevertheless, trends in size distribution revealed by these methods may be useful as a further means of describing sedimentary facies.

For descriptive purposes, the most widely used grain-size criteria is the percentage of fines (less than 62 microns) found in the total sample. The areal distribution of fine fraction percentage ranges from only a trace in the reef sands to 87% in a sample from the back-reef lagoon. The patch reef lagoon has considerably less silt and clay (16-56%) than the back-reef lagoon (68-87%). There also tends to be a higher proportion of silt and clay on the eastern side of the study area (Fig. 9).

Figure 9. Distribution of fine fraction

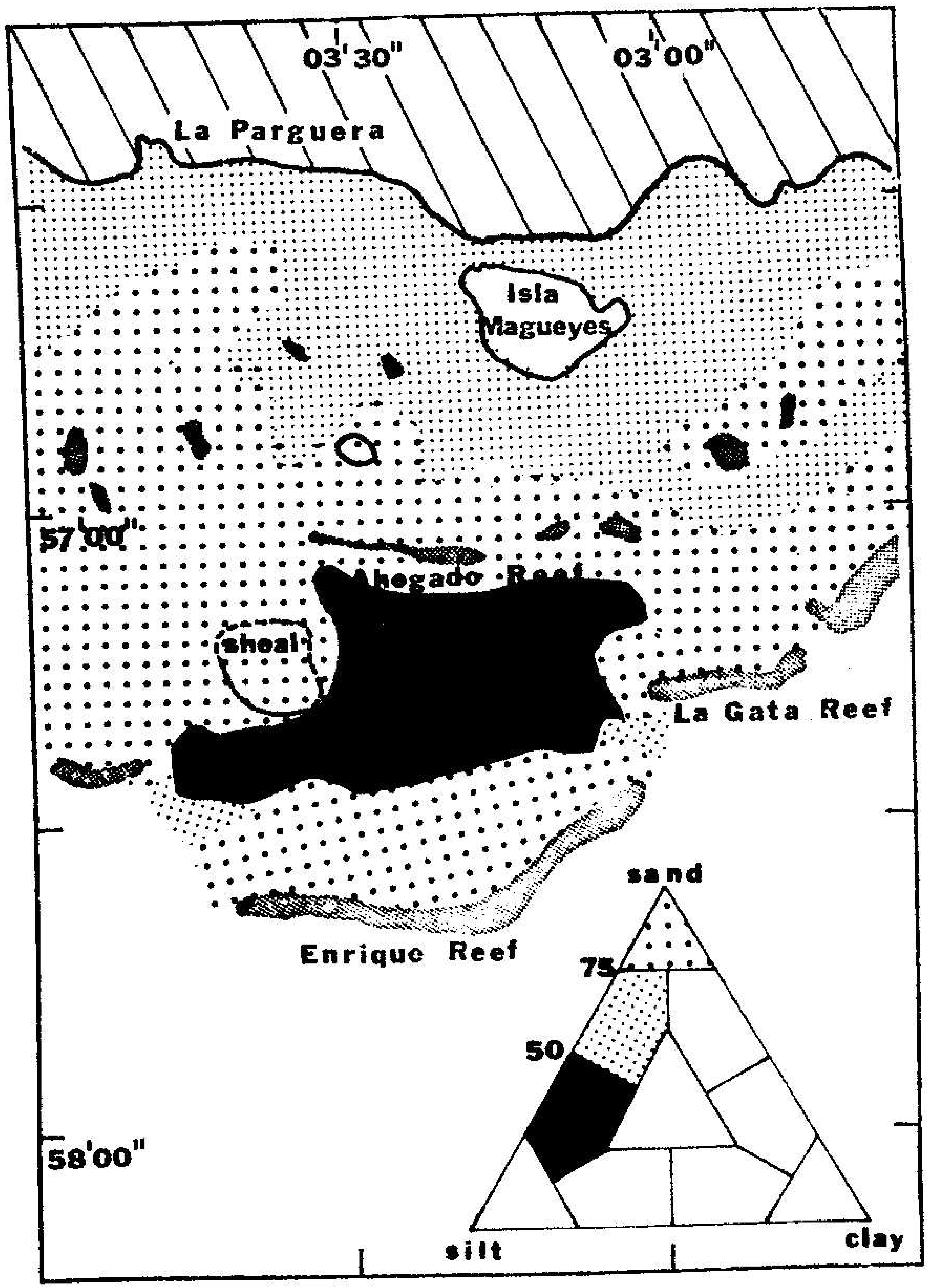

03'30"
03'00"
La Parguera
Isla Magueyes
La Gata Reef
Enrique Reef
% FINES
0-10 %
10-40 %
40-70 %
>70%
58'00"

The percentages of sand-, silt- and clay-size fractions were plotted on a ternary diagram and size class divisions were designated after Shephard (1954). The sediments in the vicinity of the reef and shoal areas are composed predominantly of sand-size particles (Fig. 10). The back-reef lagoon is composed of sandy-silt sediment, while silty sand comprises the sediment of the inner shallow lagoon.

Among the statistical perameters calculated, the mean grain size reveals the most significant relationships. The mean size of grains in each sample is dependent upon the initial grain-size distribution and the grain diminution processes at work in the respective environments of deposition. There is a wide range of particle size in the inner shelf region ranging from -6 phi (64 mm) size molluscan shells to clay-size particles of less than 8 phi (4 microns). The values of mean grain size also vary widely from a minimum of 5.88 phi in the back-reef lagoon to a maximum of -1.17 phi in the rubble adjacent to the reef flat of Enrique Reef. There is also a wide variation in mean grain size on the back-reef sand apron ranging from 2.45 to -1.17 phi. A plot of mean grain size distribution along the underwater transect (Fig. 13) indicates a decrease in mean grain size with depth.

Sorting is dependent upon the size of the particles being supplied, the mode of deposition and the current configuration (Folk, 1968). Sorting in the inner shelf region off La Parguera ranges from moderately (.71-1.0 phi) to very

Figure 10. Distribution of sand-silt-clay ratio


03'30"
03'00"
La Parguera
Isla Magueyes
57'00"
Ahegado Reef
shoal
La Gata Reef
Enrique Reef
sand
75
50
58'00"
silt
clay

poorly (2.0-4.0 phi) sorted. The back-reef lagoon samples were poorly sorted (1.0-2.0 phi), yet better sorted than the very poorly sorted shallow lagoon samples. The areal distribution of the degree of sorting is shown in Figure 11.

Much less is understood about the other two statistical perameters, skewness and kurtosis. Their values are dependent on the variation from normal gaussian distributions. These perameters were calculated and their areal distribution was plotted, however, no significant trends were recognized.

Grains examined in thin section are subrounded to rounded in the samples from the reef and shoal areas. The grains that comprise the back-reef and inshore sediments are, on the other hand, abraded and show very few rounded edges.

