THE CORAL REEF AT CAHUITA, COSTA RICA,
A REEF UNDER STRESS

By

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ABSTRACT

The coral reef at Parque Nacional Cahuita, Limón, Costa Rica, is a reef under stress due to siltation. The amount of suspended sediments is high: 7.4 mg/l (0.1 to 212.7 mg/l), resuspension of bottom sediments is also high: 30 to 360 $mg/cm^2/day$. As a consequence, growth rates of corals are low: 5.3 mm/year (3.7±0.8 to 7.7±0.4 mm/year), live coral coverage is low: 40% (4 to 80%), and coral diversity ~~is low~~: H'= 1.443 (0.038 to 1.602). Coral colonies are generally larger than in other areas studied, and recruitment of coral planulae seems to be low. Most of the corals present are good at rejecting sediments. Morphologies of some corals change to resist better the sediments (vertical fronds of *Agaricia agaricites*) or to receive more light (shingles of *Montastrea annularis* and *Porites astreoides*).

Analysis of the currents and the type of minerals present in the non-carbonate fraction (illite, montmorillonite, feldspar and kaolinite) of the sediments at the reef, point to Río La Estrella as the source of sediments. The amount of sediments carried by this river has probably increased recently as a result of watershed deforestation. The problem of siltation in reef environments is bound to increase as new areas in the tropics are being developed.

Sediments affect both the individual coral and the coral community. It can be determined if a reef is (or was) under stress due to siltation, by analysing the following: growth rates of the corals, amount of trapped sediments in the coral skeletons, live coral coverage, species composition and diversity, and coral morphologies.

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Bajo el mar ilumina el sol - extraña aurora!-
de abisinios corales el bosque enmarañado,
que en los tibios estanques de su seno ha mezclado
la bestia submarina con la viviente flora.

Y cuánto la sal tiñe, cuánto el yodo colora,
-anémonas, erizos, musgo aterciopelado,
algas-, el madrepórico lecho vermiculado
con suntuosos dibujos de púrpura decora.

Velando el vivo esmalte de su escama luciente,
cruza con indolencia la sombra transparente
enorme pez. Deslízase entre el ramaje, y luego

en el cristal inmóvil y azul choca su espalda
y hace correr, al golpe de su aleta de fuego,
un temblor de oro, de nácar y de esmeralda.

Jose María de Heredia
(1846-1905)

CHAPTER 1

INTRODUCTION

1.1 Importance of Reefs

1.1.1 Modern Reefs

Modern coral reefs are among the most diverse and productive ecosystems in the world (Stoddart, 1969; Newell, 1971; Connell, 1978). They constitute a major feature on the earth produced by organisms (Wells, 1969). The main organisms in modern reefs are the scleractinian corals and several groups of algae. In some reefs, the hydrozoan *Millepora* can be very prominent (Yonge, 1968, 1973; Goreau *et al.*, 1979).

Coral reefs are restricted to the tropical seas of the world. They develop best where the mean annual temperature ranges between 23-28^{o}C; in areas where the temperature goes below 18^{o}C there is no significant growth (Wells, 1956, 1957; Glynn and Stewart, 1973; Smith, 1976; Glynn, 1977). Salinity toleration limits for corals are between 25 and 40 o/oo. Fresh water has a detrimental effect on corals. Another environmental condition for coral growth is clear water (general reviews of reefs can be found in Yonge, 1968, 1973; Stoddart, 1969; Newell, 1972;

Goreau *et al.*, 1979). Hermatypic coral growth is restricted to the photic zone due to the contribution by symbiotic algae, called zooxanthellae. The presence or absence of these symbiotic algae is the criterion used to separate the corals into ahermatypes, without symbiotic algae, and hermatypes or reef formers, with symbiotic algae in the endodermis (Yonge, 1963, 1973).

Coral reefs are important in several ways to people who live along coasts. They have rich fishery resources (Stephenson and Marshall, 1974; Risk, 1981), they are important in the protection of the coast (Roberts *et al.*, 1975), and they are a valuable tourist attraction.

1.1.2 Fossil Reefs

Reefs evolved several times during geological history, each complex with a particular suite of plants and animals (Newell, 1971, 1972; Copper, 1974; Heckel, 1974; Wilson, 1975). Comparisons of different reef complexes seem to be difficult due to the change in organisms with time. If they are considered only as sediment producers, regardless of their classification, then they can be compared in general terms. Most fossil reef organisms have living equivalents in modern oceans that may belong to totally different phyla (James, 1978, 1979).

Fossil reefs may be economically important. Some stromatolite "reefs" of different ages are associated with important mineral deposits in several parts of the world (for a summary, see Mendelsohn, 1976). Fossil reefs, for example the Silurian reefs of the Great Lakes area, the Devonian reefs of Western Canada, the reefs around the Permian Basin of West Texas and New Mexico, the Golden Lane of México (Cretaceous) and the Cretaceous and Tertiary reef complexes of the Middle East, to mention just a few, are associated with considerable petroleum reserves. Some reefs are also rich in mineral deposits; for example, the northern edge of Presqui'ile Barrier Reef at Pine Point, on the southern shore of the Great Slave Lake, Northwest Territories, Canada, has important lead-zinc ore deposits. Also, upper Middle Triassic reefs in the Eastern Alps from Switzerland to Austria have considerable lead-zinc deposits (summary in Chapman, 1977).

1.2 Caribbean Reefs

1.2.1 General Introduction and History

To-day, coral reefs are divided into two provinces: 1) the Indo-Pacific, which extends from the east coast of Africa and the Red Sea, across the Indian Ocean, to the Pacific, all the way to the west coast of Central America, and 2) the Caribbean or Atlantic province, which extends from the east coast of North and Central America through the Caribbean Sea and the east coast of South America, to isolated outposts in western Africa (Wells, 1957, 1969;

Milliman, 1973; Laborel, 1974; Goreau *et al.*, 1979).

The first studies made on Caribbean reefs were concentrated around Florida, Bermuda and the Bahamas (Vaughan, 1915, 1916), which are noted for their marginal development. These initial studies introduced the concept that Caribbean coral reefs are inferior to their Indo-Pacific counterparts (see Wells, 1957). More recent investigations (Goreau and Wells, 1967; Glynn, 1973a) however, have suggested that, although reef growth in the Caribbean is accomplished by considerably fewer species than in the Indo-Pacific, growth rates and variety of reef types are comparable, as well as overall similarity in zonatión with depth (Dahl *et al.*, 1974; Risk *et al.*, 1980). The higher number of species in the Indo-Pacific province is partly due to the vast tropical expanse covered by reefs in the Pacific, in which more evolutionary divergence takes place than in the smaller Caribbean (Milliman, 1973). Also, the Caribbean province was isolated from the Pacific with the complete emergence of the Central American isthmus in the Pliocene (Dengo, 1973; Schmidt-Effing, 1980) and was subjected to more severe climatic conditions during the Pleistocene. During the Pleistocene, the Eastern Pacific coralline fauna was eliminated and what is found today is the product of transoceanic migrations (Glynn *et al.*, 1972; Dana, 1975; Heck and McCoy, 1978). The Caribbean corals are considered an impoverished relic of the Mid-Tertiary Tethyan sea fauna (Vaughan and Wells, 1943; Wells, 1956, 1957). This paucity of species is compensated for by the many different growth morphologies of most Caribbean species (Milliman, 1973; Macintyre and Smith, 1974).

The three main types of reef, atoll, barrier and fringing, are present in the Caribbean. The second biggest barrier reef in the world is the Belize-Yucatán complex. Most reefs around islands and along the coast in the Caribbean are of the fringing type. If an atoll is defined strictly as a geomorphic and not a genetic form, there are some ten atolls in the Caribbean (Glynn, 1973a; Milliman, 1973; Ladd, 1977; Miller and Macintyre, 1977).

1.2.2 Zonation and Species

Most Caribbean coral reefs have a zonation similar to the one described by Goreau (1959a) for Jamaica. Each zone is characterized by a series of scleractinian corals, other cnidarians and algae, and by the average depths. From inshore towards offshore, the zonation described by Goreau at Ocho Rios, Jamaica, is as follows: beach, lagoon with patch reefs (average depth 2-5 m), reef flat (0.5-3 m), crest or *palmata* zone (0.5-6 m), buttress zone (1-10 m), *cervicornis* zone (7-15 m), *annularis* zone (over 15 m). Below 50 m to 105 m, the primary framework constructors on the Jamaican fore-reef are the sclerosponges (Lang *et al.*, 1975).

The basic pattern is not constant. For example, in St. Croix, Virgin Islands, the crest is an incipient algal ridge (Adey *et al.*, 1977). In some reefs in San Blas, Panama, the main coral on the reef crest is *Agaricia agaricites* (Robertson and Glynn, 1977), while in San Andrés, Colombia, it is *Millepora complanata* (Geister, 1973). Some of the reefs at San Blas do not have a well developed lagoon (Robertson and Glynn, 1977); and part of the reef at Grand Cayman has a large lagoon (Roberts, 1977). The zonation of some reefs seems to depend on wave exposure (Roberts, 1974; Geister, 1977).

The Caribbean province has fewer scleractinian species (about 75 species and 35 genera), than the Indo-Pacific province, which has about 1000 species and 85 genera (Wells, 1956, 1969, 1973; Goreau and Wells, 1967). Jamaican reefs have the most scleractinian species in the Caribbean (Wells, 1973); which coincides with the area in the Caribbean with the highest mean temperature (Stehli and Wells, 1971). It also is the area where there has been the largest concentration of workers. The following six genera of scleractinian corals, *Acropora*, *Montastrea*, *Porites*, *Diploria*, *Siderastrea* and *Agaricia*, plus the hydrozoan *Millepora*, are present in almost all reefs in the Caribbean

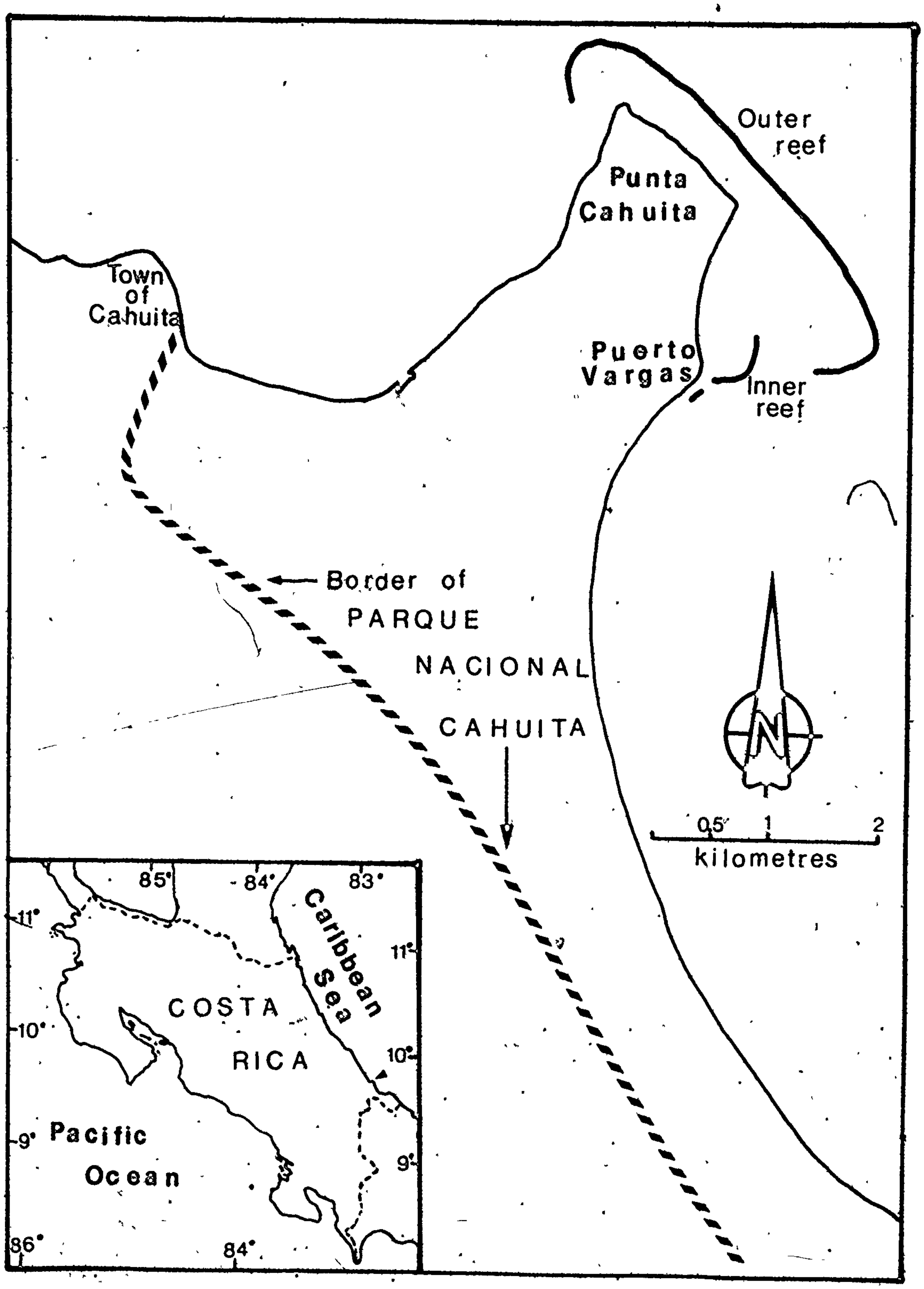
(Milliman, 1973). The dominant scleractinian species in Jamaica and in most Caribbean reefs is *Montastrea annularis* (Goreau, 1959a; Milliman, 1973; Dustan, 1975). In other reefs, for example on the Florida Reef Tract, the main coral is *Acropora palmata* (Shinn, 1963; Milliman, 1973). The most complete lists of corals from the Caribbean are found in Goreau and Wells (1967), Wells (1973) and Smith (1976).

1.3 Cahuita Reef

1.3.1 Importance of this Reef

Cahuita coral reef is located on the Atlantic coast of Costa Rica, Central America (9^{o} 45' N - 82^{o} 48' W). The reef is in the "Parque Nacional Cahuita" created by Executive Decree No. 1236-A on September 24, 1970 (Fig. 1-1). It consists of 1,100 hectares of land and 600 hectares of reef. This is the only well developed reef on the Caribbean coast of Costa Rica (Tosi, 1975; Boza, 1978). Many people from the towns of Cahuita and Hone Creek fish on the reef. During holidays and vacations several hundreds of persons visit the Park per week. Many schools from different parts of the country and several classes from the universities go to the Park at least once a year. It is an important educational centre not only for the students but for the general citizen.

FIGURE 1-1 Map of Parque Nacional Cahuita showing the reefs and location in Costa Rica.


Outer reef
Punta Cahuita
Town of Cahuita
Puerto Vargas
Inner reef
Border of PARQUE NACIONAL CAHUITA
0.5
1
2
kilometres
85°
84°
83°
11°
10°
9°
86°
84°
Caribbean Sea
COSTA RICA
Pacific Ocean

1.3.2 Previous Work

The first reference to the reef at Cahuita, as far as the author knows, was by Henri Pittier (1912 *fide* West, 1964). He was a keen naturalist who lived in Costa Rica for many years. The next reference to this area is in 1920, when drilling for oil started at Cahuita Point: "The nature of the ground made drilling slow and expensive. Gas which was encountered at a depth of 825 feet caught fire on April 24, 1921, and destroyed the derrick and part of the equipment and tools. At the end of 1921 the well had reached a depth of 3,146 feet and had cost $303,273 including a loss of $25,000 due to the fire. By use of the diamond drill, the well was completed late in 1922 at a depth of 3,800 feet, without finding oil in commercial quantities" (Redfield, 1923, p. 378).

After that fiasco, there are no reports from Cahuita until 1969 when several descriptive reports were written to evaluate the zone for the creation of a National Park (Lemieux, 1969; Miller, 1969). Two years after the creation of Cahuita National Park, Wallis (1972) provided more descriptions of the area and plans for future development of the Park. The first extensive ecological description of the reef was by Wellington (1974). Tosi (1975) described adjacent areas as well as other reefs farther south from Cahuita, in a study conducted in order to increase the area of the Park.

During the 1970's extensive collections were made by scientists from the Universidad de Costa Rica and by naturalists of the National Park Service. These collections are mainly used for teaching and information to be given to the Park visitors. The spatial distribution, correlation with substrate and degree of aggregation of the sea urchin *Diadema antillarum* from Cahuita was described by Valdez and Villalobos (1978). Risk et al. (1980) give a detailed description of various reef habitats represented in the Park, with notes on the boring sponges.

1.3.3 Description of the Reef

Cahuita is a fringing reef; the main crest runs from northwest to southeast (Fig. 1-1). It starts as an arc on the northern tip of Punta Cahuita, then it goes straight to the southeast for a distance of 4 km, being at this point farthest from the shore (800-900 m). Here it turns towards Puerto Vargas. In front of Puerto Vargas there is a small crest about 100 m from the shore that extends for 500 m. There is another small crest (200 m long) in front of the beach at Puerto Vargas. In the lagoon there are several small patch reefs.

Starting on the north of the external reef (Fig. 1-2) there are well developed buttress but they consist mainly of

FIGURE 1-2 Detailed map of the Cahuita reefs indicating the different zones.

A.- External reef;

B.- Inner reef;

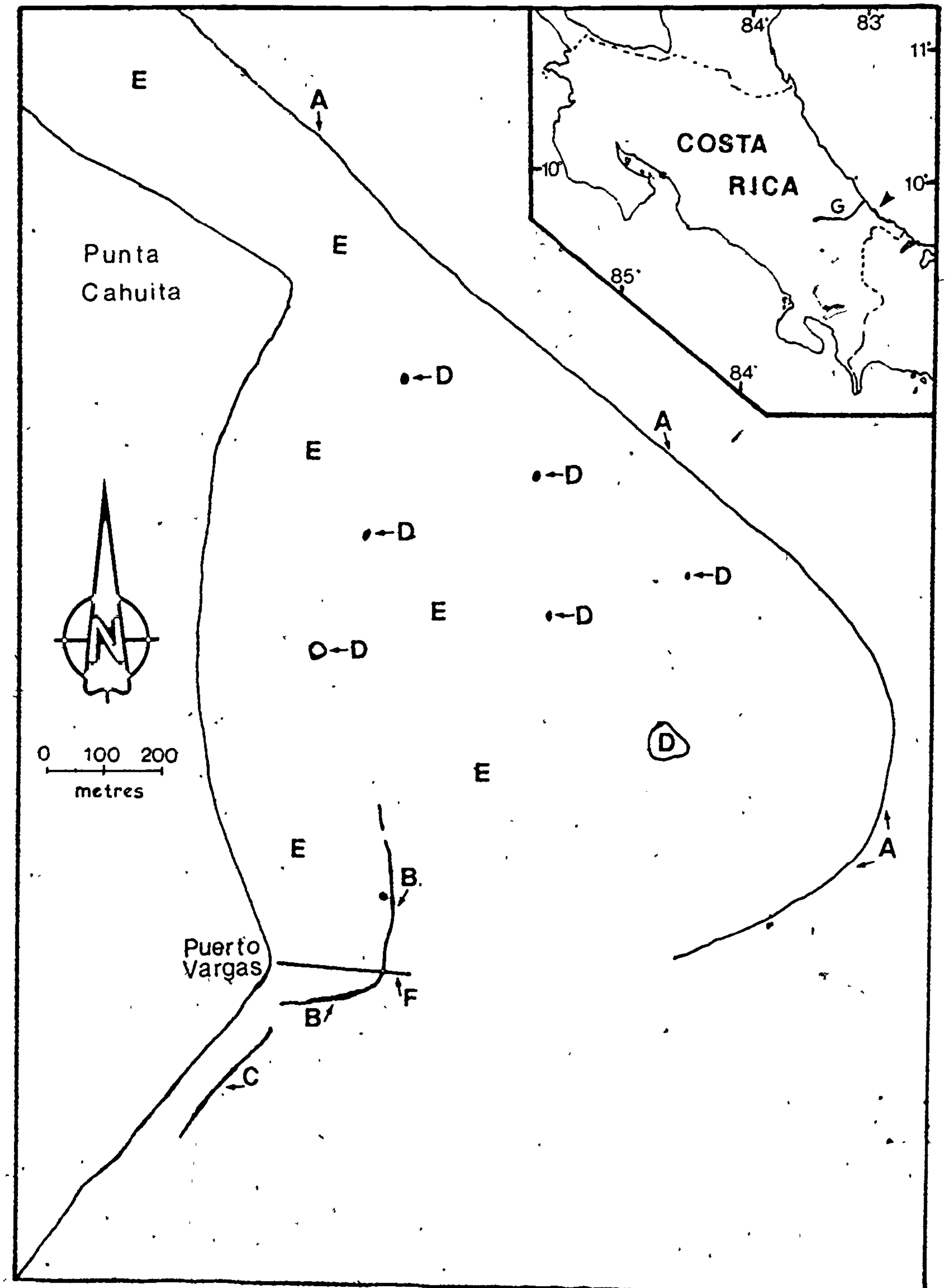
C.- Crest in front of the beach;

D.- Patch reefs;

E.- Lagoon;

F.- Transect (see Figure 3-8);

G.- Río La Estrella (inset).


E
A
Punta
Cahuita
E
D
E
D
D
D
E
D
D
D
0 100 200
metres
E
E
B.
Puerto
Vargas
F
B
C
A
A
COSTA
RICA
G
84°
83°
11°
10°
10°
85°
84°

dead coral covered with algae. In this zone there are small isolated heads of live coral: *Diploria clivosa, Colpophyllia natans, Siderastrea radians, Montastrea cavernosa, Porites astreoides* and the hydrozoan *Millepora complanata.* Big sea fans (*Gorgonia flabellum*) were observed in this area. Continuing toward the south there is more live coral. Where the crest bends towards Puerto Vargas, some rare species have been observed, for example, *Acropora cervicornis, Favia fragum, Isophyllia multiflora, Isophyllia sinuosa, Astrangia solitaria* and the hydrozoan *Stylaster roseus.*

The inner reef located in front of the house used by the Park Service at Puerto Vargas (Fig. 1-2) has the largest amount of live coral. Here, the following species are abundant: *Acropora palmata, Agaricia agaricites, Colpophyllia natans, Siderastera radians, Siderastrea siderea, Porites porites, Porites astreoides, Porites furcata, Diploria clivosa* and *Diploria strigosa. Agaricia agaricites* forma *danai* covers extensive areas between 3 and 5.5 m. Some less abundant species are: *Colpophyllia breviserialis, Montastrea annularis, Montastrea cavernosa* and *Porites divaricata.* Some rare species are *Mussa angulosa, Cladocora arbuscula, Eusmilia fastigiata, Dichocoenia stellaris, Dichocoenia stokesi, Madracis decactis, Madracis mirabilis, Stephanocoenia michelini, Agaricia fragilis, Helioseris cucullata, Solenastrea bournoni, Oculina diffusa,* *Mycetophyllia danaana* and *Mycetophyllia lamarckiana*. The biggest corals at Cahuita were observed at the base of the inner reef (4-6 m). There are heads 2-3 m in diameter of *Colpophyllia breviserialis*, *Siderastrea siderea*, *Colpophyllia natans*, heads of 1 m of *Montastrea annularis*, *Stephanocoenia michelini* and *Diploria strigosa*; plus one single colony of *Dichocoenia stellaris*, 0.75 m in diameter. In this general area, several hemispherical clusters, 0.5 m in diameter, of dead *Mussa angulosa* were observed. Individuals up to 25 cm long are found in life position. Live *Mussa* is rare and isolated, indicating that this species was more abundant in the past.

The small crest in front of the beach at Puerto Vargas (Fig. 1-2) has not been described before. There are poorly developed buttresses on the offshore side of the crest. Algae cover most of this small crest, being very abundant two species of *Caulerpa* and one of *Halimeda*. The crest is at a depth of 0.5 m and the base of the barrier lies at 3 or 4 m. The following corals were observed: *Siderastrea radians*, *Siderastrea siderea*, *Diploria clivosa*, *Porites astreoides*. There is also a large quantity of sea fans (*Gorgonia flabellum*) and other Gorgonians.

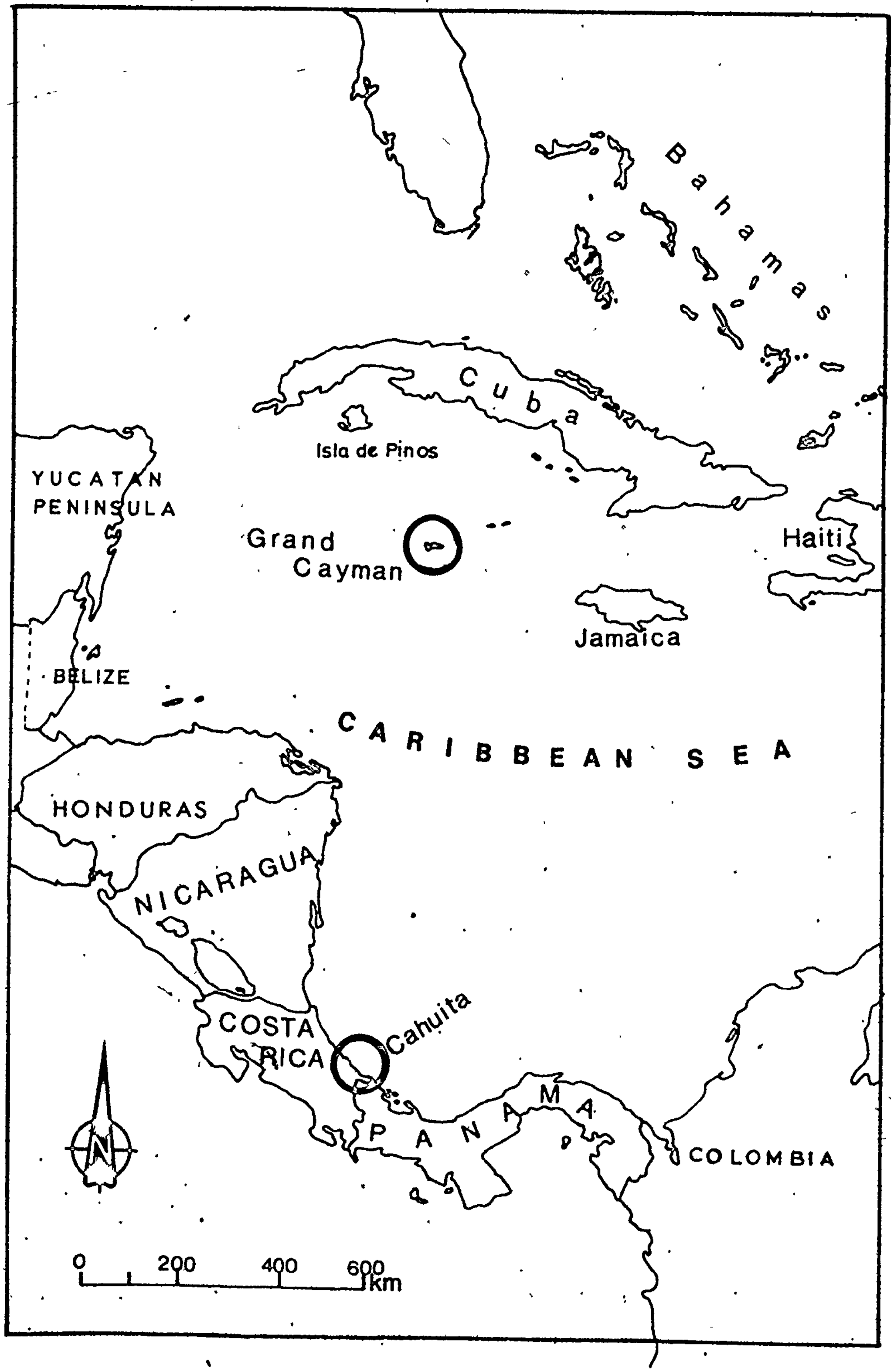
The patch reef in the lagoon (Fig. 1-2) varies in composition, from isolated heads to clusters 15 to 20 m in diameter, with many different species. The bottom of the lagoon is covered mainly by dead coral and sand. There are extensive beds of the sea-grasses *Thalassia testudinum* and *Siringodium filiforme*. The large patches have many colonies of *Acropora palmata, Diploria strigosa* and sea fans.

Previous workers (Wellington, 1974; Risk et al., 1980) have commented on the large concentrations of suspended sediments at Cahuita. The reef has low coral diversity and live coral coverage, and has extensive areas of dead coral covered by algae. High suspended sediment concentrations may be the cause.

1.4 Grand Cayman

The reef at Grand Cayman, British West Indies was studied in order to have a point of comparison with the Cahuita reef. Grand Cayman is the largest of the three Cayman Islands, located 240 km south of Isla de Pinos, Cuba, 280 km north north-west of Jamaica, and 480 km northeast of Honduras. The island is situated between 19° 16' and 19° 24' N, and 81° 05' and 81° 25' W (Fig. 1-3 and Fig. 1-4). Its dimensions are approximately 35 km east-west and 6 to 15 km north-south. Grand Cayman is a very flat island; the highest point is 18 m above sea level while most of the rest is less than 3 m above sea level. It is entirely limestone-

FIGURE 1-3 Map of part of the Caribbean showing the areas studied: Cahuita, Costa Rica, and Grand Cayman, B. W. I.


Bahamas
Cuba
Isla de Pinos
YUCATAN PENINSULA
Grand Cayman
Haiti
Jamaica
BELIZE
CARIBBEAN SEA
HONDURAS
NICARAGUA
COSTA RICA
Cahuita
PANAMA
COLOMBIA
N
0 200 400 600 km

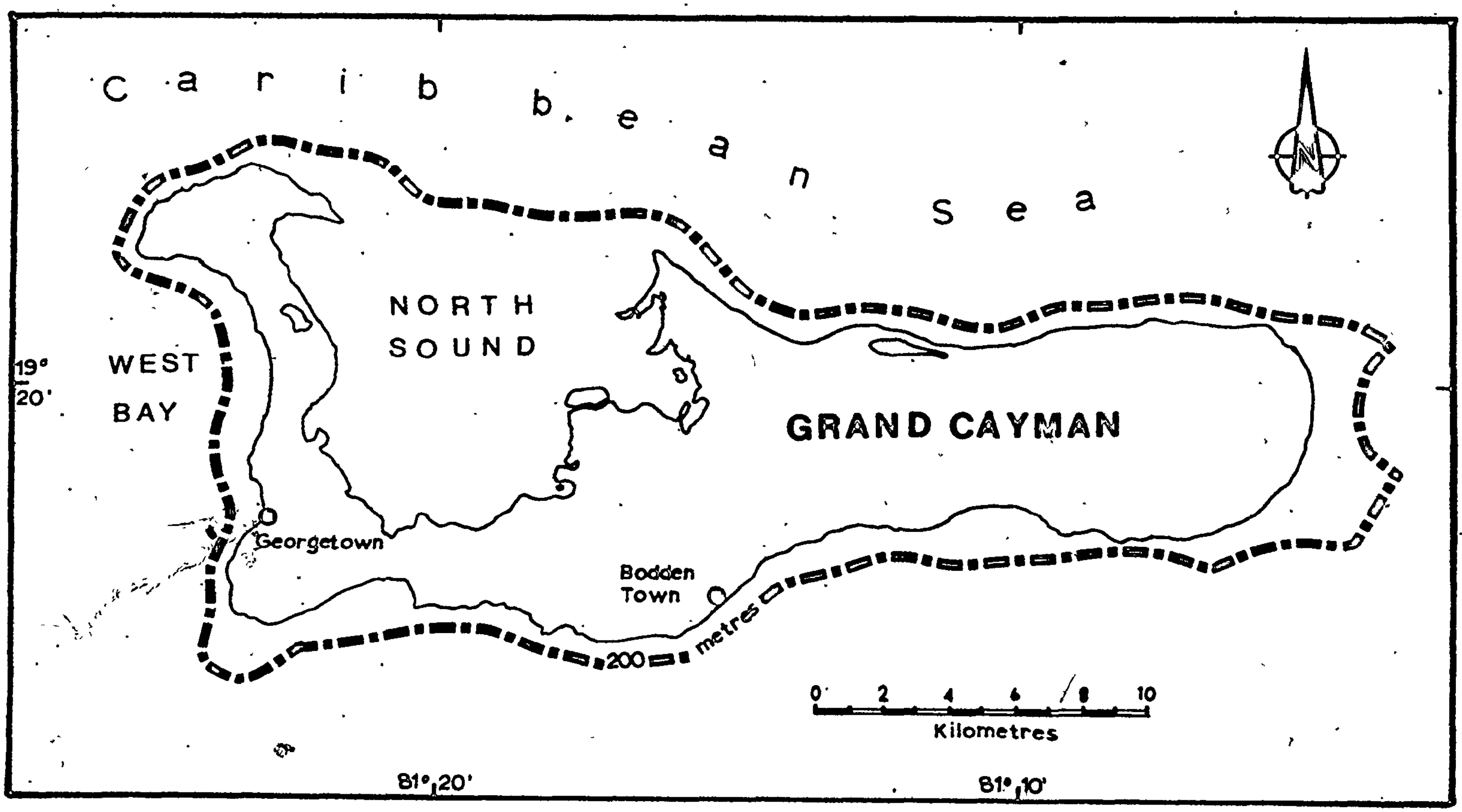


Figure 1-4 Map of Grand Cayman, B. W. I.

capped; all surface exposures are relatively young (Rigby and Roberts, 1976; Roberts, 1977).

The water at Grand Cayman is remarkably clear; air photographs show a lot of detail down to 30 m. The tides are mixed diurnal and semidiurnal with an average range of 23 cm. Salinity ranges from 35 to 38 o/oo (parts per thousand) and air temperatures range from 23.9°C to 33.3°C, with a winter average of 25.2°C and a summer average of 28.6°C. The amount of precipitation is around 1740 mm (45 years average) (Rigby and Roberts, 1976). Shallow fringing reefs surround the island on the north, east and south where the wave-power levels are high. On the west the wave power levels are very low, and deep fringing and patch reef development occurs. There is a shallow terrace at approximately 8 m that can be traced around the entire island. A deeper terrace occurs at about 20 m. Buttresses are well developed on the sides exposed to strong waves (Roberts, 1974; Roberts *et al.*, 1975).

The reef at Grand Cayman is healthy, the amount of suspended sediments is negligible and the number of different coral species is high. It is an ideal reef for baseline data since there are very little, if any, terrigenous sediments.

1.5 Scope and Objectives

The problem of siltation in corals is extensively discussed by Johannes (1972, 1975). This is a problem bound to increase as new areas are being developed in the tropics. Poor land management for residential or agricultural use, dredging, drilling for oil or gas, and deforestation of the watershed are the main sources of sedimentation. Destruction or coral reefs in various localities have been reported, for example, Australia (Stephenson *et al.*, 1958); Puerto Rico (Kaye, 1959; Loya, 1976); India (Pillai, 1971); Hawaii (Johannes, 1972, 1975); Bermuda (Dodge and Vaisnys, 1977); and Venezuela (Weiss and Goddard, 1977).