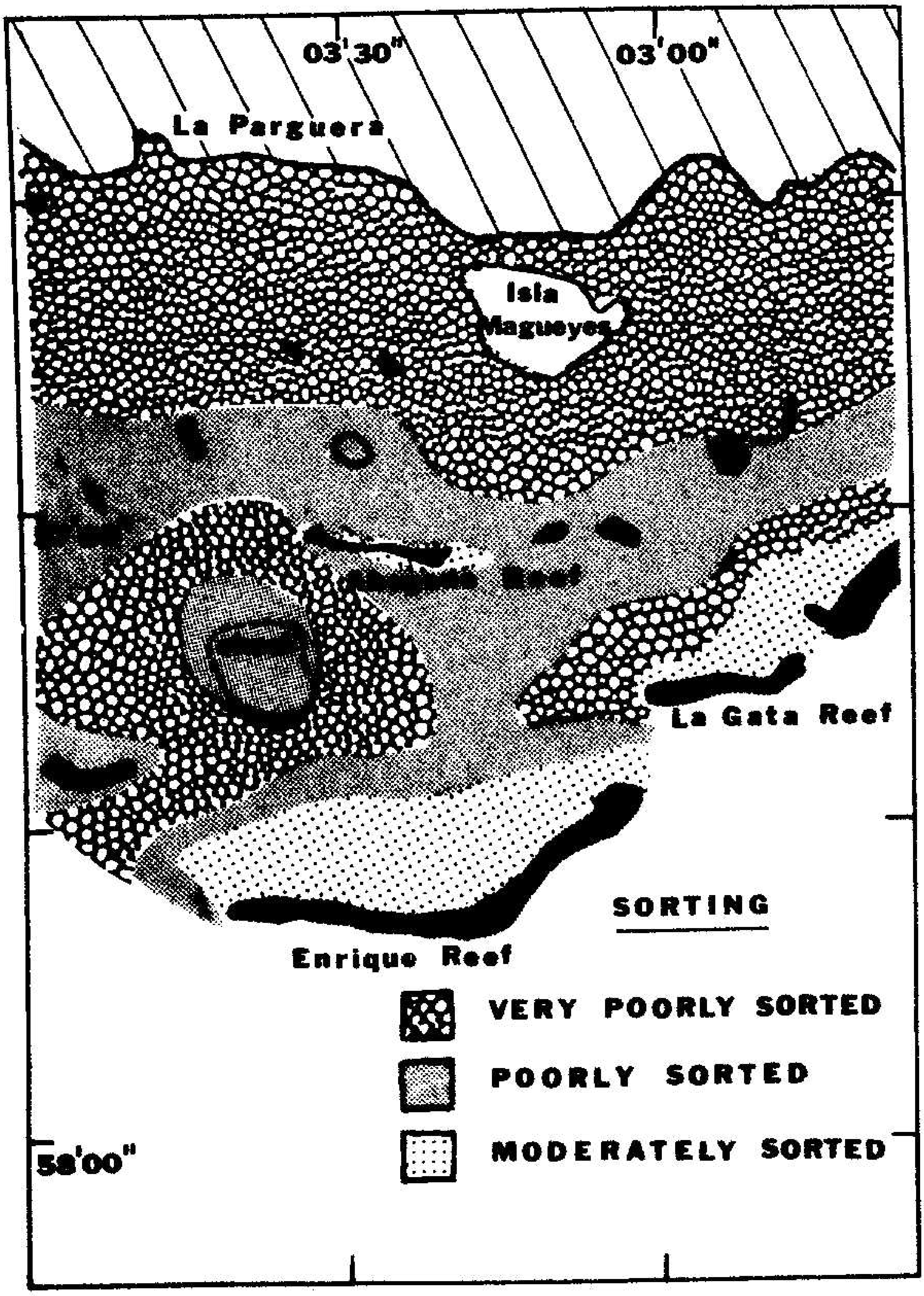
Composition

The identity of constituents and their relative distribution are important criteria for the description and interpretation of depositional environments of carbonate rocks. The ability to recognize carbonate grains is greatly inhibited as grains become increasingly fragmented. Grains in the finer sand and smaller size ranges are difficult to distinguish, and thus influence the accuracy of the counts. As grains approach these finer-size categories their recognition depends on:

(1) orientation of the grain in thin section

(2) thickness of the thin section

Figure 11. Distribution of sorting



03'30"
03'00"
La Parguera
Isla Magueyes
La Gata Reef
Enrique Reef
SORTING
VERY POORLY SORTED
POORLY SORTED
MODERATELY SORTED
58'00"

(3) degree of aggregation

(4) identity of particle

(5) degree of calcification

The ability to identify various constituents of different size classes viewed in thin sections from the inner shelf area is shown in Figure 12. Representative features, such as shell architecture, are no longer useful in identification after the particle has been reduced to individual lamellae (Ferray, Heuer and Hewatt, 1962). In addition silt-size Halimeda fragments often do not retain the utricles that facilitate their identification (Mathews, 1966). Some constituents, however, such as foraminifera and echinoid fragments are more easily identified in the fine-size ranges, and for this reason counts of these constituents may appear relatively higher than in actual occurrence. For the purpose of this study all grains were counted and those not identified were counted under the category "unknown."

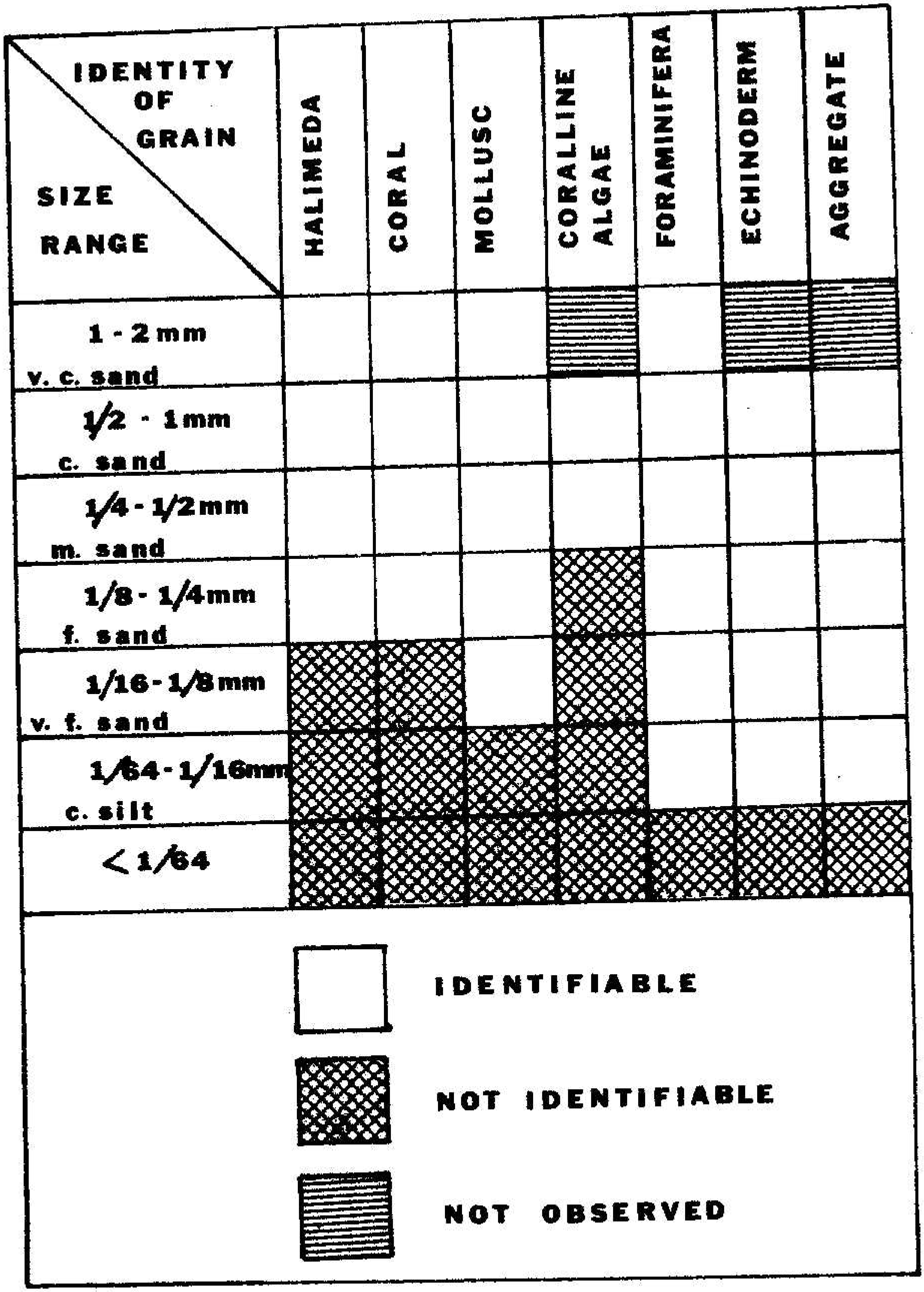
The constituents of carbonate sediment are commonly divided into skeletal, nonskeletal, and terrigenous components. Skeletal components are, by far, the most important material constituting the sediments of the inner shelf region off La Parguera. In order of decreasing abundance the following skeletal components were recognized:

(1) Halimeda plates and fragments

(2) Coral fragments

(3) Molluscan shells and fragments

Figure 12. Limits of recognition of constituents


IDENTITY OF GRAIN
SIZE RANGE
HALIMEDA
CORAL
MOLLUSC
CORALLINE ALGAE
FORAMINIFERA
ECHINODERM
AGGREGATE
1 - 2 mm
v. c. sand
1/2 - 1 mm
c. sand
1/4 - 1/2 mm
m. sand
1/8 - 1/4 mm
f. sand
1/16 - 1/8 mm
v. f. sand
1/64 - 1/16 mm
c. silt
< 1/64
IDENTIFIABLE
NOT IDENTIFIABLE
NOT OBSERVED