Even though corals can clean themselves of sediments (Hubbard and Pocock, 1972; Hubbard, 1973; Bak and Elgershuizen, 1976), it is generally accepted that sediments have detrimental effects on corals:

a) growth rate decreased (Aller and Dodge, 1974; Dodge *et al.*, 1974; Dodge and Vaisnys, 1977);

b) death of colonies under the sediments (Bak, 1978; Thompson, 1979);

c) changes in the coral community (Loya, 1976; Dryer and Logan, 1978);

d) reduction of the area covered by live corals

(Roy and Smith, 1971; Loya, 1976);

e) depressed coral recruitment (Rogers, 1977; Sammarco, 1980).

In this work, the detrimental effect of sediments on the corals and the coral community of Cahuita, Costa Rica, will be evaluated. This information will be useful as an argument for protection of virgin forest in the Caribbean low lands of Costa Rica. Recently, with the construction of roads in the south eastern portion of the Province of Limón, forests are being cut down; in this regard, there is very little management or control, with the end result of complete erosion. The harmful effects of erosion are not only felt at the mountain sides, but also farther down, in the sea. Elimination of the reef would mean loss of an important source of food, recreation and educational ground.

CHAPTER 2

METHODOLOGY

2.1 Suspended Particulate Matter

The amount of suspended particulate matter (S.P.M.) was determined by filtration in the field (Fig. 2-1). Samples of one litre of water were taken in different parts of the reef during the first field season. Afterwards, areas of particular interest were chosen and sampled regularly during the study. The Río La Estrella, a large river north of the reef, was also sampled (Fig. 2-2). These water samples were taken with a wide-mouth plastic bottle (Nalgene, 1 litre). The samples were filtered using pre-weighed Millipore filters (0.45μ, 47 mm). An approximately 0.001 M solution of sodium azide (NaN_3) was used to poison the samples and thus prevent the decomposition of organic matter. The filters were oven dried at 45^0C for six hours, cooled down and then reweighed. The difference in weight of each filter is the S.P.M. load. These filters were kept for further mineral analysis by X-ray diffraction (Section 2.7) and for Scanning Electron Microscope (SEM) observation.

FIGURE 2-1 Filtering water samples in the field. Cahuita, Costa Rica.

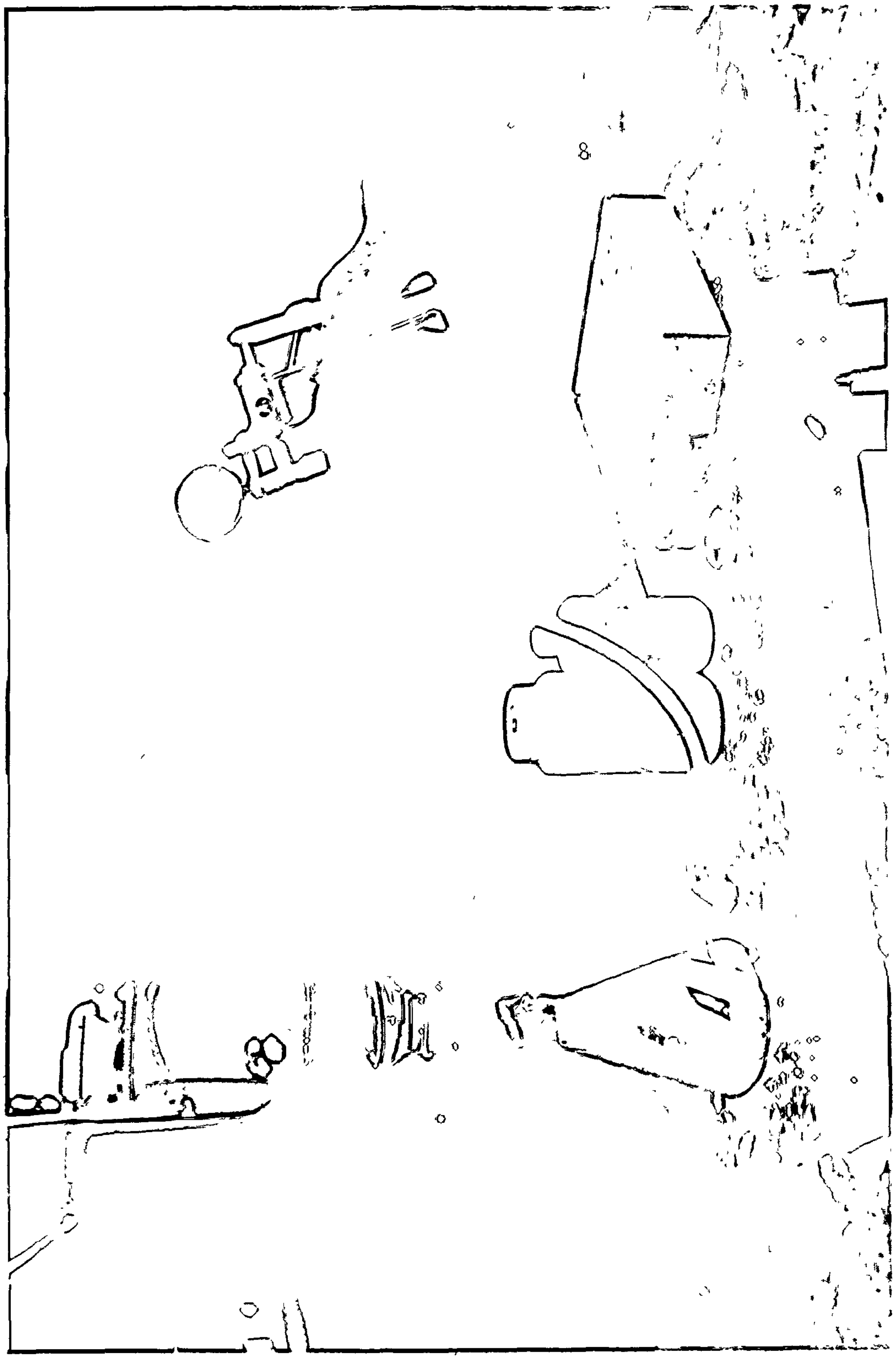
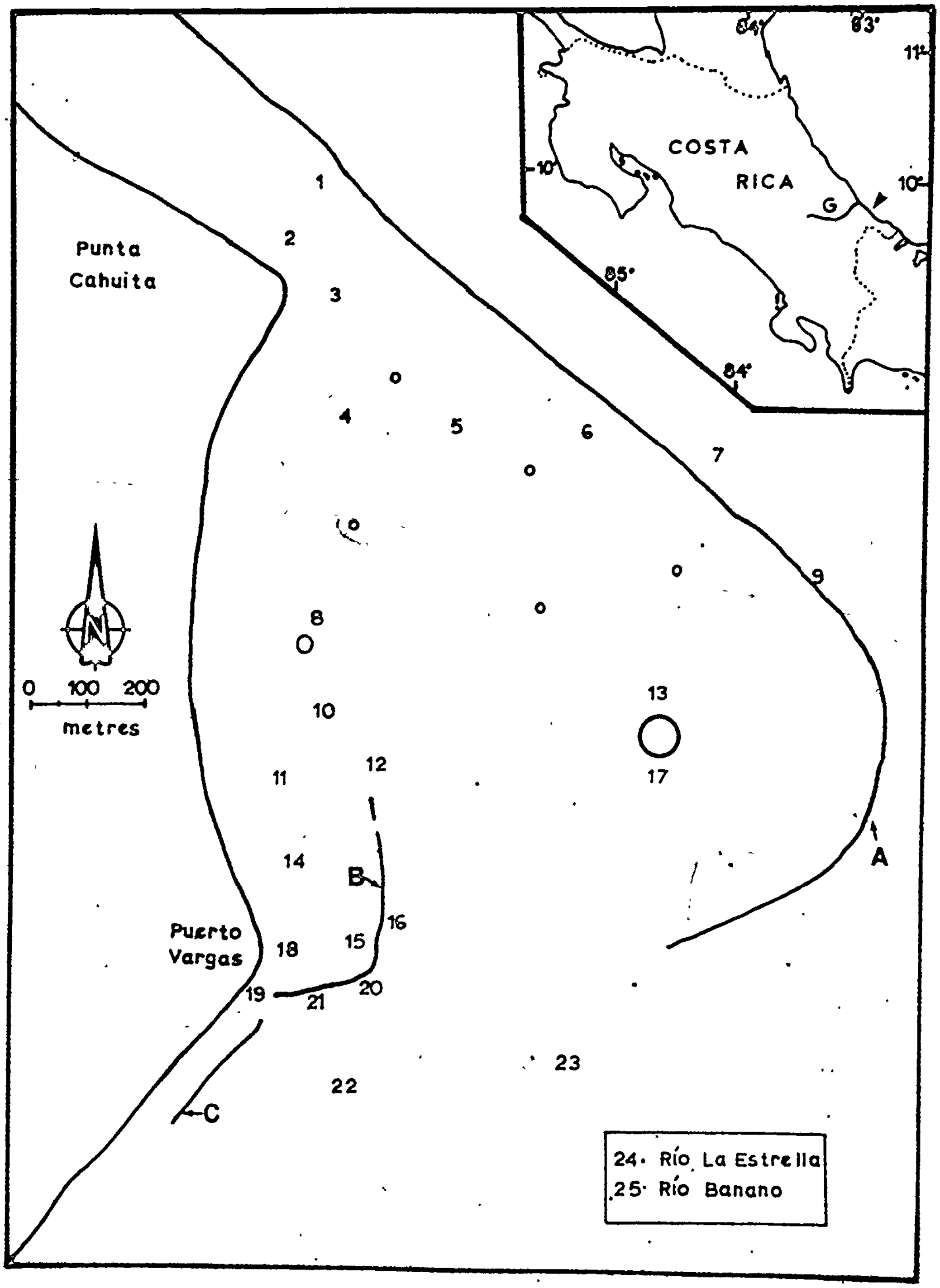


FIGURE 2-2 Location of sampling sites for suspended sediments at Cahuita Reef. A, B, C, and G as in Figure 1-2.


COSTA
RICA
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84°
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11°
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Punta
Cahuita
Puerto
Vargas
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22
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A
B
C
24. Río La Estrella
25. Río Banano

2.2 Resuspension of Sediments

After the first field season and a short Christmas visit (1979), it became apparent that the resuspension of bottom sediments was very important. For the second field season, traps similar to the ones described by Young and Rhoads (1971) were made (Fig. 2-3). The shape of the trap was that of an equilateral prism, 40 cm by 75 cm high. They were anchored to the bottom with guy lines from its corners. The 1 litre Nalgene bottles used had an opening of 21.23 cm^2. The lower bottles were 25 cm from the substrate, the next ones were at a height of 50 cm and the top ones at 75 cm. These bottles were held in position using thick rubber bands. This proved to be a very cheap and effective method for placing and removing the bottles. The sediments trapped in the bottles were recovered by filtering the water on pre-weighed paper filters (Whatman No. 1, 12.5 cm). The sediments were washed with some distilled water and poisoned (either NaN_3 or buffered formaldehyde) to remove salt and to prevent organic decomposition. Filters were dried for six hours at 45^0C, cooled down and re-weighed. They were kept for mineral analysis (Section 2.7) and for visual inspection.

Five sediment traps were stationed around the reef (Fig. 2-4); two in the lagoon, one on the inner reef crest, one on the upper fore-reef and one on the lower fore-reef.

FIGURE 2-3 Traps used for determination of resuspended sediments. The ruler shown is 50 cm long.

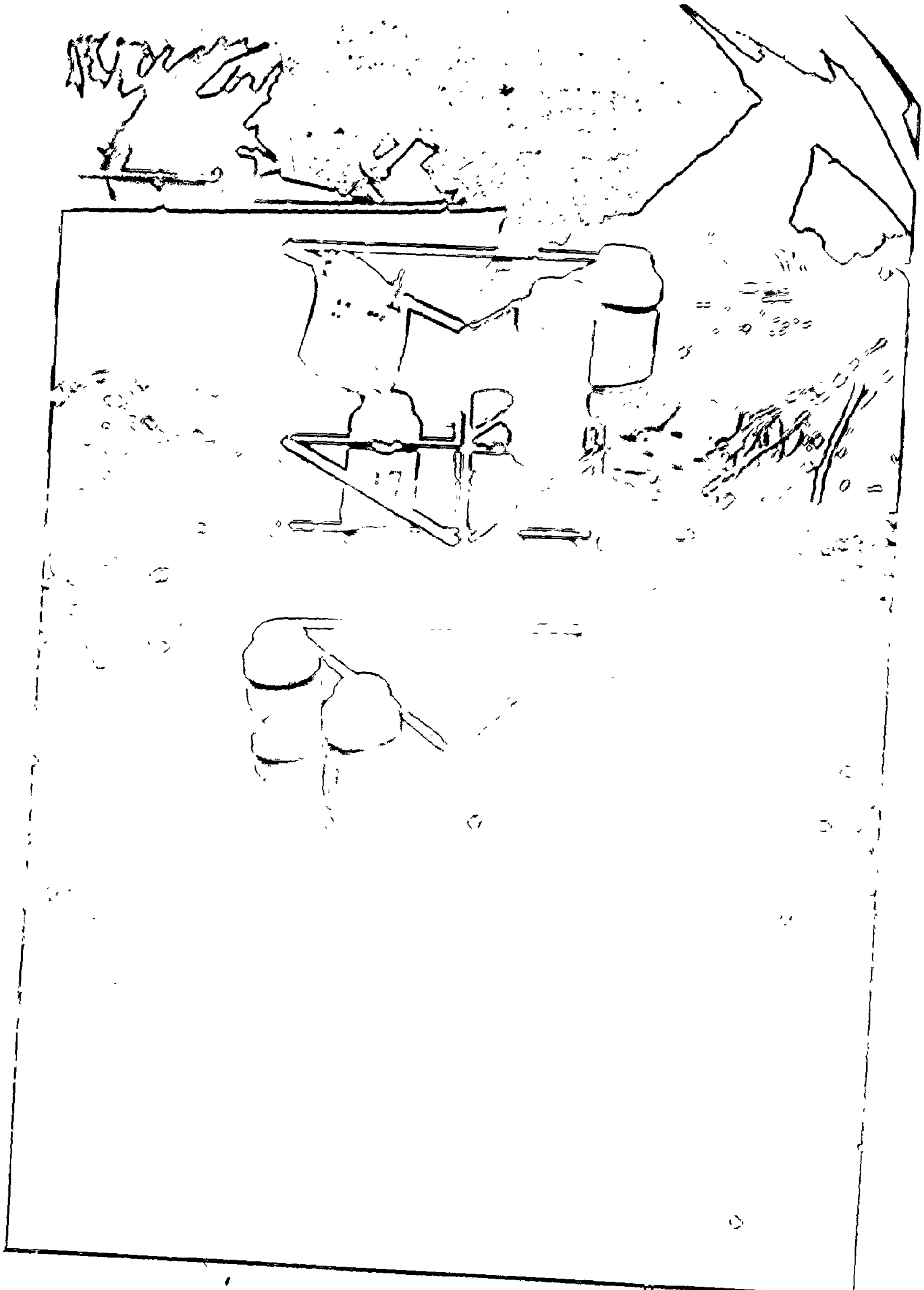
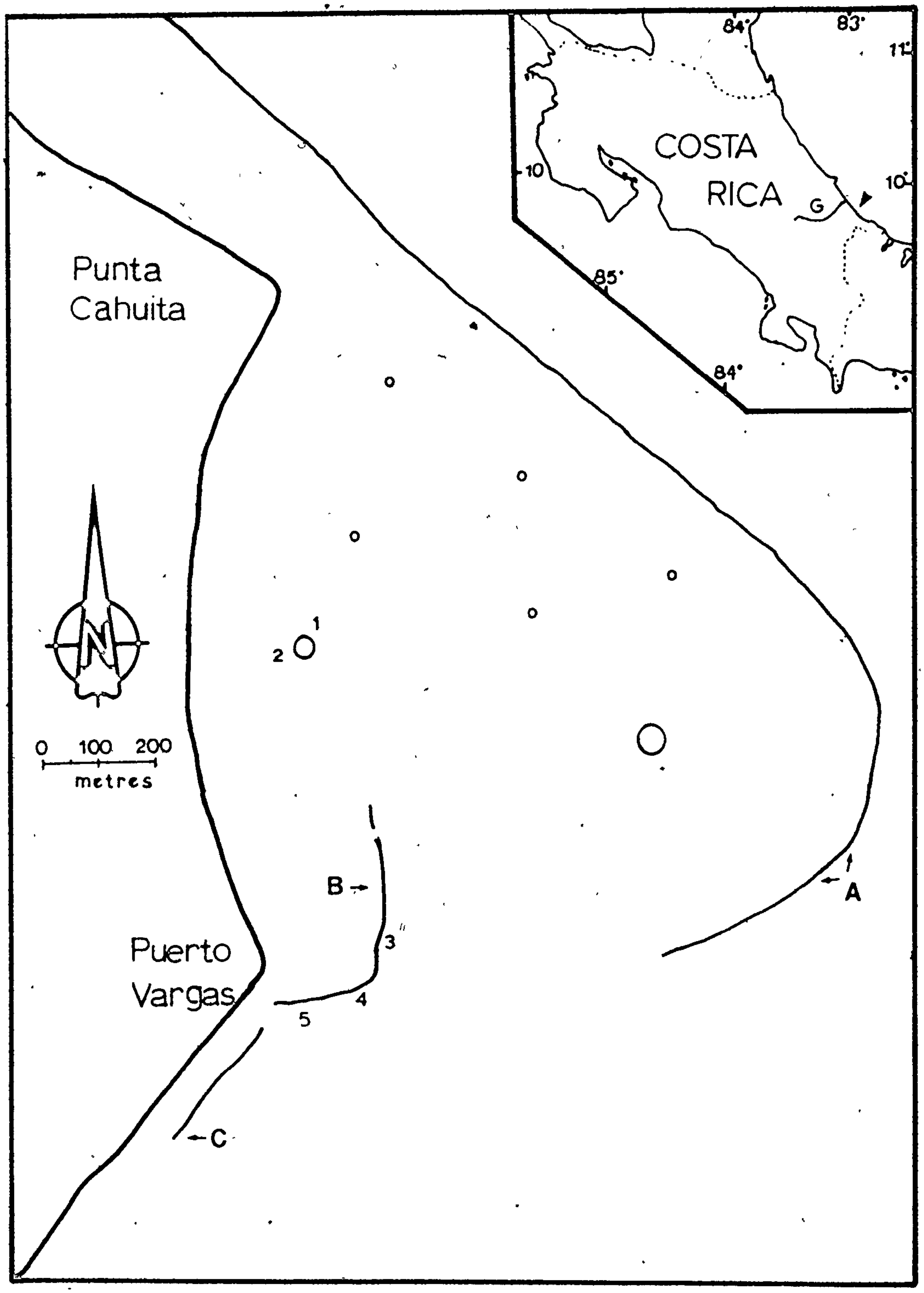


FIGURE 2-4 Position of the sediment traps at Cahuita. A, B, C and G as in Figure 1-2.