(4) Benthic foraminifera

(5) Coralline algae, whole and fragments

(6) Echinoderm plates and spines

(7) Minor skeletal fragments

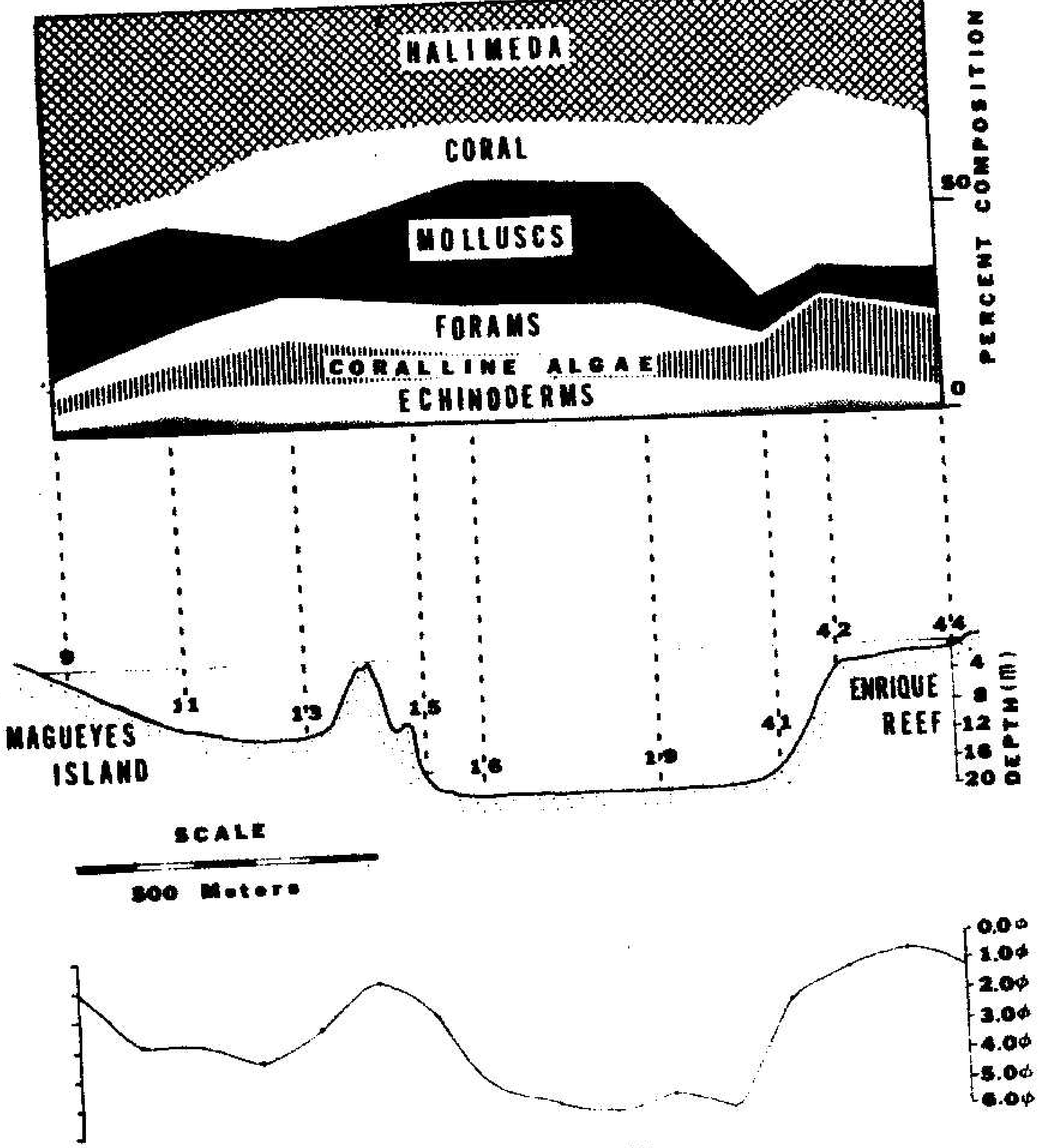
The relative distribution of constituents along the underwater transect is shown in Figure 13.

Halimeda.--*Halimeda* appears in the sediments as plates and fragmented plates, which appear brownish in thin section and slightly transluscent in transmitted light (Fig. 14a). Characteristic tubules called utricles branch freely through the plates. The plates represent a significant portion of the coarse sand fraction, and fragmented plates are equally abundant in the fine sand fractions. Fragments are usually highly abraded. *Halimeda* fragments are the most important contributor to the sediment in the inner-shelf region where they make up as much as 53 per cent of the sand fraction of samples from the grass-covered shallow lagoon environment. The relative abundance of *Halimeda* plates and plate fragments decreases in the barren lagoon and reef apron and talus slope environments. This may be a result of the relative increase of *in situ* production of corals and molluscs rather than a decrease in the production of *Halimeda*.

Corals.--Recognition of coral fragments (Fig. 14d) in thin section was based on their radially oriented arrangement of aragonitic needles. The hydrozoan, *Millepora*, was also

Figure 13. Distribution of skeletal constituents and mean grain size along the underwater transect

UNDERWATER TRANSECT DISTRIBUTION



MEAN GRAIN SIZE

Figure 14. Photomicrographs of constituents

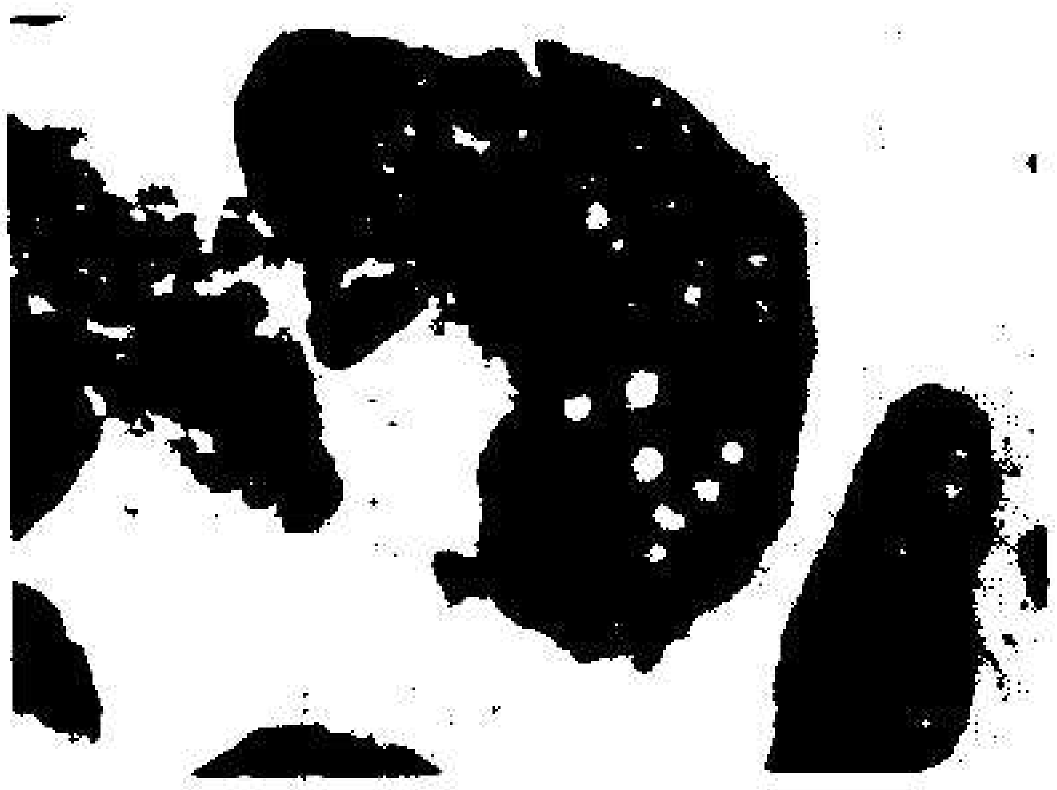
a. *Halimeda* fragment, x 100

b. Coralline algae fragment, x 100

c. Aggregates, x 100

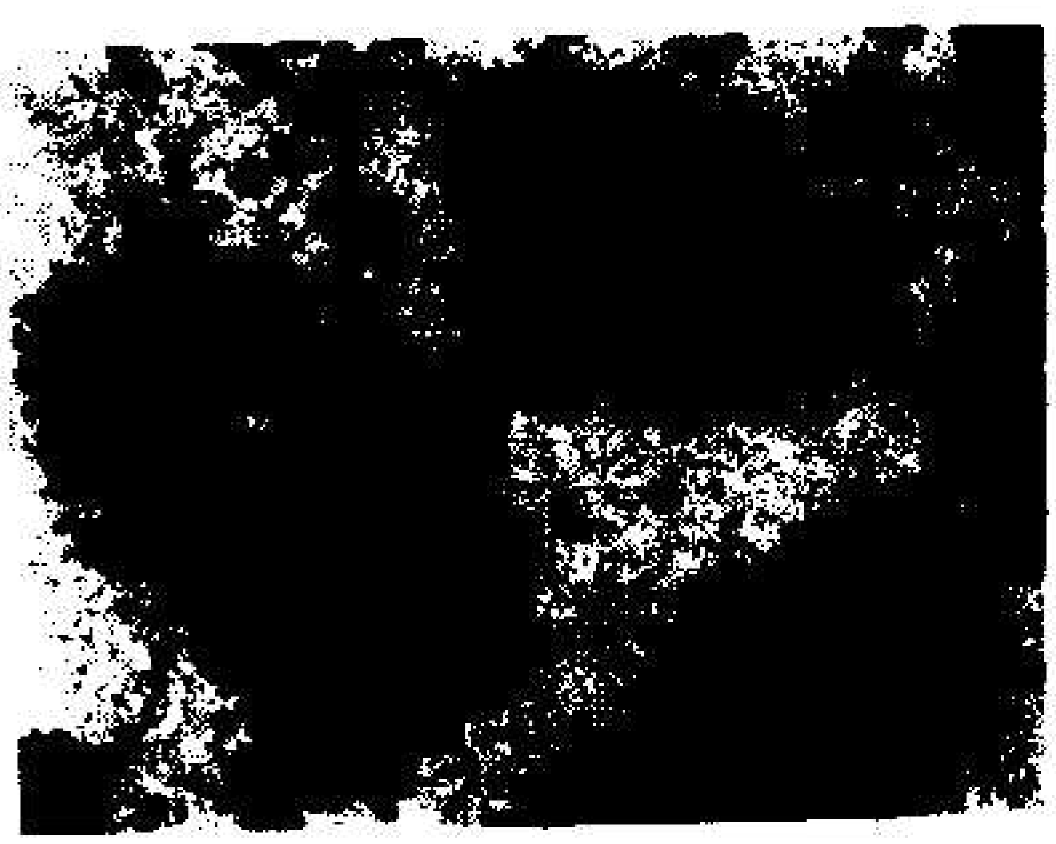
d. Coral fragment, x 100

e. Foraminifera, x 100



a

b



c

d

e

included in this category and has similar radial structure with abundant pores perforating the skeletal fragments (Pusey, 1964). Although coral is found in the pebble and larger size ranges, coral fragments appear to be more abundant in the finer fractions. Illing (1954) has described the tendency of coral fragments to be easily reduced to finer size particles. Most of the coral fragments are abraded. They constitute a significant part of the sands forming reef deposits (31%-67%) and are much less abundant in the shallow inshore and back-reef lagoon environments where they represent only 9%-18% of the total grains counted.

Molluscs.--Because of the difficulty in differentiating molluscan classes in fine-size grains, this category includes both gastropods and pelecypods. In thin section the fragments are recognized by their wavy extinction caused by the parallel orientation of crystallites and the layered structure. Molluscan fragments appear to occur most frequently in the coarse and medium sand fractions of the grains counted. Often very small whole pelecypod shells make up a major portion of the coarse sand fraction of some samples. The greatest abundance of molluscan fragments (27%-29%) is found in samples from the barren lagoon environment. Samples from the grass-covered lagoon and mangrove channel environments also contain a significant amount of molluscan fragments (20%-28%). Molluscan fragments are considerably less important in the reef sands where they only represent 5%-10% of the total grains counted.

Foraminifera.--Foraminiferal assemblages are sensitive to environmental conditions and consequently provide a valuable tool in the interpretation of facies relationships. Seiglie (1971) points out the usefulness of foraminifera as barometers of environmental changes and their role in characterizing various facies. Foraminifera are usually differentiated by their variety of wall structures and the arrangement of their chambers. They constitute a significant portion of the sediment of the inner shelf region under study. Results of thin section counts indicate that the greatest relative abundance of foraminifera (10%-16%) is in the back-reef lagoon.

Identification of living foraminiferal assemblages from washed out samples representing various environments in the study area was made by George A. Seiglie of the Department of Geology, University of Puerto Rico. Although quantitative comparisons have not been attempted, distinct assemblages of living foraminifera can be seen to represent different bottom environments. A list of the major environments and the more common benthonic species of foraminifera found therein is included in Table 1. The descriptions that follow refer to living assemblages unless otherwise mentioned.

Samples from the sands from reef and shoal areas contain large discoidal foraminifera (Fig. 14e) and miliolids of

TABLE 1

FORAMINIFERA ASSEMBLAGES

Environment	Common Species Observed
Shallow inshore lagoon environment	Archaias angulatus Sorites orbitolitoides Triloculina trigonula
Patch reef environment	Pyrgo subspaerica Peneroplis proteus Quinqueloculina lamarckiana Articulina sp. Ammonia advena Amphistegina gibbosa Triloculina trigonula
Barren lagoon environment	Quinqueloculina candeiana Q. seminulum Q. sp. Ammonia catesbyana Triloculina trigonula Protoelphidium sp. Criboelphidium discoidale C. poeyanum Miliolina sp.
Reef apron and talus slope environment	Archaias angulatus Quinqueloculina sp. Rotorbinella rosea

various sizes. Archaias angulatus is the most characteristic species associated with reef sands. Mostly worn, dead representatives of this species are found in the deeper lagoon environments. A wide range of species diversity is apparent in the assemblages from the reef environments. Assemblages from shoal and patch reef areas indicate a very high species diversity of foraminifera while those from the back-reef area of Enrique Reef have much lower species diversity. Amphistegina gibbosa, a species dominating the reef areas on the western shelf of Puerto Rico (Seiglie, 1971), is present in samples from the shoal and patch-reef areas, but is absent in samples from Enrique Reef.

In the back-reef lagoon leeward of Enrique Reef there is a varied assemblage of foraminifera species including Ammonia catesbyana and Criboelphidium discoidale, along with various small miliolids. Bandy (1964) describes a similar assemblage in a low energy lime-mud environment in Batabano Bay, Cuba. The occurrence of Ammonia and Criboelphidium is common in coastal lagoons, but in assemblages with far less species diversity (George A. Seiglie, personal communication). Small miliolids of the type found in the back-reef lagoon are usually associated with algae.

In the patch reef lagoon only two living species were identified: Sorites orbitolitoides and Archaias angulatus. Archaias angulatus is extraordinarily abundant in the shallow grass environment south of Magueyes Island. In numerous areas of the West Indies Bock (1969) described this species living on blades of *Thalassia*.

Coralline Algae.--Coralline algae are best recognized by arrangement of cells and the fine detail of their calcified tissue (Fig. 14b). Fragments of coralline algae are quantitatively important in samples from the reef environments where they account for 9%-18% of the sand fraction. Coralline algae are not a significant constituent of the non-reef environments in which they represent less than 7% of the total grains counted.

Echinoderms.--Echinoderm fragments consist mainly of plates and spines. Each fragment usually behaves as a single crystal under crossed nicols and has parallel extinction. The plates can also be distinguished by their mesh-like structure. The distribution of echinoderm fragments ranges from 2% to 5% in the reef sands, 4% to 6% in the inshore areas, and 5% to 11% in the back-reef lagoon.

Minor constituents.--Those constituents representing less than 2% of the total grains have been grouped together in this category. Here I include spines and spicules of sponges and gorgonians, worm tubes and parts of crustaceans. These constituents together do not exceed 4% of the total grains in any sample.

Nonskeletal grains.--Ovoid to rod shaped aggregates of micrite-size carbonate particles are a significant component of the sediment of the inner shelf. The aggregates exhibit no orientation or structure. Generally, large pellets are composed of coarser component particles. It is impossible to make quantitative estimates of the pellets' abundance due to their disaggregation during sample preparation and sieving. A fresh sample from the barren lagoon environment was composed of 20%-30% of these pellets. Pellets were examined in thin section (Fig. 14c) and under an ETEC Autoscan scanning electron microscope (Fig. 15c) by Dr. Nahum Schneidermann of this department, but it is difficult to tell whether they are natural aggregates or aggregates formed after collection. The occurrence of pellets in the vicinity of benthic animals, and their rounded and structureless appearance are substantial evidence for their origin as faecal pellets.

Composition of the fine fraction.--The sand fractions from the samples in the study area consist entirely of calcareous material. The fine fractions from the barren lagoon, on the other hand, contain as much as 15% noncarbonate material. Samples from this environment contain more noncarbonate material in the fine fraction (10%-15%) than the shallow inshore environments (5%-10%). Analysis of different size fractions indicates that as much as 75% of the clay fraction (which represents up to 20% of the total sample) is composed of noncarbonate material. The silt fraction contains only a small percentage of noncarbonate material, thus most of the terrigenous material in this region consists of clay-size particles.

Identification of the nature of carbonate constituents in the silt- and clay-size range was not possible with a light microscope due to the limitations in resolution. A major portion of this fine-grain material examined under the scanning electron microscope is composed of skeletal debris, mainly the nacreous layers of molluscan shells (Fig. 15f). Figure 15b shows a larger molluscan fragment together with a diatom fragment. Prismatic aragonitic needles of algal origin appear to be a significant constituent of fine fractions (Fig. 15e), but they are less abundant here than in the Bahamas-Florida region (Cloud, 1962; Stockman, et al., 1967; Steiglitz, 1972). Coccoliths are present (Fig. 15d) and may represent as much as 10% of the fine fraction in some samples (Dr. Nahum Schneidermann, personal communication). Other particles such as sponges (Fig. 15c) and clay minerals (Fig. 15e) were identified.