COSTA
RICA
84°
83°
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10°
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G
Punta
Cahuita
0 100 200
metres
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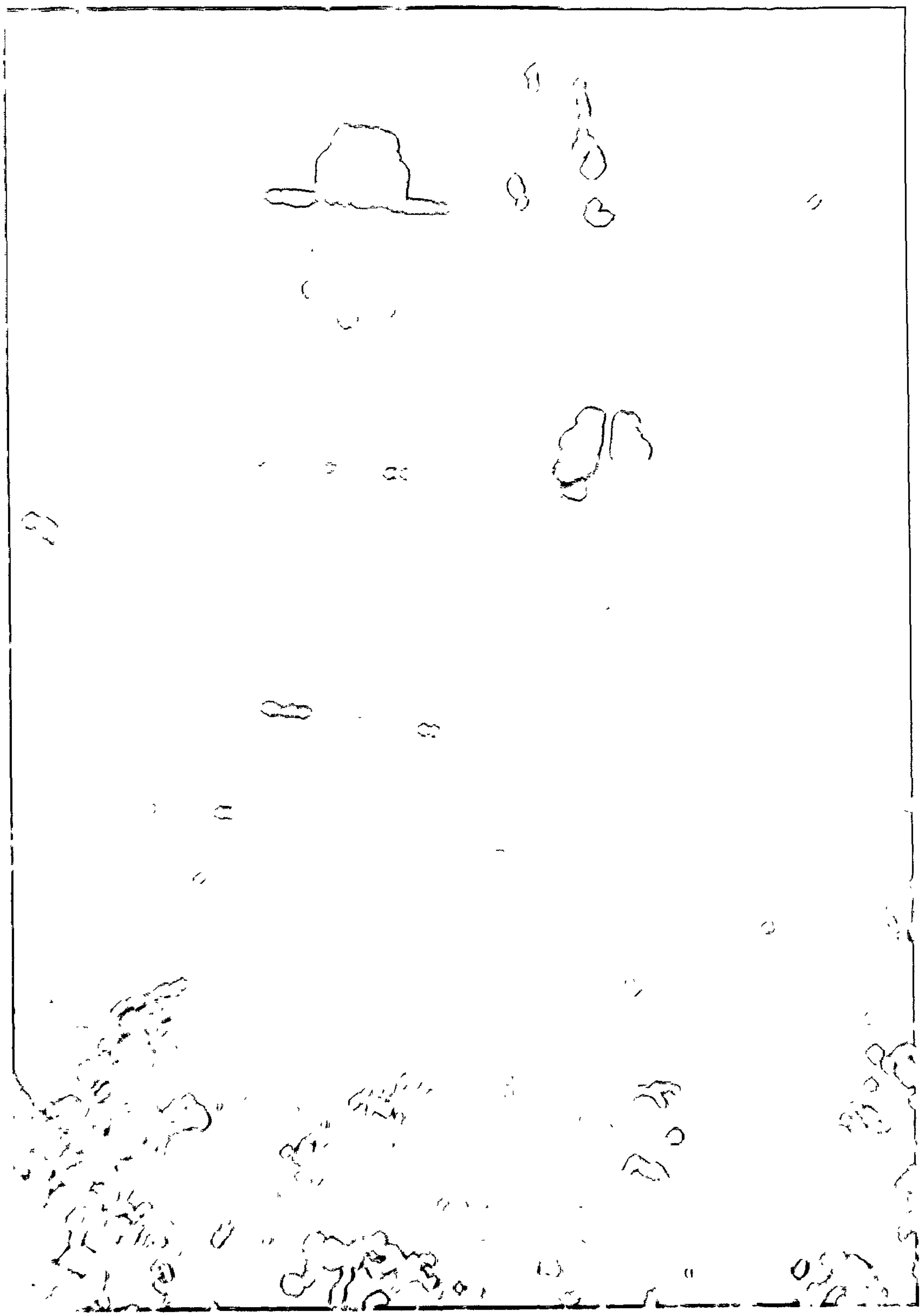
2
B
3
4
5
Puerto
Vargas
A
C

Trap 1 was on the windward side of a patch reef in the lagoon, at a depth of 2 m. The bottom was covered by coral fragments. Next to it was a patch reef with the following corals: *Acropora palmata*, *Diploria strigosa*, sea fans and small heads of *Siderastrea radians*, *Siderastrea siderea* and *Montastrea annularis*. Many filamentous algae were growing on the trap a week after it was placed. Trap 2 was located in 1 m of water on the leeward side of the patch reef described above. Trap 3 was near the crest of the inner reef (Fig. 2-5) in 1 m of water. It was placed over *Porites porites* and was next to *Acropora palmata* and a large head of *Colpophyllia natans*. Few algae grew on the trap after the first week under water. Trap 4 was on the upper fore-reef at a depth of 1.5 m, over dead coral and small colonies of *Porites porites*, *Agaricia agaricites*, *Porites astreoides* and *Millepora complanata*. Two weeks after it was set, corals were growing on the trap's frame. Trap 5 was placed on the lower fore-reef at a depth of 2.5 m. It was surrounded by live coral: *Siderastrea siderea*, *Siderastrea radians*, some *Agaricia agaricites* and *Porites porites*. There was a thin layer of fine sediments over the bottom.

The amount of sediment lost by resuspension inside the bottles was not measured but observation made underwater did not show appreciable amounts of sediments coming out of the bottles.

FIGURE 2-5 Trap # 3 near the crest of the inner reef, Cahuita. Depth is about 1 m.



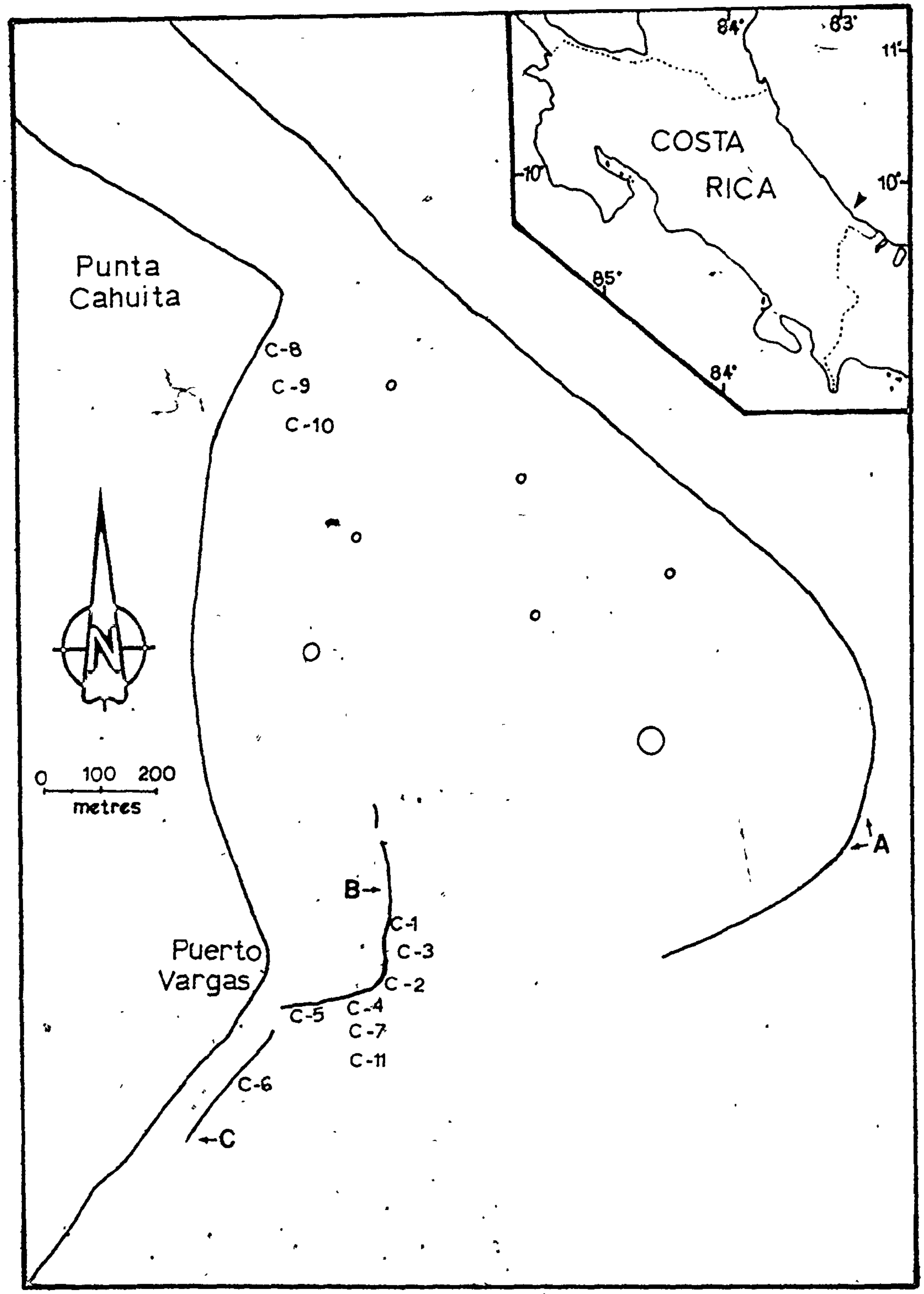
The first time the traps were used, the bottles were left for several days. The amount of sediments accumulated was high and there was algal growth in the bottles. From then on, the bottles were left only for one or two days, in order to prevent losses by resuspension and to avoid the abundant algal growth.

Laboratory and field evaluation of many different sediment traps showed that cylinders with a height to width ratio between 2 and 3 are very efficient in still and moving waters (Gardner, 1980a, 1980b). The bottles used here have a H/W ratio a little over 3.

2.3 Bottom Sediments

Samples of bottom sediments from different parts of the reef (Fig. 2-6) were taken by hand. The general appearence and consistency were recorded. The sediments were dried for transportation to Canada. In order to determine the amount of organic matter and the percentage of insoluble matter, part of the sample was dried and weighed. Subsequently, it was treated with 10% H_2O_2 until the bubbling stopped (after one to two hours), subsequently 20% and 30% H_2O_2 were added. More than 24 hours later, they were dried and weighed; the weight difference represents the amount of organic matter. The following step was to treat the samples with diluted HCl, to dissolve the calcium carbonate. Once the activity stops, that is, once no more

FIGURE 2-6 Location of bottom sediment samples at Cahuita. A, B, and C as in Figure 1-2.



COSTA
RICA
84°
83°
11°
10°
10°
85°
84°
Punta
Cahuita
C-8
C-9
C-10
0 100 200
metres
B
C-1
C-3
C-2
C-4
C-7
C-11
C-5
Puerto
Vargas
C-6
C
A

bubbles from the dissolving $CaCO_3$ are evident, the samples are filtered on pre-weighed paper filters (E-D Laboratory Filter Papers No. 613, 25 cm). The change in weight is the insoluble part in dilute HCl.

The other part of the sample that was not treated was visually examined. The constituents of the carbonate fraction were identified. The non-carbonate fraction was analysed by X-ray diffraction (Section 2-7).

2.4 Coral Samples

2.4.1 Collecting

Different species of live corals were collected in several places of the reef and at different depths (Fig. 2-7 and Table 2-1). These coral samples were used for several analyses: growth rates (Section 2.4.2), trapped sediments (Section 2.4.3), SEM observation and for geochemical analyses (Section 2.7). The coral samples were collected in two ways: a) with a pneumatic hand drill (Armstrong-Whitworth -Pneumatic Tools- Ltd., Model 7495 W), with a 2.5 cm wide by 10 cm long drill bit; b) with a rock saw, hammer and chisel.

The pneumatic hand drill method is slow but convenient because the damage caused to the corals is reduced to a small area. The drill was connected to the first stage of a SCUBA regulator which in turn was connected to a 72 cu. ft. aluminum SCUBA tank. Three

FIGURE 2-7 Locations where the live coral samples were collected at Cahuita. A, B, and C as in Figure 1-2.

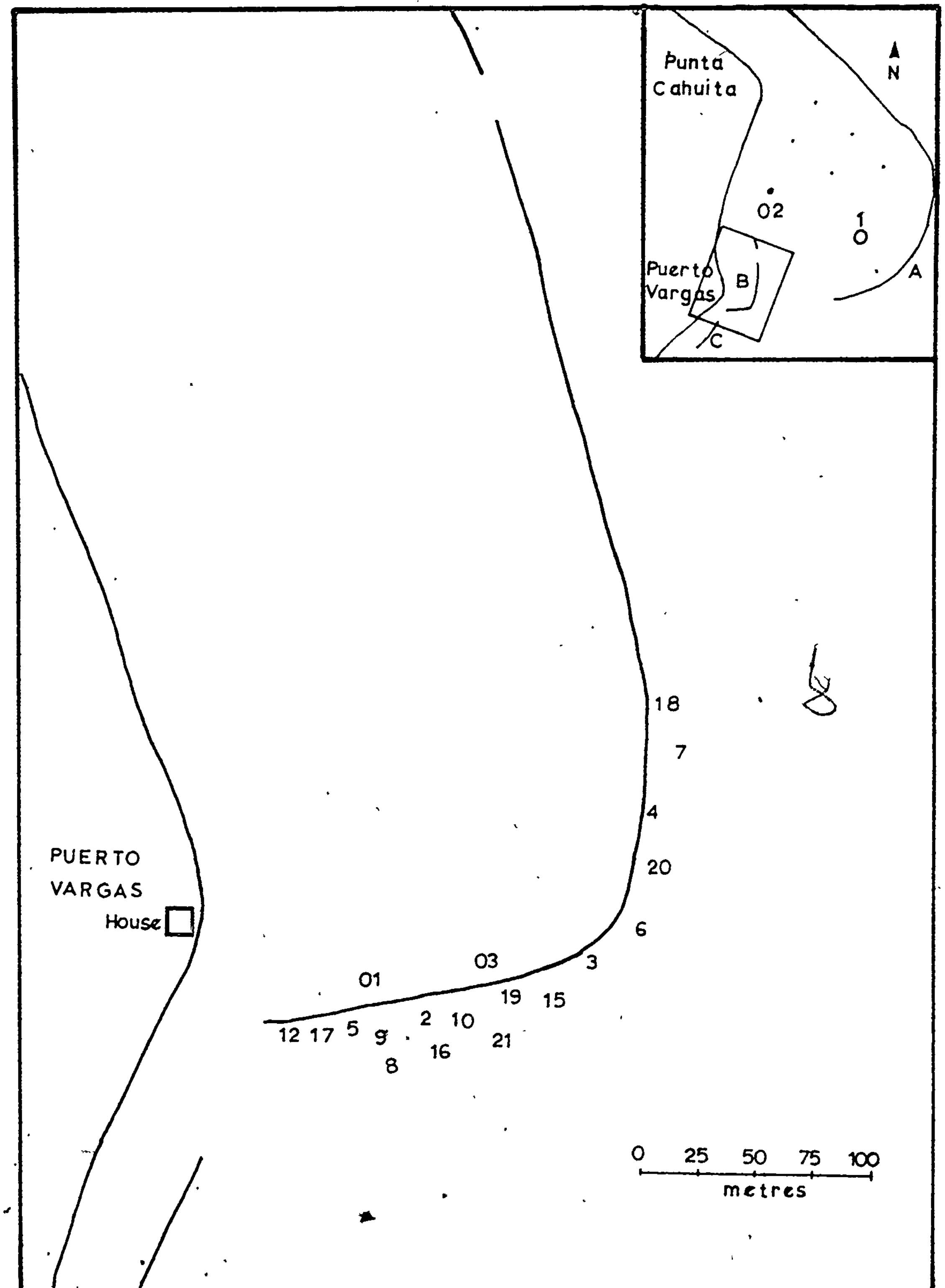

Punta
Cahuita
N
02
1
A
Puerto
Vargas
B
C
18
7
4
20
6
3
03
01
19
15
12 17 5 9
2 10
16
21
8
PUERTO
VARGAS
House
0 25 50 75 100
metres

TABLE 2-1 Coral samples from Cahuita and Grand Cayman*

For location of samples see Figure 2-5.

Sample #	Species[1]	Depth (m)	Sample #	Species[1]	Depth (m)
01	S.r.	1.5	12	S.r.	2
02	S.r.	1.5	15	S.m.	4
03	S.r.	1	16	S.r.	4
1	M.a.	2	17	S.r.	2
2	S.r.	3	18	S.r.	1
3	S.r.	4	19	S.r.	3
4	D.s.	2	20	S.r.	1
5	D.s.	2	21	S.r.	5
6	S.r.	4	*GC-1	D.s.	3
7	S.r.	4	*GC-2	D.s.	3
8	S.r	5	*GC-3	S.s.	3
9	D.s.	4	*GC-4	S.s.	3
10	S.s.	2	*GC-5	S.r.	3

[1] S.r.: *Siderastrea radians*
S.s.: *Siderastrea siderea*
M.a.: *Montastrea annularis*
D.s.: *Diploria strigosa*
S.m.: *Stephanocoenia michelini*

problems were encountered while using this drill:

1) The drill rusted very fast; even after washing it thoroughly and keeping it in diesel fuel, it had to be opened every week for cleaning and lubrication.