Carbonate Mineralogy

Samples from the inner shelf sediments off La Parguera contain the following ranges of abundances of carbonate minerals: aragonite (62%-91%), high-magnesium calcite (8%-31%), and low-magnesium calcite (0%-13%). Sands from the reef deposits have the highest concentration of

Figure 15. Electronmicrographs of the fine fraction

a. a large aggregate, x 1000

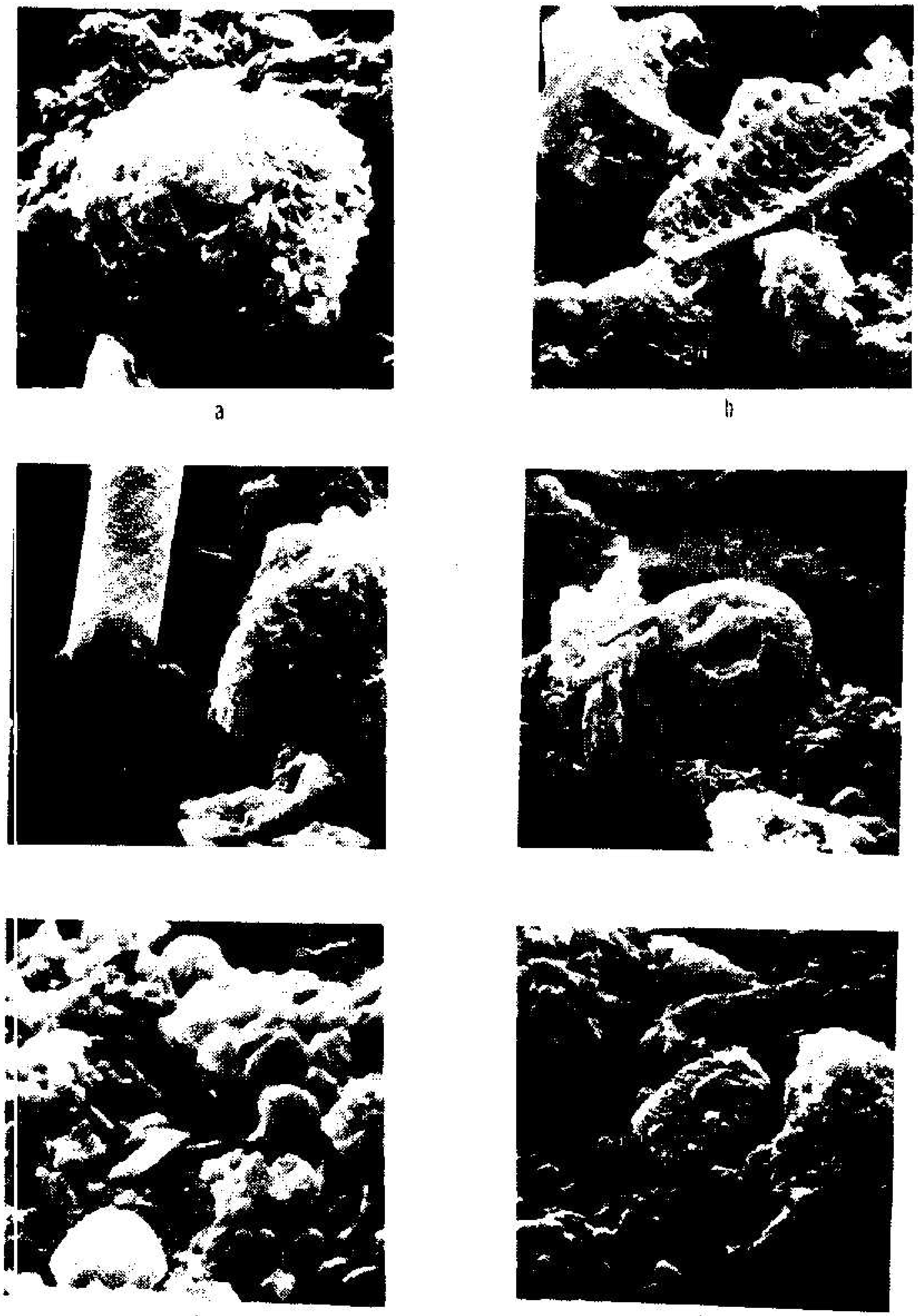
b. a molluscan fragment (upper left hand corner) and a diatom fragment (center), x 500

c. a large sponge spicule, x 500

d. a coccolith is viewed in the center of the picture, x 1000

e. needles of aragonite (left hand side of the picture), the angular particle (bottom of the picture) may be a clay mineral, x 3333

f. the nacreous layers of a molluscan fragment, x 1500

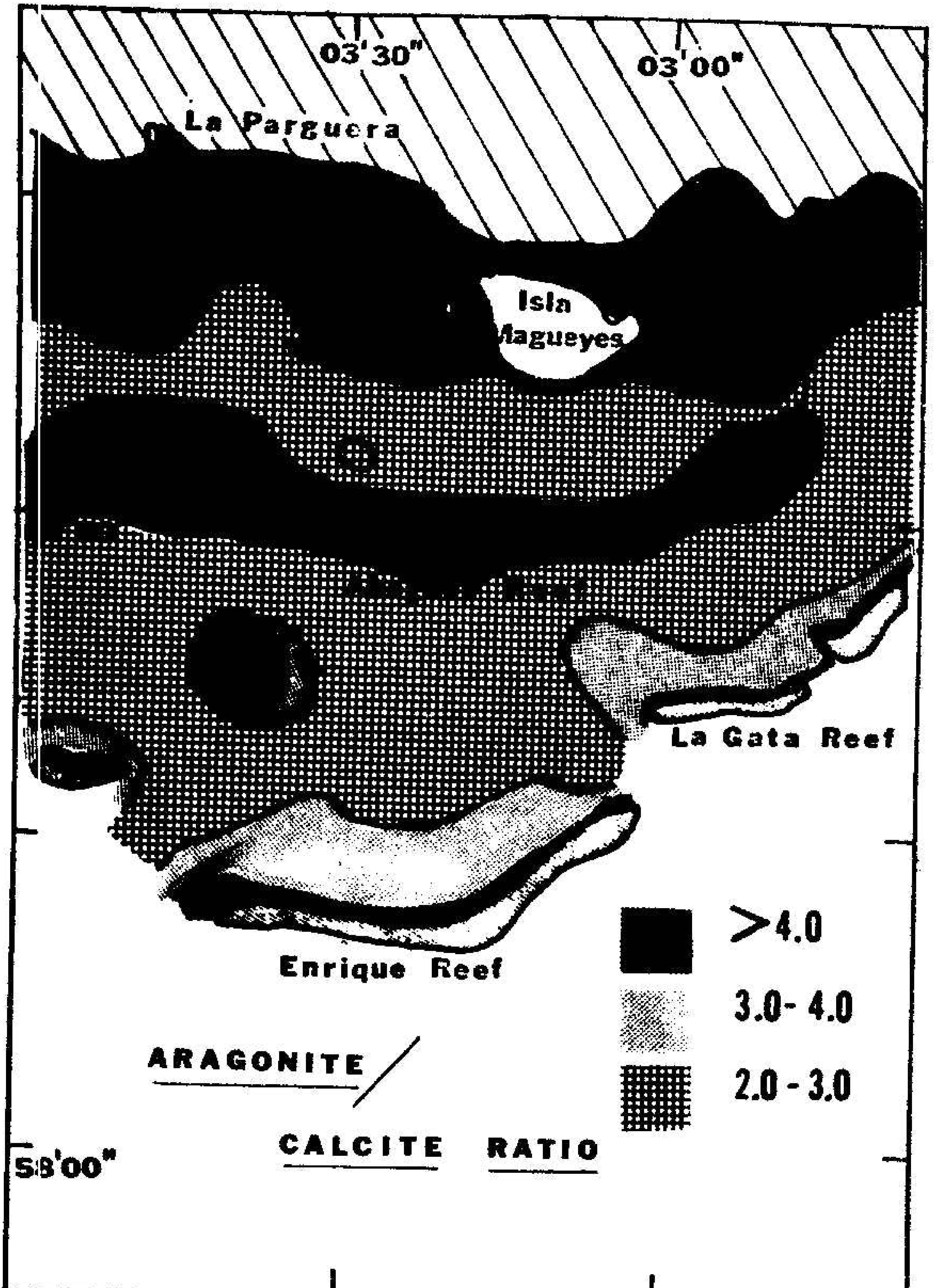


a b e f

aragonite. Although aragonite is prevalent in the reef sands, its relative abundance is variable (71%-91%). Percentages of aragonite in the barren lagoon environment are comparatively lower (62%-69%) than in the surrounding deposits. Behind the patch reefs aragonite increases shoreward from 64% in the patch reef lagoon to 86% near shore. The distribution of high-magnesium calcite is generally complimentary to that of aragonite. Ratios of aragonite to calcite have been determined for the sand fractions of selected samples and their areal distribution is shown in Figure 16.

The distribution of carbonate minerals predictably parallels the relative abundance of skeletal components. The chief producers of aragonite are Halimeda, corals and molluscs, while benthonic foraminifera, coralline algae and echinoderms are responsible for the production of high-magnesium calcite. Low-magnesium calcite is produced by some planktonic and benthonic foraminifera, several types of molluscs, and coccolithophores. A high percentage of aragonite inshore exemplifies the relative abundance of Halimeda in the sediment. The abundance of high-magnesium calcite in samples from the barren lagoon environment represent the relative increase in foraminifera and echinoderm fragments in this environment. Variations in aragonite percentage in samples from the reef areas appear to be dependent on the abundance of coralline algae. In the back-reef lagoon the

Figure 16. Distribution of the aragonite/calcite ratio


03'30"
03'00"
La Parguera
Isla
Magueyes
La Gata Reef
Enrique Reef
>4.0
3.0- 4.0
2.0 - 3.0
ARAGONITE
CALCITE RATIO
58'00"

concentration of high-magnesium calcite appears to be higher in the fine fraction as compared to the sand fraction from the same samples. Similar results were reported in a lagoonal environment off British Honduras by Mathews (1966), on a carbonate bank in Shark Bay, Western Australia by Davies (1970), and on the Great Bahama Bank by Husseini and Mathews (1972).

Grain Alteration

Following deposition carbonate sediments are subject not only to erosion and reworking by physical processes, but also to a wide spectrum of bioerosional processes. Furthermore, in shallow seas sediments are also subject to the precipitation of carbonate cement.

The role of biological activity in diminution and redistribution of skeletal grains has often been underestimated (Swinchatt, 1964). Many deposit-feeding invertebrates, such as holothurians and gastropods, ingest sediment and excrete them as sand size faecal pellets. Burrowing worms, pelecypods and sponges are known to burrow deep into corals causing the weakening of the skeletal structure. Active participants in the breakdown of skeletal material are several varieties of Caribbean reef fishes. Randall (1967) described several local species of fish that grind skeletal material in their jaws and pharyngeal mills. One of the most active of these sediment-grinding fish is the Parrot fish (Scaris), which scrape and grind coral to obtain the symbiotic algae growing below the coral surface.

Some of the skeletal grains examined in thin section show evidence of extensive boring comparable to those described by Perkins (1970) in sediments from the outer shelf of southwestern Puerto Rico. The bores result from the boring activity of septate green algae, red algae and fungi. Figure 17a & b show the effects of endolithic boring on the wall of a porcelaneous foraminifer and of an unidentified fragment, respectively. Fragments of molluscs (Fig. 17e) and corals appear to be selectively attached by boring activity. As a result of the boring activity of endolithic algae and fungi skeletal grains may be altered in two ways. First, the continued perforation of skeletal grains results in greater susceptibility to abrasion. Some grains viewed in thin section are visibly weakened by borings. Secondly, the vacated bores may fill with calcareous micrite after the organism has vacated the bore (see, for example, Bathurst, 1971). As boring and filling progress the grain becomes gradually micritized. Figure 17d shows the centripetal mictritization of a molluscan fragment.

Perkins and Halsey (1970) have recognized the inner shelf area between the intertidal zone and 25 m of depth as the most active region of algal borings. In the area of this study borings do not appear to have any preferred environmental distribution. On the sand apron behind Enrique Reef, for

Figure 17. Micrographs of altered grains

a. electronmicrograph of bore holes in the wall of a foraminifera test, x 4500

b. electonmicrograph showing boring by endolithic algae in an unknown fragment, x 900

c. photomicrograph of void filling in the chambers of a foraminifera, x 100

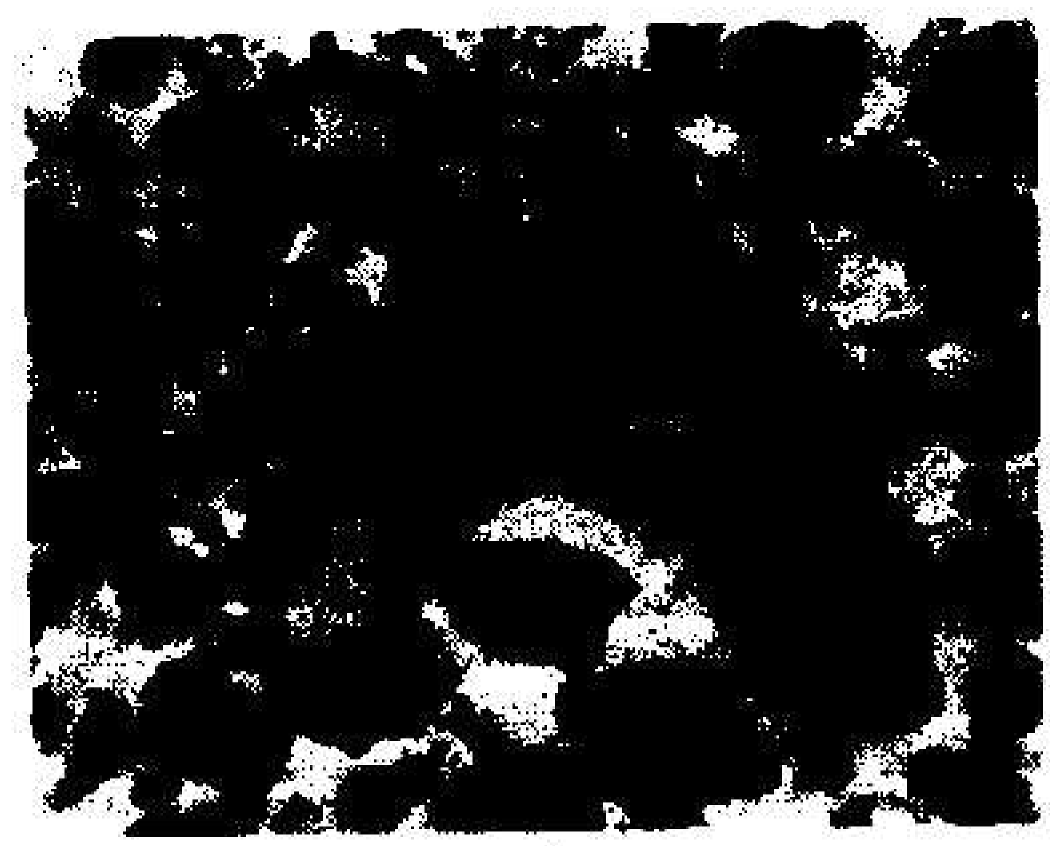
d. photomicrograph of centripetal micritization of molluscan fragment, x 100

e. photomicrograph of endolithic boring in a molluscan fragment, x 100

a

b

c



d

e

example, one sample showed a high degree of boring, while another adjacent sample from the same environment showed very few bored grains.

The filling of grain cavities, such as the utricles of Halimeda and foraminifera chambers, with micrite-size particles is common in samples from transitional areas between reef and mud deposits. Reef talus slope deposits, in particular, contain numerous grains with void fillings. Figure 17c shows the void filling of chambers of a foraminifera test.

Blackened grains, mostly molluscan fragments, make up 3% to 10% of the sand fractions of samples containing appreciable percentages of silt and clay. There are gradations in staining from slightly grayish to blackened fragments. Blackening of shell fragments has been reported in organic-rich sediments by Ginsburg (1957) in South Florida, Maiklem (1967) on the Great Barrier Reef, MacIntyre (1967) in shallow sediments off Barbados, and Davies (1970) in Shark Bay, Western Australia. Various grains exhibit different potential for blackening, as shown by the selective staining of molluscan shells (see also Pilkey, et al., 1969). Blackened grains appear to be abundant in the barren lagoon and the grass-covered inshore lagoon environments. Davies (1970) described the reducing conditions in grass beds as optimal for blackening of shell fragments. The abundance of fine sediment together with the presence of an algal mat may have created similar reducing conditions in the back-reef lagoon.

The precipitation of sparite cement into voids and between grains of skeletal material in reef deposits has been well documented (Purdy, 1963; Pusey, 1964; Boyer, 1972). Traces of cement can be seen lining the cavities of some skeletal grains in the reef sands. However, no conspicuous cementation, such as the precipitation of aragonitic needles in the utricles of Halimeda was observed.

CHAPTER VII

SEDIMENTARY FACIES

For reconstructing ancient depositional environments, a recent model of sedimentation must relate characteristically different sediment types to their environments of deposition. For this purpose lithological properties should be considered, such as those described, in order to establish arbitrary boundaries between differing facies. Based on the textural, compositional and mineralogical properties of the samples from the inner-shelf area three distinct lithofacies have been recognized:

(1) Reef skeletal sand facies

(2) Lagoonal mud facies

(3) Inshore *Halimeda* facies

A summary of the most important characteristics of these facies is included in Table 2. The areal distribution of the described facies is shown in Figure 18.