2) The drill used the air very fast; a full tank was good only for two or three cores.

3) Finally, care must be taken in order to drill parallel to the corallites (Fig. 2-8). If this is not done, it will be hard to measure the bands on the X-rays of the skeleton, and also, fewer bands will be X-rayed.

The second method of collecting is faster but the damage caused to the corals is greater. Complete heads or part of heads, preferably including the centre, were cut with a rock saw and completely removed with the help of a hammer and chisel. This method was used most of the time due to the drill's problems mentioned above.

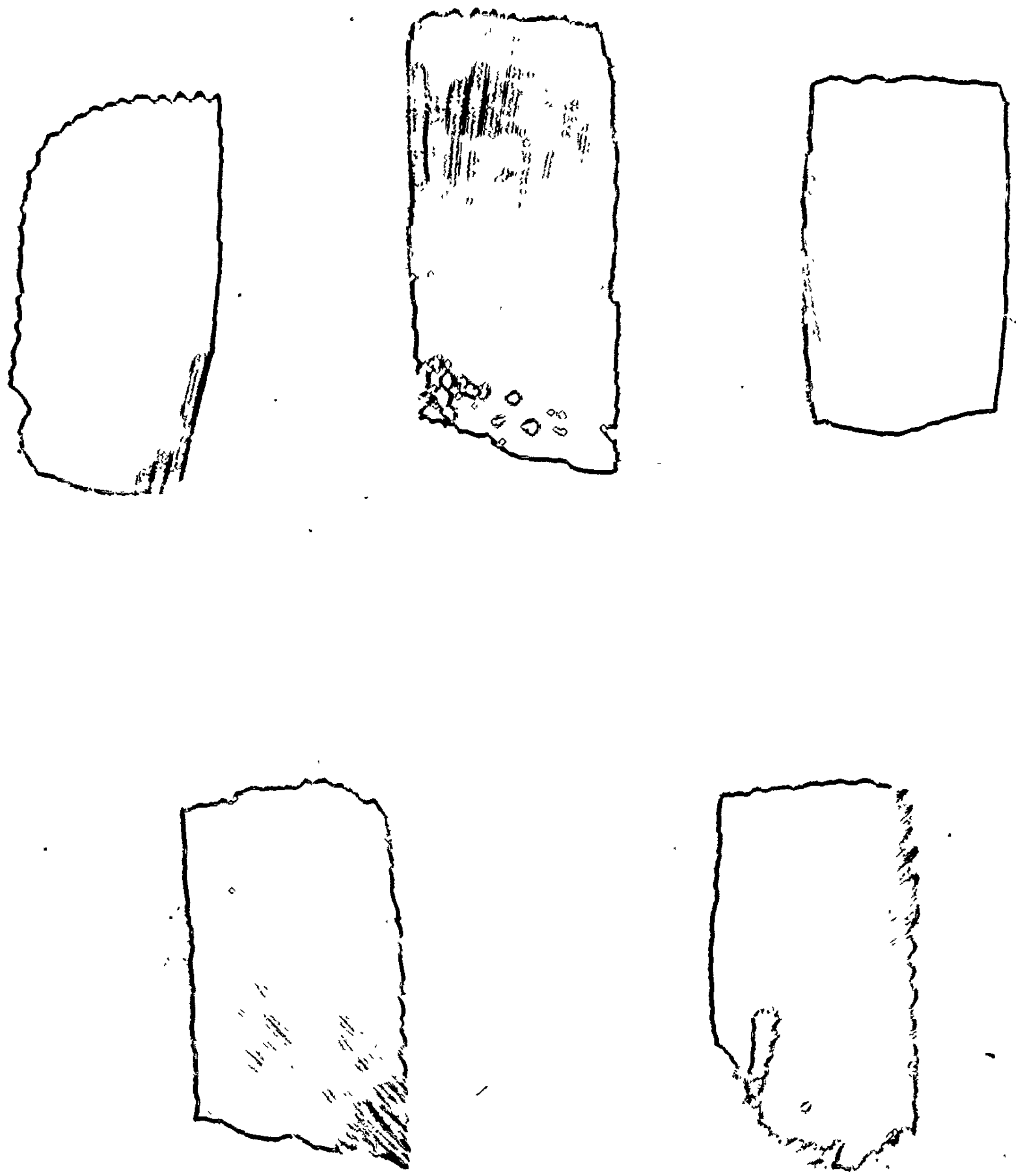
The coral samples collected were washed with fresh water and sun dried. Some were soaked in Chlorox to remove all the tissues

2.4.2 Growth Rates

Many methods have been developed to measure growth rates in corals but the most commonly used now is X-ray radiography (Knutson *et al.*, 1972). For this purpose, a slab (no more than 1 cm thick) is cut through the centre of the coral head, parallel to the corallites. Corals, like

FIGURE 2-8 X-rays of corals that were collected at Cahuita using a pneumatic drill. For the corals to be used in growth rate determination, care must be taken in order to drill parallel to the corallites (top photographs). The bottom photographs show cores not taken parallel to the corallites.

Species *Siderastrea radians*. Actual size.



trees, deposit one or more bands of different densities per year (Knutson *et al.*, 1972; Highsmith, 1979; Dodge, 1980). This can be seen on the X-ray as a series of light and dark bands which are relatively easy to point out and thus easy to measure (Fig. 2-9). This method has now become common practice but must be used with caution (Hughes & Jackson, 1980).

Slabs about 0.5 cm thick were cut and X-rayed with a Macrotank L X-ray apparatus. The setting was 90 KV, 3 mA, with exposure times of 4 to 6 minutes on Kodak Tri-X Pan Professional Film. Positive prints were made of X-ray negatives. Measurements were made by two persons on different copies of the same negative. Values were compared and if there were significant differences, other negatives of the same coral were measured.

2.4.3 Trapped Sediments

Scleractinian corals are able to remove sediments from their calices (Hubbard and Pocock, 1972; Hubbard, 1973), but some of the suspended sediments are trapped in their skeleton as they grow (Macintyre and Smith, 1974). This has been used as a possible environmental index by Barnard *et al.* (1974).

For the determination of trapped sediments, the corals were cut and washed in hydrogen peroxide, to eliminate organic matter. Pieces of coral which had no borings were

FIGURE 2-9 X-ray positive of coral slab. Sample # 1 from Cahuita. Species *Montastrea annularis*. Actual size.

chosen. After soaking in H_2O_2 for a day or two, they were rinsed with distilled water, dried at 100^0C for 6 hours, cooled and weighed. To dissolve the corals, dilute HCl was used. Once all the coral had been dissolved, the liquid and residue remaining were filtered through pre-weighed Millipore filters (HA 0.45μ, 47 mm). The filters were dried at 45^0C for 6 hours, then weighed again. The difference constituted HCl-insoluble matter trapped in the coral skeleton. These filters were kept for X-ray diffraction analysis (Section 2.7). In order to see the trapped sediments in the corals, several samples were prepared and observed in the Scanning Electron Microscope.

2.5 Transects

2.5.1 Species composition and colony sizes

To study the coral community, transects were made over the reef at different depths (Fig. 2-10). The transects consisted of a 10 m long line stretched over the corals (Fig. 2-11). The distance covered by each species under the line was recorded. This method was used by Loya and Slobodkin (1971) and Loya (1972) in the Gulf of Eilat, Red Sea, but what they recorded was the number of colonies of the different species under the line. Porter (1972), Risk (1972) and Glynn (1976) recorded the distance covered by each species under a chain. This last method is preferable because some colonies are divided by

FIGURE 2-10 Positions where transects were run at Cahuita. A, B, and C as in Figure 1-2.

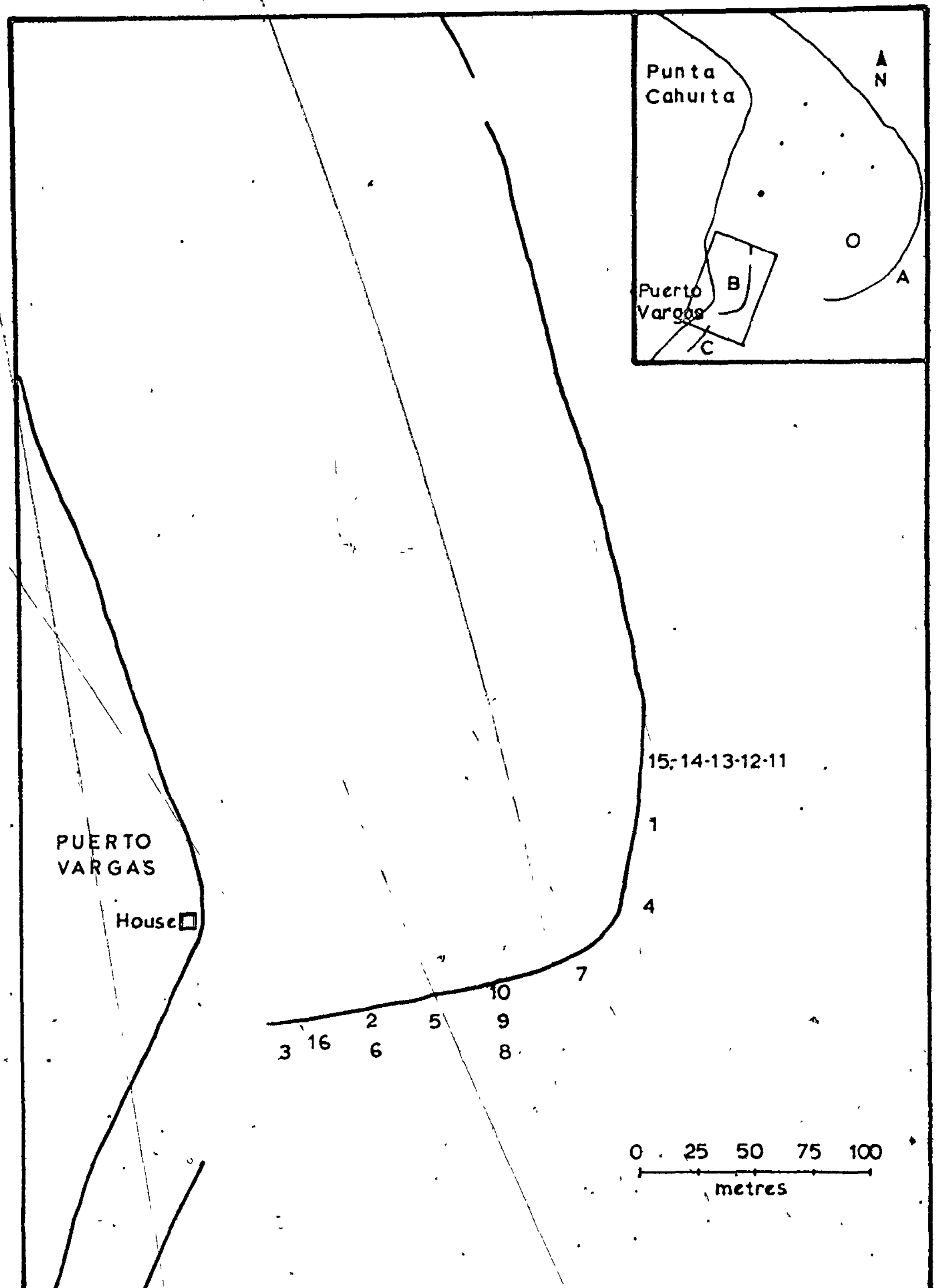
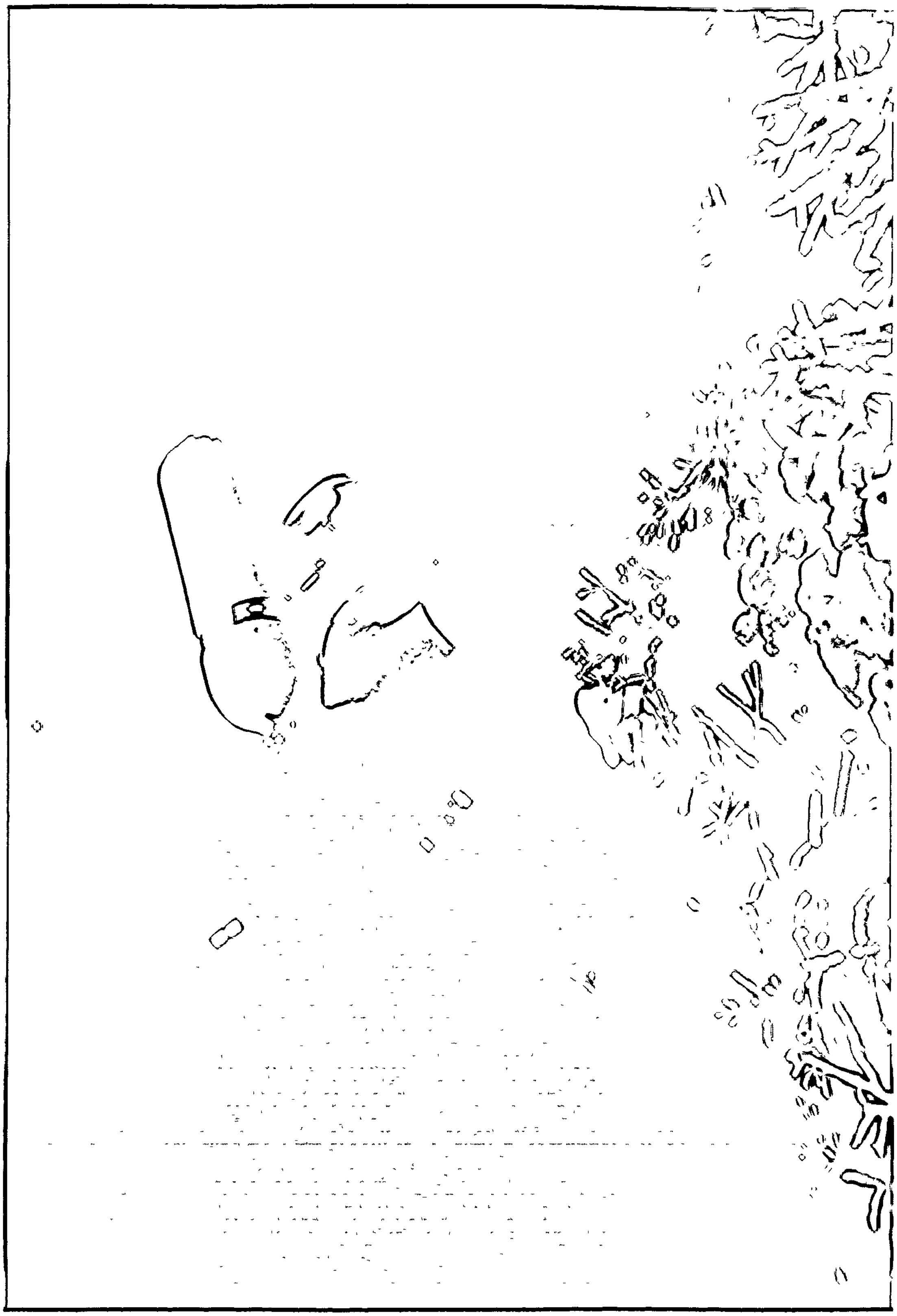

Punta
Cahuita
N
O
A
B
Puerto
Vargas
C
15-14-13-12-11
1
4
7
10
9
8
2
5
3
16
6
PUERTO
VARGAS
House
0 25 50 75 100
metres

FIGURE 2-11 Measuring the coral species under the transect line. The species on the front is *Acropora cervicornis* and the one being measured *Montastrea annularis*. Grand Cayman, depth 5 m.



dead portions (Lewis, 1974). The area of each portion is recorded. In the Red Sea, the coral colonies are usually small and discrete so the colony count method will be useful. However, in most cases in the Caribbean, it is hard to determine what is one colony, and it is easier to measure the area covered by one species. Also, the area covered by each species is a better indication of the coral coverage than is the number of colonies. Loya (1976) working in Puerto Rico, measured the colonies.

Different types of transects and other methods of quantitative description of coral reef communities are given in Loya (1978). Data taken on transects made at Cahuita include: percentage of live and dead coral, composition of the coral species, and the size of the different species.

2.5.2 Diversity

Species diversity is not only the number of species present (species richness or species abundance) but also their distribution in the community (species evenness or species equitability). Species diversity of the different areas of the reef and of the reef as a whole were calculated using several indices (Table 2-2). The indices used here are the ~~most commonly~~ employed in studies of population ecology and palaeoecology. All these indices have their advantages and disadvantages. Theoretical and practical

TABLE 2-2 Diversity indices used to calculate diversity, evenness and richness of the coral communities at Cahuita and Grand Cayman.

Shannon-Weaver	$H' = -\Sigma \frac{Ni}{N} \ell n \frac{Ni}{N}$	(1)
Simpson	$\ell = \Sigma \frac{Ni\ (Ni-1)}{N\ (N-1)}$	(2)
Evenness	$E = \frac{H}{H_{max}}$	(3)
	$H_{max} = \ell nS$	
	$E = \frac{(e^{H} - 1)}{S - 1}$	(4)
Richness	$R = \frac{(S - 1)}{\ell nN}$	(5)

N = Total distance covered by the corals in each transect

Ni = Distance covered by species i

S = Number of species

---

(1) Shannon & Weaver (1949); Margalef (1974); Lloyd *et al.* (1968)

(2) Simpson (1949)

(3) Lloyd & Ghelardi (1964); Pielou (1966)

(4) Heip (1974)

(5) Margalef (1957)

usefulness of them are discussed in Heip and Engels (1974), Margalef (1974), Peet (1974), Poole (1974) and Pielou (1975).