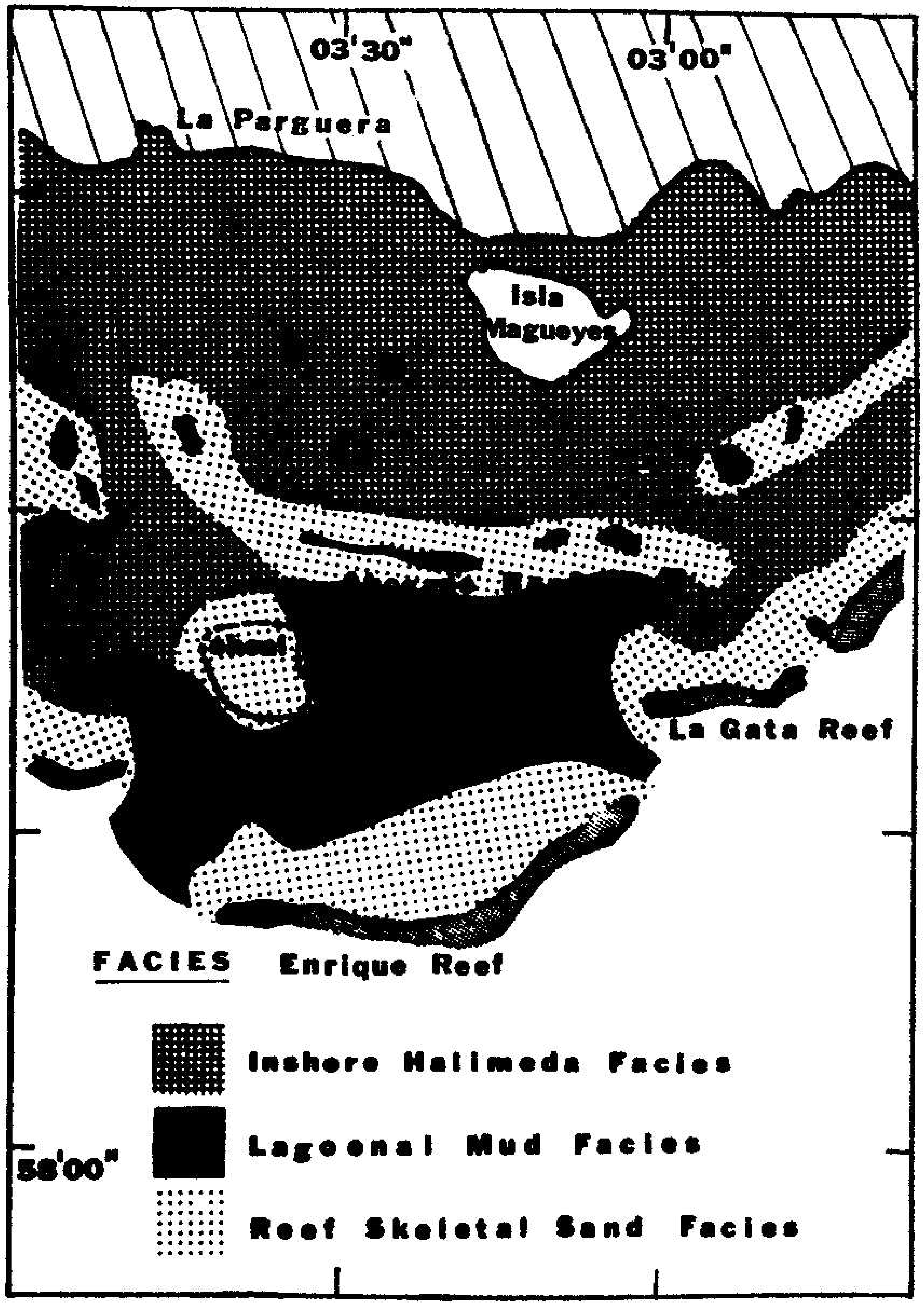
The reef skeletal sand facies is derived from the production of skeletal material by reef organisms and is deposited in the reef apron and talus slope and patch reef environments. Very little fine material is present in the sediment of this facies (Fig. 19), although the relative abundance of finer material appears to increase towards the

TABLE 2

FACIES CHARACTERISTICS

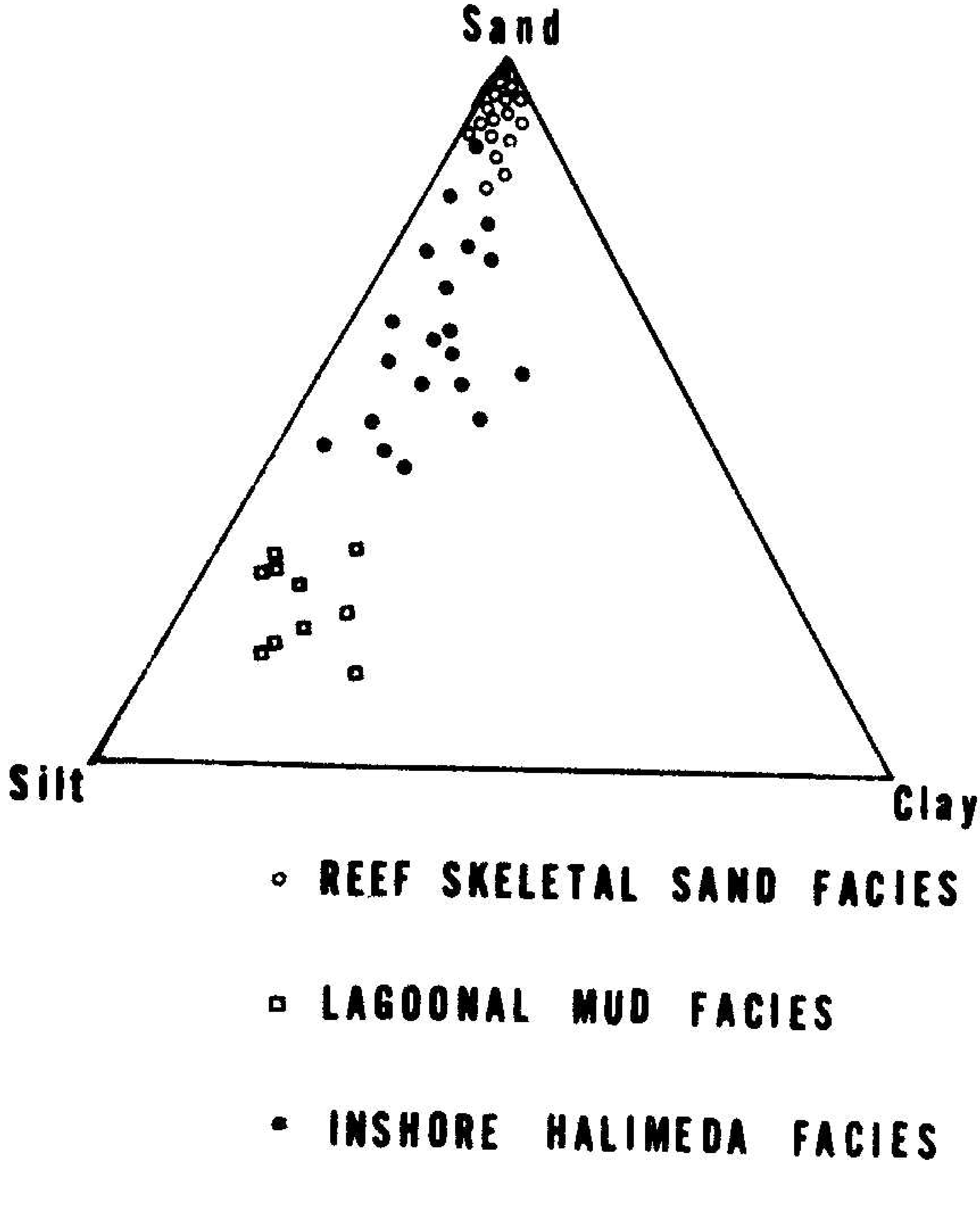
Sediment Characteristics	Skeletal Reef Sand Facies	Lagoonal Mud Facies	Inshore Halimeda Facies
Location	Reef apron and talus slope & patch reef	Barren lagoon	Mangrove channel and shallow lagoon
Mean grain size	-1.17-2.14 phi	4.89-5.89 phi	1.09-4.03 phi
Sorting	Moderate-poor	Poor	Very poor
% Fine fraction	1-14%	68-87%	12-56%
Composition (sand fraction)	Coral > Hal. >> Moll.	Hal. = Moll. >> Coral	Hal. > Moll. >> Coral
% Terrigenous Material	1%	8-11%	1-5%
Aragonite/calcite ratio	2.4-11.5	1.6-2.6	1.3-11.5

Figure 18. Facies distribution map



03'30"
03'00"
La Parguera
Isla
Magueyes
La Gata Reef
Enrique Reef
58'00"
FACIES
Inshore Halimeda Facies
Lagoonal Mud Facies
Reef Skeletal Sand Facies

Figure 19. Sample distribution on the sand-silt-clay diagram


Sand
Silt
Clay
REEF SKELETAL SAND FACIES
LAGOONAL MUD FACIES
INSHORE HALIMEDA FACIES

periphery of these sand deposits. A range in mean grain size from -1.17 to 2.45 phi represents local variations in the size of the supply of skeletal constituents. These sands are moderately sorted with an average phi deviation of .96. Coral fragments are, by far, the most important constituent, and they account for 37% to 67% of the sand fraction. *Halimeda* fragments are also abundant (22%-32%). Other grain types include coralline algae (7%-18%), molluscan fragments (5%-9%), echinoderm fragments (2%-3%), and foraminifera (1%). Comparison with back-reef sand deposits in the literature (Ginsburg, 1956; Milliman, 1967; and Swinchatt, 1964) shows similar relative composition, although percentages of coral fragments appear higher and molluscan fragments lower in the sands deposits in the study area. The abundance of aragonite is generally higher in the reef sands than in the other environments in the study area due to the abundance of coral and *Halimeda*.