The rarefaction method for characterizing and comparing the diversity of plant and animal communities has come to be widely used today in ecological and paleoecological studies since its introduction by Sanders (1968). This method consists basically of estimates of species richness for smaller sample sizes of one parent collection. The graphs of number of individuals against number of species are termed "Rarefaction Curves".

Sander's methodology is inaccurate and tends to overestimate the number of species (Hurlbert, 1971; Fager, 1972; Simberloff, 1972). The formula for calculating the points along the rarefaction curves is given in Heck *et al.* (1975) and in Tipper (1979):

$$E(Sm) = \sum_{i=1}^{S} \left[1 - \binom{N-N_i}{m} \Big/ \binom{N}{m} \right]$$

where: E(Sm) = the expected number of species in the rarefied sample

S = number of species in the original sample

N = number of individuals in the original sample

N_i = number of individuals in the i'th species

m = number of individuals in the rarefied sample

The utility of the rarefacion method has been demonstrated by authors such as Raup (1975), who analysed the diversity of higher taxa of post-Paleozoic echinoids, and Antia (1977) who compared the diversity of live and dead molluscan faunas from the Essex Chenier Plain, England. For a complete discussion of the use and abuse, and on the theoretical and practical aspects of the rarefaction method, see Tipper (1979).

2.6 Oceanographic Data

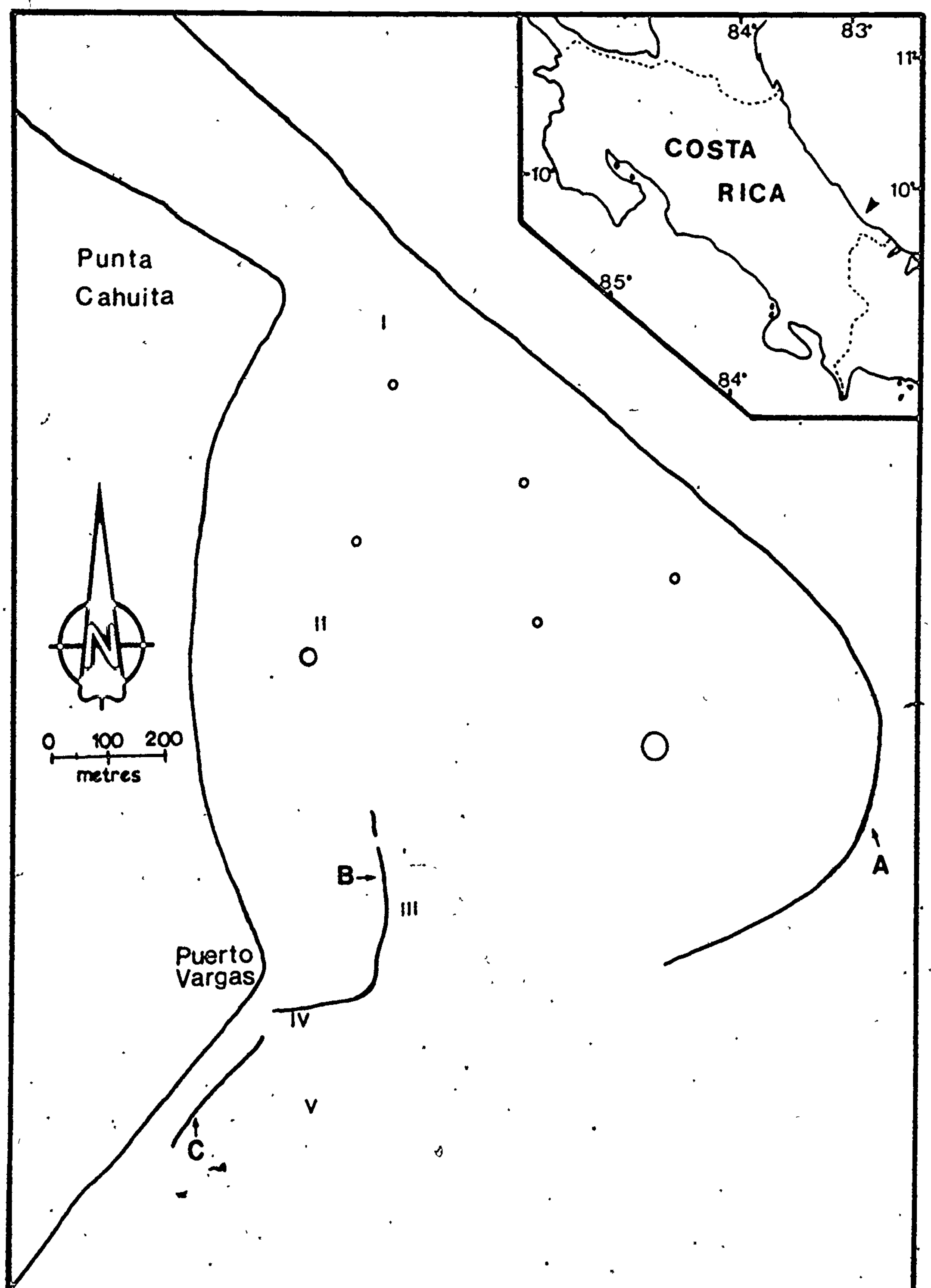
2.6.1 Currents

To determine the speed and direction of currents over the reef, two drogues were used. They consisted of two pieces of galvanized sheet metal (30 x 40 cm) mounted at right angles and a plastic jug that served as a floater. The drogues were always dropped on the northern part of the lagoon, one farther from shore that the other one. Their trajectory was recorded using a Brunton compass, from two fixed points on the beach set 100 m apart. The bearings were plotted to scale on graph paper and the direction and speed calculated.

2.6.2 Salinity

Approximate values of salinity in five stations around the reef (Fig. 2-12) were determined using a Hand Refractometer, American Optical Corporation. With this apparatus, salinities are read in a direct and rapid way. It is not very accurate, but satisfactory as a first approximation.

FIGURE 2-12 Location of stations where salinity was determined, Cahuita Reef. A, B, and C as in Figure 1-2.


84°
83°
11°
10°
10°
COSTA
RICA
85°
84°
Punta
Cahuita
I
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100
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metres
B
A
Puerto
Vargas
C

2.6.3 Temperature

Temperatures were determined several times at the surface and at various depths. A regular mercury thermometre with 0.5^{0}C divisions was used.

2.7 Geochemical Analysis

2.7.1 Atomic absorption

Since corals trap sediments in their skeletons as they grow (Barnard *et al.*, 1974; Macintyre & Smith, 1974), the qualitative and quantitative determinations of the trapped sediments will shed light on a very important environmental parameter, the amount of suspended particulate matter. Most of the S.P.M. at Cahuita are aluminum-silicate clays. To quantify the amount of detrital material trapped in the skeletons, several methods to determine aluminum by atomic absorption were tried, all with negative results.

Basically, two of the methods, one developed here and the other suggested by Dr. L. S. Land (written communication) are as follow: 1) one gram of coral is dissolved in 5 ml HF and 5 ml HNO_3, in a polytetrafluoroethylene (TEFLON) container; 2) the container is then placed in a warm water bath overnight for digestion; 3) the next day it is transferred to a sand bath to boil off the HF; 4) the precipitate left is dissolved in HCl (1:1 by volume). To dissolve the precipitate, the sample has to be agitated vigorously and at a high temperature; 5) after it has cooled down it is transferred to a 100 ml volumetric flask. The volume is then taken to 100 ml with deionized water.

The other method used is described by Barnes (1975) and consists of an extraction of the alumina in methyl isobutyl ketone (MIBK). Procedure: 1) 400 ml of a sample are transferred to a 500 ml separatory funnel; 2) 2 ml of 5% 8-hydroxyquinoline are added; 3) 10M NH_4OH is added to raise the pH to around 5 or 6, then; 4) 15 ml of MIBK are added and shaken vigorously for at least 10 seconds but no more than 30 seconds. 5) After the phases have separated, the aqueous phase is drained off and part of it is saved for analysis of Al that has not been extracted. The MIBK is collected and saved for analysis.

A Perkin-Elmer 603 Atomic Absorption Spectrophotometre was used with flame and graphite furnace; a Perkin-Elmer 56 Recorder was connected. The aluminum cathode ~~lamp~~ was set at 309 nm with a 0.7 nm slit.

The first two methods described above, in which the Al is in solution with $CaCO_3$, gave problems both with the nitrous oxide flame and with the graphite furnace. Regarding the flame, deposits (presumably of $CaCO_3$) formed near the nozzle after two runs, causing distortions of the flame, which in turn caused changes in the absorption readings. With the graphite furnace (drying 150^{0}C for

40 seconds, charring at 800^0C for 10 to 20 seconds and atomizing 2650^0C for 7 to 8 seconds), the problem was the production of white smoke which interfered with the signal of the cathode lamp, giving a higher absorbance reading.

Since most of the problems seemed to be caused by the high concentration of $CaCO_3$, an extraction of the alumina was made in MIBK. 50 microlitres were analyzed using the graphite furnace at 309 nm and 396,2 nm as wave length for aluminum. There was no smoke and most of the peaks were clean, that is, there were no additional peaks due to impurities or interference. Some peaks were still not clean and apparently the extraction was not complete. Different extractions of the same original sample gave very different results.

2.7.2 X-Ray Diffraction

X-ray diffraction was used to determine the type of clays in the reef, trapped in the coral skeletons and in the river north of the reef. The method followed was outlined in Barnard *et al.* (1974).

To analyze the trapped sediments in the coral skeletons, fragments were ground and left in 30% H_2O_2 for two or three days in order to remove oxidizable organic matter. The powder was dried and weighed. Afterwards, it was dissolved either in dilute hydrochloric acid, ethylenediaminetetraacetic acid (EDTA) or in disodium ethylenediaminetetraacetate (2Na-EDTA),(Glover, 1961). Once all the carbonate went into solution, it was filtered using Millipore filters (0.45μ, 47 mm). The filters were dryed at 60^0C during 6 hours. Dilute HCl is preferable, since it is much faster.

The filters with the trapped sediments and the filters used to determine the amount of suspended particulate matter were cut and mounted on petrographic slides (Buehler, regular, 27 x 46 mm).

The bottom sediments were treated with 30% H_2O_2 for two or three days. Samples with a high percentage of calcium carbonate were dissolved in dilute HCl and the residue was recovered on Millipore filters which were mounted on petrographic slides. Samples with a low percentage of calcium carbonate were mounted directly on the glass slides by dispersion, either in water or in acetone. The river samples were placed on petrographic slides, slurried (either with water or acetone) and shaken to smooth the surface.

The samples were analyzed with a standard Phillips X-ray diffraction unit (copper K alpha radiation 30 kilovolts, 16 milliamps, chart speed 4 cm/min). Some samples were first scanned from 5^0 to 90^0, then reduced to 5^0 to 60^0 since no significant peaks were found past 60^0. It was unfortunate that the machine did not go below 5^0. The samples were scanned at a rate of 2 degrees a minute.

The two theta angles of the main peaks were measured and the d spacing calculated using Bragg's equation $\lambda = 2d \sin \theta$ where λ was 1.54178. The minerals were identified from the d spacings using the Joint Committee of Powder Diffraction Files (JCPDS 1974a, 1974b).

2.8 Grand Cayman

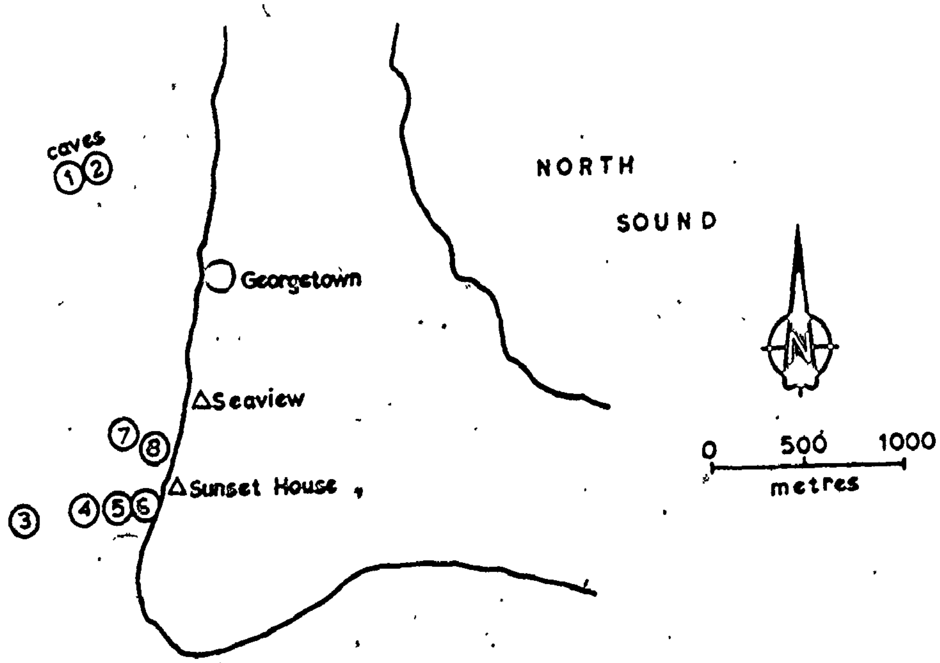
The reefs at Grand Cayman were studied in a similar way to Cahuita for comparison. The island was visited three times. One week was spend there in August, 1979; and two short visits were made in January, 1980 and August, 1980.

In order to determine the amount and composition of the suspended sediments, several water samples were taken on different parts of the west coast of Grand Cayman (Fig. 2-13). Bottom sediment samples were also collected (Fig. 2-14). To determine growth rates and trapped sediments, corals were collected from the shallow reef (Fig. 2-15). To characterize the coral community, transects were made in different areas of the reef (Fig. 2-16). This information served as a baseline for comparison with the Cahuita reef.

FIGURE 2-13 Location of sampling sites for suspended sediments at Grand Cayman.

FIGURE 2-14 Location of bottom sediment samples at Grand Cayman.

GRAND CAYMAN



GRAND CAYMAN

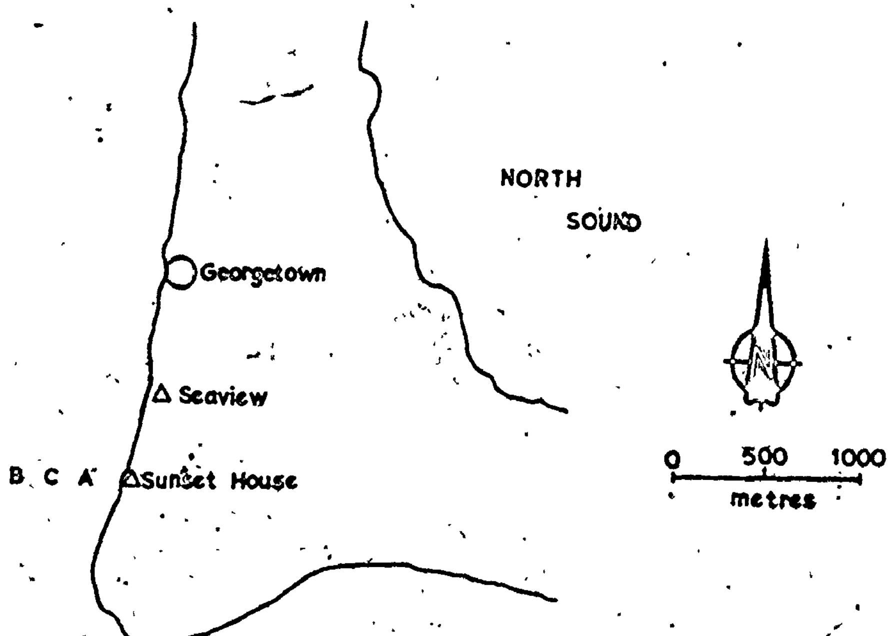
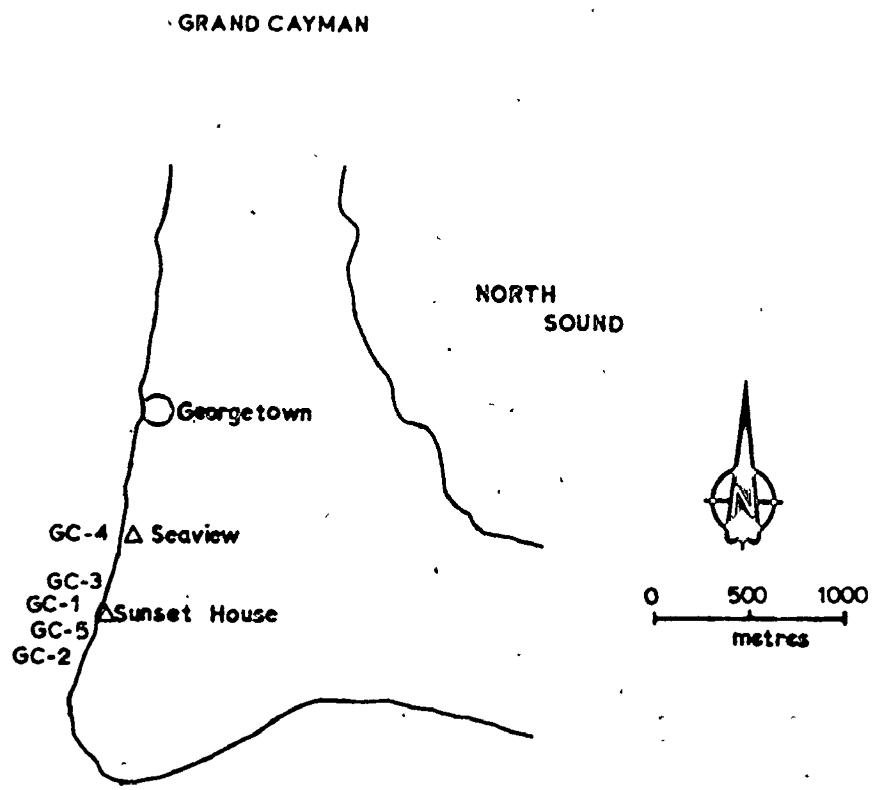
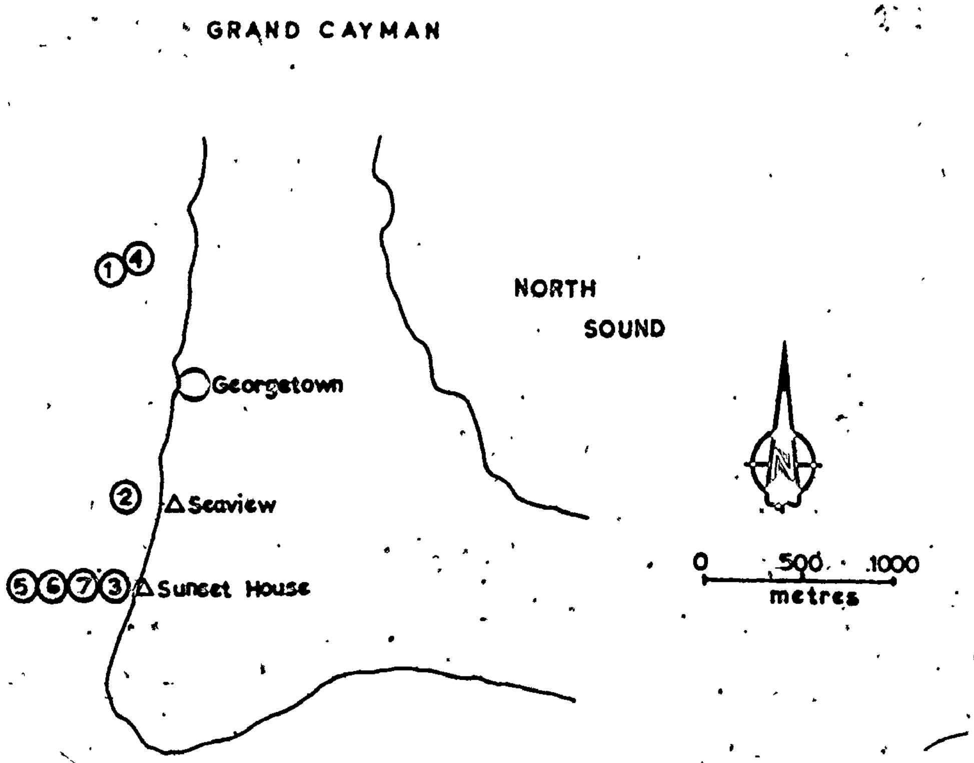


FIGURE 2-15 Locations where the live coral samples were collected at Grand Cayman.

FIGURE 2-16 Positions where transects were run at Grand Cayman.


GRAND CAYMAN
NORTH SOUND
Georgetown
GC-4
Seaview
GC-3
GC-1
GC-5
GC-2
Sunset House
0
500
1000
metres


GRAND CAYMAN
NORTH SOUND
1
4
Georgetown
2
Seaview
5
6
7
3
Sunset House
0
500
1000
metres

CHAPTER 3

RESULTS

3.1 Suspended and Resuspended Sediments

3.1.1 Suspended sediments

Most of the suspended particulate matter at Cahuita consists of inorganic sediments. To emphasize this condition, in the discussion that will follow, the term suspended sediments will be used instead of the term suspended particulate matter. The name suspended sediments is in accordance with the terminology used in the literature.

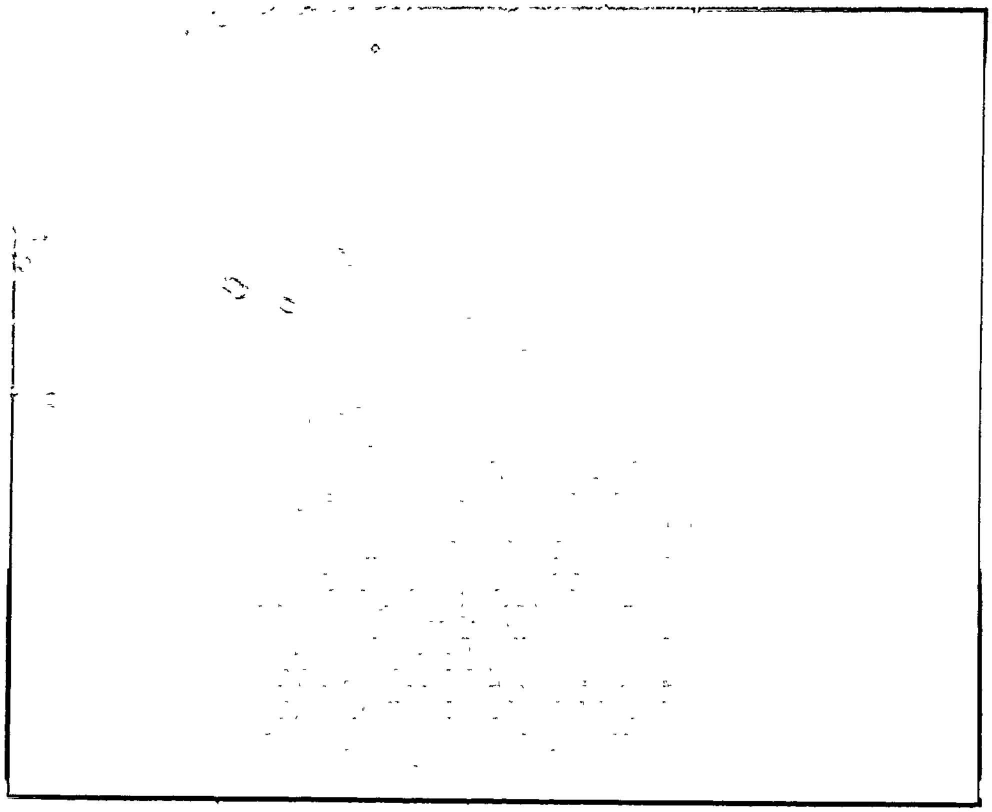
Previous workers had observed that the amount of suspended sediments at Cahuita Reef is generally high (Wellington, 1974; Risk *et al.*, 1980, and Figure 3-1A), while at Grand Cayman the water is always extraordinarily clear (Rigby and Roberts, 1976; and Figure 3-1B).

The suspended particulate matter loads from Cahuita are given in Table 3-1. During the first two field seasons, many areas of the reef were sampled. During the last field season, six station (number 3, 8, 16, 21, 22 and 24 in Figure 2-2) were sampled regularly. Five of the stations were at the reef and one (station 24) at Río La Estrella, a large river north of the reef. The five stations located in

FIGURE 3-1 Photographs of the reefs at Cahuita and Grand Cayman showing the difference in water transparency.

A.- Cahuita on a normal turbid day. Depth: 2m. Coral: *Acropora palmata.*

B.- Grand Cayman on a typical day. Depth: 17 m. Corals: Mainly *Acropora cervicornis* and *Montastrea annularis.* Sponges and other species of coral are also present.



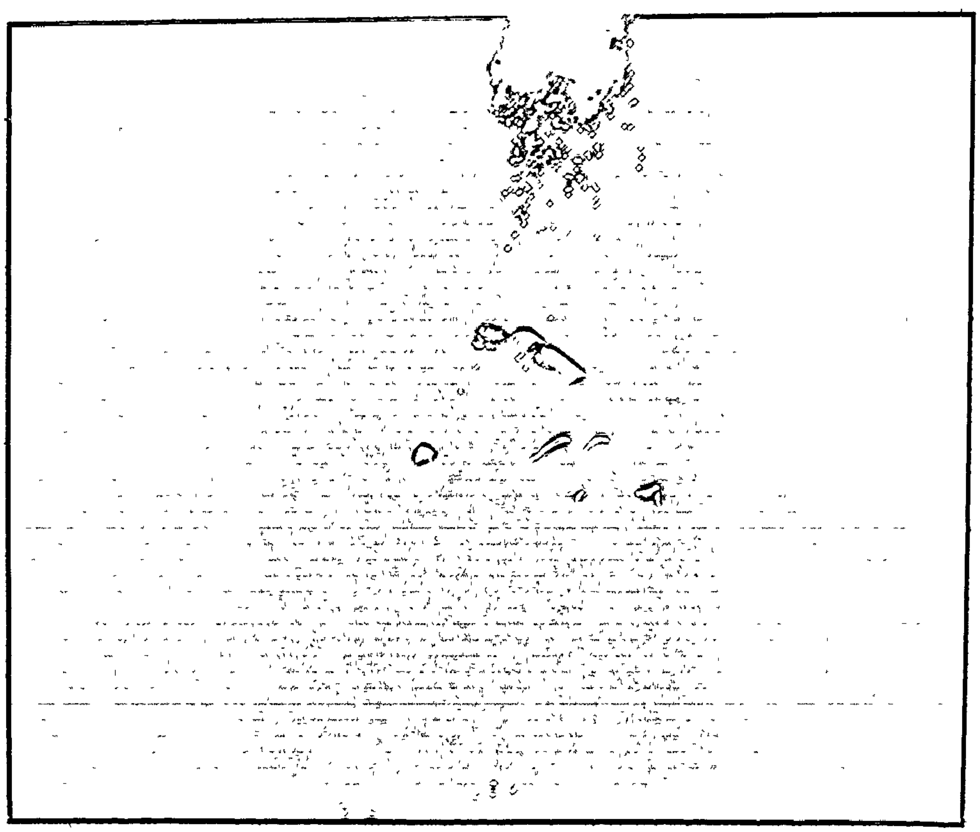


TABLE. 3-1 Suspended particulate matter loads in miligrams per one litre of sample, from Cahuita.

All samples are from the surface unless otherwise indicated.
For location of sampling sites see Figure 2-2.

DATE/LOCATION	3	5	7	8	12	13	15	16	17	19	21	22	23	24	25
8-VI-1979			0.3	1.0											
9-VI-1979						2.2			2.3						
10-VI-1979											0.8 2.0				
11-VI-1979														13.5	27.3
29-VI-1979	3.6	2.6							1.6			1.8	2.3		
30-VI-1979						1.9		2.1	2.3 2.5	2.6 4.6		5.4 1.8			
1-VII-1979								2.4 2.2 2.5 5.0		2.9 6.6		2.1 3.0		4.8 4.4	20.5 20.5
10-VII-1979	11.8 12.7	19.5 17.4		20.3 40.0	212.7		5.8	7.4 7.4	4.6 4.4			3.2 7.0 13 5			
11-VII-1979		1.7 2.7	1.9											4778.6 6201.1	
17-VII-1979											12.0 15.6	7.1 6.9			

TABLE 3-1 (cont'd)

DATE/LOCATION	1	2	3	4	5	6	8	9	10	11	13	14	16	18	19	20	21	22	24	25
14-XII-1979 (morning)																	11.1 11.2 32.0 (4m) 90.2 (5m)			
14-XII-1979 (afternoon)	8.5	8.8	12.2	21.2	15.8															
15-XII-1979																7.9 10.6 (2m)	9.6 6.4	7.2 10.5 (2m)	27.6	
20-XII-1979 (morning)					6.8		2.1										1.4 4.9 (5.5m)	6.3		
20-XII-1979 (afternoon)							6.7		4.6	5.2		3.4		7.6						
21-XII-1979			4.9 3.9		4.4 4.0		4.3 1.8			3.3 2.8				5.7				3.7		
22-XII-1979																			4.0 4.3	3.2 5.8
27-XII-1979			2.7			3.4	3.3	4.6		4.5	3.5		5.0							
28-XII-1979 (morning)			5.8		4.9		5.5			4.1			3.5		2.4	3.1		3.7		
28-XII-1979 (afternoon)			3.3		3.0	3.6	4.7	3.5		3.8			3.6				4.1	5.0		

TABLE 3-1 (cont'd)

DATE/LOCATION	3	5	8	11	16	20	21	22	24
29-XII-1979 (morning)	5.0	5.9	4.8	4.8	5.8 6.5(2m) 7.3(3m) 12.4(5m)	4.6(5.5m)	10.1	6.8	
29-XII-1979 (afernoon)	3.8	3.6	4.4	3.9	4.2				
18-VI-1980	6.8		6.5		10.9		18.8	10.9	
19-VI-1980	5.0	7.1	9.6		4.8		6.5	5.4	
24-VI-1980		6.8	7.2		4.6		6.7	5.7	26.2
25-VI-1980 (morning)	5.7		5.7		4.0		5.3	5.1	
25-VI-1980 (aternoon)	3.8		5.5		4.2		6.4	4.6	
26-VI-1980	10.9		13.4		6.7		10.4	10.8	
27-VI-1980									154.0 131.1
2-VII-1980	4.6		3.5		2.2		5.3	13.2	
3-VII-1980	9.4		4.7		6.0		4.0	9.0	39.6 64.3

TABLE 3-1 (cont'd)

DATE/LOCATION	3	8	16	21	22	24
8-VII-1980	4.4	4.9	2.7	6.4	7.5	54.4
15-VII-1980	5.6	3.7	3.0	3.7	4.4	8.3 9.2
22-VII-1980	6.3	4.9	2.9	5.5	4.1	7.8 7.3
23-VII-1980	4.3	4.1	3.4	3.7 4.6 (1m) 4.9 (2m)	1.4	
24-VII-1980	1.2	0.1	0.3	3.3	1.4	
25-VII-1980	1.2	2.5	2.8	3.5	0.1	
30-VII-1980	4.6	1.6	2.0	4.8	1.8	
31-VII-1980	4.7	3.2	4.4	9.0	5.1	
1-VIII-1980	6.9	7.8	6.8	16.7 20.6 (1m) 20.9 (2m)	9.1	15.4
5-VIII-1980	2.2	1.2	1.8	3.1	1.3	9.6
6-VIII-1980	72.9	63.6	20.1	54.0	12.7	
7-VIII-1980	5.5	6.1	5.5	8.6	4.3	
8-VIII-1980	3.4	0.9	1.8	4.1	0.1	1.4

the reef (Fig. 2-2) were set in a line from north to south over representative and accessible areas. Station 3 was near Punta Cahuita, on the north. Here the water was about 1 m deep. The bottom consisted of isolated corals, algae and bare substrate. Station 8 was near a patch reef in the lagoon where live corals occur in profusion. The water depth was about 2 m and the bottom was covered with coral fragments. Trap number 1 for resuspended sediments was also set here. Station 16 was near the inner reef crest, over the upper fore-reef where the depth is about 1.5 m. The crest consists mainly of *Acropora palmata* with other isolated corals. Sediment trap number 3 was set here. The bottom was covered with *Porites porites* and the echinoid *Diadema antillarum*. Station 21 was over the lower fore-reef in an area with a large amount of live coral. The water depth was 4 m. Traps number 4 and 5 were set near this area. Finally, station 22 was set in the bay, over 6 m of water.

From all the suspended sediment data given on Table 3-1, the following generalizations can be made:

The lowest values of suspended sediments were generally found near the crest of the inner reef, that is, in stations 16 and 20. The amount of suspended sediments in the lagoon (stations 3, 8 and others, for example 5, 6, 13 and 17) was lower than in the inner reef (station 21) except for the crest (station 16) or the bay (station 22).

The values of suspended sediments from Río La Estrella (station 24) were always higher than the ones over the reef. After several days of heavy rains, this river was carrying around 5 g of sediment per litre of water. This is phenomenally high; values are usually much lower, but still higher than the values from the reef. There does not seem to be a relation between the amount of suspended sediments in the river and the amounts found in the reef. From satellite photographs, the plume of the river does not reach the reef, about 11 km away. No measurements of sediment movement were made between the river mouth and the reef, but sediments may move toward the reef by long-shore drift and during storms. On July 6, 1980, there was a large storm on the Atlantic coast of Costa Rica, due to the passage of Hurricane Allen farther north in the Caribbean. At that time, it was observed that the values of resuspended sediments at stations 3 and 8, which were on the north end of the reef, were much higher than the other sampling stations (Table 3-1). These stations, as mentioned before, normally had lower values of suspended sediments than the rest. This suggests that sediments were moving into the reef from the north, where the river is.

The amounts of suspended sediments from Grand Cayman were much lower than the values obtained from Cahuita (Table 3-2). The samples taken on the 19 and 20-VIII-1980 were remarkably low. There are two samples taken on the

TABLE 3-2 Suspended particulate matter loads in miligrams per one litre of sample, from Grand Cayman.

All samples taken at the surface unless otherwise indicated.
For location of samples see Figure 2-13.

DATE/LOCATION	1	2	3	4	5	6	7	8
13-VIII-1979	6.9	10.9 (4m)						
	8.8 (3m)	9.4 (4m)						
14-VIII-1979				9.2				
3-I-1980			1.4	1.1		1.4		
			2.2 (3m)					
4-I-1980			2.4	1.3				
				2.2 (2m)				
				1.5 (3m)				
19-VIII-1980			<0.1	0.1	<0.1	1.2		
			1.1 (1m)					
20-VIII-1980			<0.1	1.0			18.9	33.4

20-VIII-1980, stations 7 and 8, which show high suspended sediment values. Dredging for a marina was taking place in that area. Values for the 13 and 14-VIII-1979 were also high. Observations of the filters under the microscope revealed more plankton on them than on filters from other days. The higher weight of those filters could have been due to the plankton.

3.1.2 Resuspended Sediments

Several observation at Cahuita indicate that resuspension of sediments already in the reef is more important than entrance of allochthoneous sediments. First: samples taken at different depths had invariably higher values closer to the bottom than farther up in the water column (Table 3-1). Second: if the sediments are being introduced to the reef, it would be from the north, where the large river mentioned above is located. Were this the case, then the values of suspended sediments should be higher in the northern part of the reef (stations 1, 2, 3, 4, and 5. Fig. 2-2), but they are not. Only during the strong storm of August 6, 1980, were the values at these stations higher, when new sediments seem to be transported to the reef. Also, if the sediments are coming straight from the river, then there should be a relation, with some delay, between the river values and the reef values. This is not observed in the data (Table 3-1). Finally, it was observed that when the sea at the reef was rough, the amount of suspended sediments was high and when it was calm, the values were low.