Both physical and biological mechanisms are responsible for the destruction of skeletal material in the reef areas. Such mechanisms include breakage and abrasion of particles by wave action, the removal of organic binding material (Mathews, 1966; and references therein), reduction through grinding and ingesting of sediments by reef animals (Cloud, 1962; Randal, 1967), and boring activity of siphonaceous algae, fungi and various boring invertebrates (Perkins, 1970; Ginsburg, 1957; and Swinchatt, 1964). Callinassid shrimp also plays an important role in the diminution of skeletal grains by resupplying grains to the more active surface region. As particles reach silt sizes they may be transported to leeward depositional sites.

The lagoonal mud facies is located in the barren lagoon environment to the lee of Enrique Reef. Of the three facies described, this facies is the most uniform texturally, compositionally and mineralogically. This facies is characterized by a high percentage of fine material (68%-87%). Sorting is poor and varies between phi standard deviations of 1.14 and 1.76. Counts of the sand size fraction indicate a high relative abundance of Halimeda (28%-34%) and molluscan fragments (27%-29%). Molluscan fragments are also an important constituent in mud-rich sediments in Batabano Bay, Cuba (Daetwyler and Kidwell, 1959) and on the Campeche Bank (Logan, et al., 1971). Coral fragments (13%-18%) and coralline algae fragments (4%-5%) are less important sediment contributors, while foraminifera (12%-16%) and echinoderm fragments (7%-10%) are more important here than in other facies. A variety of foraminifera, which includes Ammonia and Criboelphidium and several small miliolids, is characteristic of this facies. Pellets, probably faecal in origin, are also an important component. The fine fractions of the lagoonal mud facies contain a considerable amount of terrigenous material (10%-15%), skeletal fragments (mostly molluscan), coccoliths, and aragonite needles. In the sand fractions the concentrations of high-magnesium calcite are higher than in the reef skeletal facies, probably due to the abundance of foraminifera and echinoderms in the back-reef lagoon. Fine fractions from these sediments contain more high-magnesium calcite than do the sand fractions.

The barren lagoon environment, by nature of its depth and position behind the inner reef barriers, provides a trap for fine-grain sediment. The variety of grain types suggests that the fine material has several different sources. Skeletal fragments are most conspicuous and they appear to be the result of two processes active in the inner shelf region:

(1) *in situ* production of fine material by biodestruction

(2) transport of fine-grain material produced on the elevated reefs

Molluscan fragments are much more abundant in the sand fractions of the lagoonal mud facies than in the adjacent reef deposits. The activity of endolithic algae and fungi may play an important role in the destruction of *in situ* skeletal grains and although this boring may not lead directly to the diminution of molluscan particles, the activity of bottom dwelling organisms may break apart these grains. The abundance of faecal pellets in this environment attests to the active reworking of sediments by these organisms.

Winnowing of fine debris from reef deposits is probably the primary source of skeletal fragments in the lagoonal muds. The presence of worn tests of Archaias angulatus, a shallow water foraminifera, in the deeper back-reef lagoon is evidence of the transport of reef material to the lagoonal mud facies. Experimental data described by Force (1969) have shown that as a result of the disintigration of their organic binder, molluscan particles of sizes finer than 8 microns can be selectively transported from sand deposits. This type of selective winnowing process may also explain the higher percentages of high-magnesium calcite in the fine fractions of this facies. Chave (1962) suggests that rapid disintigration of coralline algae might explain such increases of high-magnesium calcite in the finer fractions of a back-reef lagoon on the Campeche Bank. The abundance of fine skeletal debris in the deposits of the lagoonal mud facies then is probably a result of both winnowing and in situ processes. Without detailed quantitative evaluation of the fine fraction, however, it is impossible to judge the relative importance of these two processes.

Several explanations have been suggested for the origin of aragonite needles. Cloud (1962) suggested that aragonitic needles were being precipitated in the Bahamas in shallow waters supersaturated with respect to calcium carbonate. The post mortem disintigration of calcareous algae was postulated by Lowenstam and Epstein (1957) as a possible origin of these needles. More recent work by Stockman, *et al.* (1967) has proven that the green algae, *Penicillus*, is a major producer of aragonitic needles. Chave (1962; 1964) has attributed the production of needles to the breakdown of skeletal particles, such as *Halimeda* and coral. The origin of aragonite needles in the back-reef lagoon is most likely due to the destruction of skeletal material on the elevated reefs. Several types of calcareous algae and corals are abundant in the reef areas in the study area and it would appear that needles are a plausible end product of the active physical and biological destruction in the reef environment. From here the needles may easily be removed by the prevailing landward waves and redeposited in the lagoon.

Coccoliths are present in notable quantities in the fine fractions of samples from the back-reef lagoon. Coccolith-rich sediments were considered to indicate deep oceanic or open shelf deposition. However, Scholle and Kling (1972) have recently found that coccoliths make up as much as 15% of the lime mud deposits in a lagoonal environment off British Honduras. Coccoliths that are found in the inner shelf region off La Parguera may have been washed in through passages in the inner reefs. Alternatively, some of the species found may be indigenous to shelf waters.

The dilution of carbonate sediment by terrigenous material has been reported in many shelf environments, usually close to the mou hs of rivers. In the study area up to 15%

of the fine fraction is composed of terrigenous material, yet no river systems are present. Some muds may be carried in suspension by longshore currents, however, the bulk of terrigenous material is probably supplied by runoff during torrential rains.

A prominent feature in the environment of deposition of the lagoonal mud facies is a film covering of blue-green filamentous algae, such as Schizothrix calciola. When such an algal mat exhibits laminar structure of alternating layers of algae and carbonate sediments it is termed an algal stromatolite (Logan, et al., 1964). These algal stromatolites owe their formation to periodic accretion due to fluctuations in environmental factors and the absence of grazing organisms. Gebelein (1969) reported that stromatolites accrete only in areas with slow bottom-sediment movement and with an adequate supply of sediments. No laminations were observed in the algal mat in this location and this is probably a result of the grazing of benthic animals and the reworking of sediment by burrowing organisms.

The inshore Halimeda facies includes the sediment deposited in the grass-covered shallow lagoon and the mangrove channel environments. Although a wide variation in lithologies, such as variation in the relative percentage of fine material, is recognized, the uniform composition of the sand fraction is sufficient to place the sediment in this region into one facies. The percentage of silt and clay varies between 12% and 56%. The sediments are very poorly sorted with a wide range of standard deviation phi values (1.72-4.15). Halimeda fragments are the most abundant constituent of this facies making up between 35% and 53% of the sand-size grains. Molluscan shells and fragments are also abundant (20%-28%). Other lesser significant sediment contributors are corals (5%-16%), coralline algae (4%-9%), echinoderms (3%-9%), and foraminifera (8%-14%). The dominant species of foraminifera is Archaias angulatus. X-ray data show a steady increase in the aragonite content inshore from 64% to 86%, generally coinciding with the increase in grass cover and relative abundance of Halimeda.

One of the most important controlling factors of sedimentation in the inshore area is the frequency and distribution of marine grass, principally Thalassia testudinum. In addition to providing a habitat for a variety of bottom organisms, Thalassia is known to play an important role in trapping fine-grain sediment and in stabilizing sand grains (Scoffin, 1969; and Ginsburg and Lowenstam, 1958). The dense growth of blades tends to diminish current strength along the sediment-water interface, thereby producing conditions favoring the settling out of fine-grain material. Together with this reduction of current strength, the complex system of roots of this marine grass prevents the erosion of the underlying substrate. Recent observations on shallow areas off Bimini in the Bahamas have shown that the growth of vents the removal of fine-grain material, thereby resulting in poorer sorted sediments. The accumulation of poorly sorted sediments in grass beds in South Florida was reported by Earley and Goodell (1968).

The sediments of the inshore *Halimeda* facies are predominantly the result of *in situ* production of skeletal material. The patch reefs contribute considerable amounts of sediment as flank deposits, but as a result of reduced currents in this region transport of fine material to the inshore regions is less important. Fine sediments are being produced primarily by the *in situ* destruction of skeletal grains, as well as the production of aragonite needles by the locally abundant algae.

CHAPTER VIII

CONCLUSIONS

The following conclusions can be drawn from this study:

(1) The inner-shelf area off La Parguera is an active site of recent carbonate deposition of biogenic origin.

(2) There is a variety of back-reef depositional environments in the inner-shelf area. A line of discontinuous patch reefs divides the back-reef area into seaward back-reef lagoon and reef environments and shoreward shallow lagoon, mangrove channel and tidal flat environments.

(3) Biological factors play an important role in the reduction of particle size in the inner-shelf region. This includes the boring activity by endolithic algae and fungi, grazing by deposit feeders, grinding of coral and other reef skeletal material by reef fishes, and extensive reworking of sediment by Callinassid shrimp.

(4) Despite the absence of rivers in the coastal area of the southwest coast of Puerto Rico, terrigenous material comprises as much as 15% of the fine fraction of samples from the inner-shelf area. Erosion of coastal soil cover by torrential rains and their deposition in the relatively calmer inner-shelf region must account for much of this terrigenous mud.

lagoonal mud facies, composed of an abundance of silt and clay, is located in the deeper lagoon to the lee of Enrique Reef. An inshore *Halimeda* facies, characterized by *Halimeda*-rich silty-sand, comprises the inshore areas.

CHAPTER IX.

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