The above observations made us consider the resuspension of bottom sediments, and therefore, sediment traps were built and stationed around the reef (Fig. 2-4). The values of resuspended sediments are given in Table 3-3.

The average values of resuspended sediments (Fig. 3-2) are always higher at Trap 5. Trap 4 had the second highest values. The values of the other three traps were always lower, being lowest at Trap 3, then Trap 2 and finally Trap 1. This last one had values intermediate between Traps 2 and 3, and Traps 4 and 5.

There is a significant relation at Traps 1, 2, 4, and 5 (α:0.05) between the amount of resuspended sediments 75 cm from the bottom and the sea conditions. The relation at Trap 2 is not significant at α:0.05, maybe because of relatively few data available. No statistically significant relation was found between the amount of resuspended sediments and the amount of suspended sediments over the trap. The suspended sediment sample is an instantaneous measurement over the sediment trap; the resuspended sediment value represents one or more complete days. This is probably why no significant relation was found between the suspended and resuspended sediments, even though it was observed that when

TABLE 3-3 Resuspension of bottom sediments in milligrams per cm^2 per day, and amount of suspended particulate matter (S.P.M.) over the traps, in milligrams per litre of sample, at Cahuita Reef, 1980 field season.

	Trap	Height above substrate (cm)	Sea conditions	Resuspended sediments	S.P.M.
26-VI-1980	5	75	Very rough	651.5	10.8
		50		747.4	
2-VII-1980	1	75	Rough	109.1	3.5
		50		136.2	
	3	75		41.1	2.2
		50		46.9	
	5	75		233.6	13.2
		50		278.9	
3-VII	4	75	Relatively calm	289.2	4.0
		50		358.7	
8-VII-1980	3	75	Calm	24.4	6.4
		50		26.8	
16-VII-1980	1	75	Calm	28.4	3.7
		50		32.7	
	2	75		18.2	N.M.**
		50		19.2	
	3	75		14.2	3.0
		50		15.7	
	4	75		28.4	3.7
		50		36.5	
	5	75		--	4.4
		50		43.7	

TABLE 3-3 (cont'd)

Date	Trap	Height above substrate (cm)	Sea conditions*	Resuspended sediments	S.P.M.
23-VII-1980	1	75	Very calm	27.5	4.1
		50		29.7	
		25		34.8	
	2	75		24.9	N.M.
		50		25.2	
		25		32.6	
	3	75		17.0	3.4
		50		19.5	
		25		20.9	
	4	75		34.9	3.7
		50		47.3	
		25		69.3	
	5	75		53.1	N.M.
		50		60.9	
		25		76.4	
30-VII-1980	1	75	Very rough	77.6	1.6
		50		112.7	
		25		148.8	
	2	75		69.2	N.M.
		50		92.2	
		25		111.9	
	3	75		21.8	2.0
		50		35.2	
		25		64.9	
	4	75		528.1	4.8
		50		701.6	
		25		1060.3	

TABLE 3-3 (cont'd)

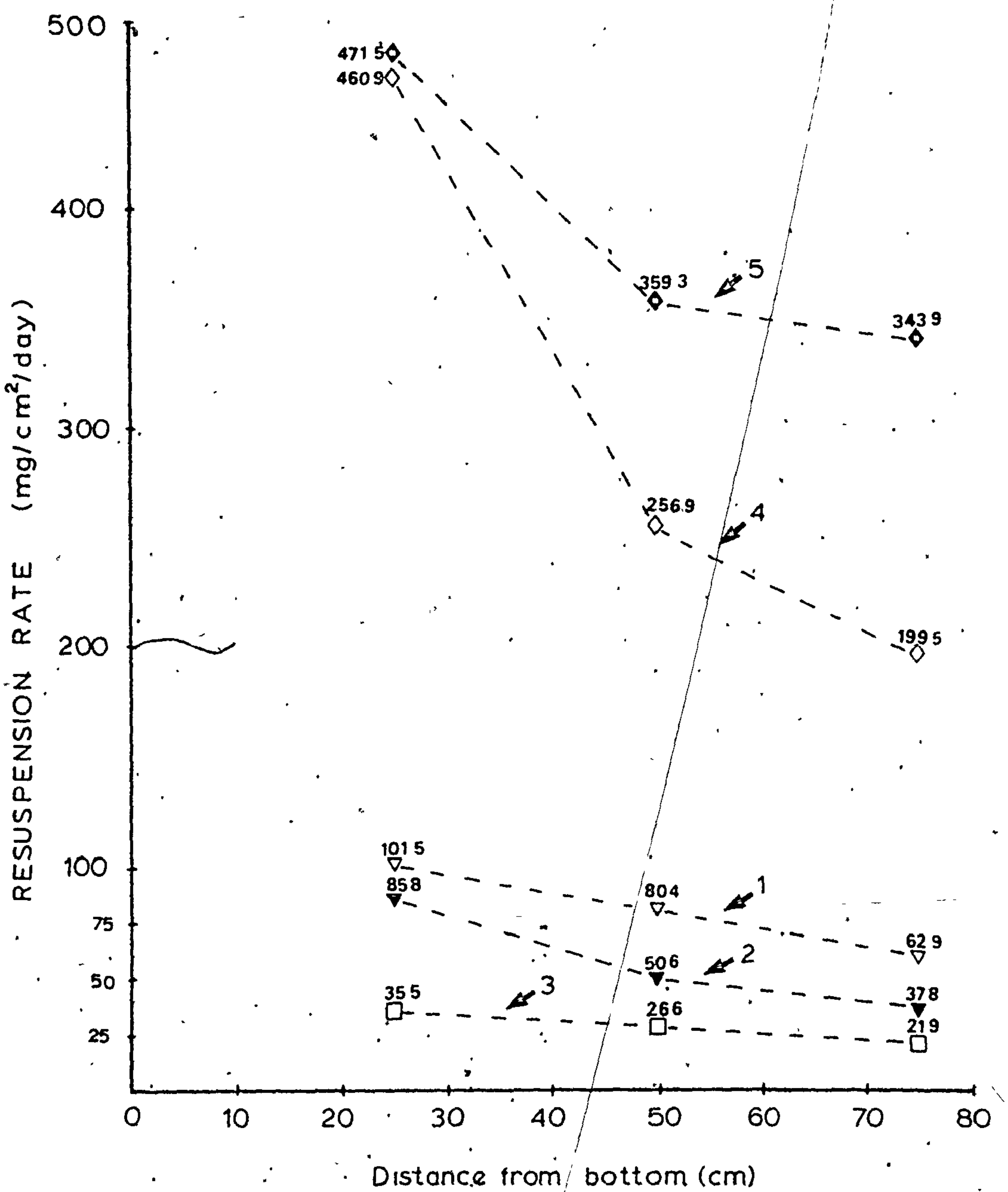
Date	Trap	Height above substrate (cm)	Sea conditions	Resuspended sediments	S.P.M.
30-VII-1980	5	75	Very rough	666.9	N.M.
		50		889.4	
		25		1179.9	
7-VIII-1980	1	75	Relatively calm	72.2	6.1
		50		90.9	
		25		120.8	
	2	75		38.8	N.M.
		50		65.9	
		25		112.8	
	3	75		12.8	5.5
		50		15.3	
		25		20.6	
	4	75		116.9	8.6
		50		140.4	
		25		253.1	
	5	75		114.2	N.M.
		50		135.6	
		25		158.1	

* Sea conditions:
Very rough: large waves, strong currents (>20 cm/sec) and windy.
Rough: large waves, moderate currents (15-20 cm/sec), moderate wind.
Relatively calm: small waves, currents not too strong (5-15 cm/sec).
Calm: small waves, almost no currents (<5 cm/sec).
Very calm: no waves, currents or wind.

**N.M.: not measured.

For location of traps see Figure 2-4.

FIGURE 3-2 Amount of resuspended sediments at different heights from the bottom, at the five sediments traps, Cahuita.



500
400
300
200
100
75
50
25
RESUSPENSION RATE (mg/cm²/day)
0
10
20
30
40
50
60
70
80
Distance from bottom (cm)
471 5
460 9
359 3
343 9
256 9
199 5
101 5
85 8
80 4
62 9
50 6
37 8
35 5
26 6
21 9
1
2
3
4
5

the sea was calm the amounts of suspended sediments were lower than when it was rough.

3.2 Bottom Sediments

3.2.1 Composition

Sediments from the bottom of the reef and from the shore were collected at Cahuita and Grand Cayman. Their general appearance, percentage of organic and percentage of insolubles in diluted HCl are given in Table 3-4. The percentage of organic matter in the bottom sediments is higher at Cahuita (average 1.0±0.1%) than at Grand Cayman (average 0.57±0.17%). The percentage of insoluble matter is also much higher at Cahuita (33.42±29.87%) than at Grand Cayman (0.16±0.08%).

From all the samples taken at Cahuita, only five have low values of insoluble material (Table 3-4). Three of these five samples (C-8, C-9 and C-10) come from the lagoon (Fig. 2-6). The other two samples come from the inner reef, towards the lagoon. These low values are comparable to values found in other reefs (Scholl, 1966). The rest of the samples from Cahuita show high values of insoluble matter (47.7% and up). They come from the external edge of the inner reef, that is, towards the bay. The two samples from the bay (C-11 and C-6) have the highest value of insolubles: 68.61 and 73.80% respectively. Measurements made

TABLE 3-4 Description of gross appearance of bottom sediment samples from Cahuita and Grand Cayman. For location of samples see Figures 2-6 and 2-14.

BOTTOM SEDIMENTS

CAHUITA

Sample #	Description	Percentage Organic Matter	Percentage Non-soluble fraction
C-1	Depth 5 m Coral and shell fragments in mud	1.0	2.80
C-2	Depth 3 m Coral fragments and sand covered with fine sediments	1.1	3.30
C-3	Depth 5 m Top layer of very fine sediments	1.1	67.41
C-4	Depth 5 m Coral fragments and coarse sand in mud	0.8	47.70
C-5	Depth 6 m Sand and mud	1.0	51.20

TABLE 3-4 (cont'd)

BOTTOM SEDIMENTS

CAHUITA

Sample #	Description	Organic Matter	Percentage Non-soluble fraction
C-6	Depth 2 m Clean sand	1.0	73.80
C-7	Depth 5 m Coral and shell fragments in mud	1.2	39.11
C-8	White sand, at the beach	0.9	5.18
C-9	Depth 1 m White sand, near beach	1.1	3.55
C-10	Depth 2 m Coral and shell fragments	1.0	4.95
C-11	Depth 6 m Layer of fine sediments over sand	0.8	68.61

TABLE 3-4 (cont'd)

BOTTOM SEDIMENTS

GRAND CAYMAN

Sample #	Description	Organic Matter	Percentage Non-soluble fraction
A	In sand channels, coarse sediments with a thin layer of fine sediments	0.45	0.25
B	Depth 15 m Layer of very fine sediments over coralline sands	0.77	0.15
C	Depth 13 m Coral fragments in sand with some fine sediments	0.50	0.09

by Risk *et al.* (1980) show values very similar to the ones obtained in this study. Analyzing the data, it can be seen that the lowest values of insolubles are the ones obtained near the reef and lagoon, while the highest come from the bay.

The percentages of the non-carbonate fraction from Grand Cayman are very low (0.09 to 0.25%). A detailed description of the carbonate fraction of the bottom sediments is given in Table 3-5.

Foraminifera were classified to the generic level when possible. Genera of the family Miliolidae and Sortidae are relatively easy to identify, as opposed to genera from the Discordidae. A high percentage of the Foraminifera at Cahuita are Miliolids, mainly *Quinqueloculina*. *Quinqueloculina* is also the dominant genus in the patch reefs in the Glovers Reef Atoll, Belize (Wallace and Schafersman, 1977). This genus was not found in Grand Cayman where *Homotrema* was the predominant one. *Homotrema* was also found at Cahuita but only near the beach, where the percentage of calcium carbonate is the highest. *Archaias* and Discordidae are common to both reefs.

The carbonate composition of the bottom sediments from Cahuita and Grand Cayman are similar: coral and shell fragments, sea urchin spines and foraminifera. These seem to be common components of the carbonate fraction in the Caribbean reefs

TABLE 3.5 Detailed description of the calcium carbonate fraction of the bottom sediments. Location of samples from Cahuita is given in Figure 2-6 and Figure 2-14 for Grand Cayman.

CAHUITA

Sample #	Calcium carbonate fraction
C-1	Fragments: bivalves, gastropods, sea urchins, bryozoa, corals. Small fragments that cannot be identified.
C-2	Fragments: gastropods, sea urchins, corals, bivalves. Small fragments that cannot be identified.
C-3	Shell fragments. Mostly very small fragments that cannot be identified.
C-4	Fragments: coral. Small unidentifiable fragments.
C-5	Fragments: sea urchins, bivalves, gastropods. Foraminifera: *Quinqueloculina*, *Archais*.
C-6	Fragments: corals, bivalves, scaphopods, sea urchins. Foraminifera: *Archais*, *Quinqueloculina*.
C-7	Fragments: corals, polychaete tubes. Small fragments that cannot be identified.

TABLE 3.5 (cont'd)

CAHUITA

Sample #	Calcium carbonate fraction
C-8	Small fragments of gastropods, sea urchins and foraminifera.
C-9	Small fragments of sea urchins, gastropods, corals. Foraminifera: *Homotrema*.
C-10	Small fragments of corals, crustaceans, bivalves, gastropods. Foraminifera: *Archais*, *Homotrema*.
C-11	Fragments: sea urchin spines, bivalves, gastropods, crustaceans. Foraminifera: *Quinqueloculina*, *Triloculina*. Small unidentifiable fragments.

TABLE 3-5 (cont'd)

GRAND CAYMAN

Sample #	Calcium carbonate fraction
A	Fragments: corals, gastropods, bivalves, crustaceans, echinoderm and scaphopods. Whole specimens of ostracods and gastropods. Foraminifera: *Homotrema*, *Criboelphidium* and Discorbidae.
B	Fragments: bivalves, echinoderms, gastropods, foraminifera, corals, scaphopods. Foraminifera: *Homotrema*, *Archais*, Discorbidae.
C	Fragments: echinoderms, corals, gastropods, bivalves, foraminifera. Foraminifera: *Homotrema*, *Archais*.

and atolls (Milliman, 1974, p. 170).

3.3 Coral Samples

3.3.1 Growth rates

Coral growth rates have been used as environmental indicators (Shinn, 1966) and as environmental recorders (Dodge and Vaisnys, 1975; Hudson *et al.*, 1976; Buddemeier, 1978). Growth rates of corals decrease as turbidity increases (Dodge *et al.*, 1974; Dodge and Vaisnys, 1977). In this work, growth rates were determined by measuring the density bands on positives on X-rayed corals. A total of twenty-six samples were X-rayed; of these, only seventeen had bands that were clear enough to measure. Fifteen corals from Cahuita and two from Grand Cayman were measured (Table 3-6 and 3-7). Growth rates of some Caribbean corals from the literature are included in Table 3-8.

The growth rate of *Siderastrea radians* at Cahuita ranges from 3.7±0.8 to 7.7±0.4 mm/year, with an average around 5.3 mm/year. This genus at Grand Cayman grows between 10.0±2.3 and 14.8±7.9 mm/year. Measurements of *Siderastrea* in the literature (Table 3-8) are sparse, 3.7 mm/year between 2-3 m of water at Florida (Hein and Risk, 1975) and between 5.0 and 15.0 mm/year at Cahuita, Costa Rica (Risk *et al.* 1980). This last value is extraordinarily high. *Diploria strigosa* at Cahuita has a growth rate of 4.0±1.1 mm/year, which is less

TABLE 3-6 Growth rates of scleractinian corals from Cahuita and Grand Cayman, in mm/year. $\bar{X}$= average; S.D.= standard deviation; S.E.= standard error; n= number of bands measured. For location of coral samples see Figures 2-7 and 2-15.

Species and sample number		Growth	Species and sample number		Growth
Siderastrea radians	$\bar{X}$=	6.4	*Siderastrea radians*	$\bar{X}$=	4.5
01	S.D.=	0.9	02	S.D.=	1.6
	S.E.=	0.28		S.E.=	0.68
	n =	11		n =	6
Siderastrea radians		4.8	*Siderastrea radians*		3.7
2		1.6	3		0.8
		0.93			0.37
		3			5
Diploria strigosa		4.0	*Siderastrea radians*		3.7
4		1.1	6		1.3
		0.42			0.60
		7			5
Siderastrea radians		5.9	*Siderastrea radians*		5.4
7		1.4	8		0.9
		0.60			0.28
		6			12

TABLE 3-6 (cont'd)

Species and sample number	Growth		Species and sample number	Growth	
Siderastrea radians	X̄=	5.5	*Siderastrea radians*	X̄=	3.8
12	S.D.=	1.4	17	S.D.=	0.7
	S.E.=	0.41		S.E.=	0.24
	n =	12		n =	10
Siderastrea radians		5.5	*Siderastrea radians*		6.0
18		0.8	19		0.9
		0.30			0.31
		8			10
Siderastrea siderea		10.0	*Siderastrea radians*		14.8
G.C.3*		2.3	G.C.5*		7.9
		1.06			3.23
		5			6

* Grand Cayman

TABLE 3-7. Growth rates of corals from Cahuita, in mm/year. Top= bands deposited less than 10 years ago; Bottom= bands deposited more than 15 years ago; All= measurements from top to bottom.

Species and sample number		Top	Bottom	All
Montastrea annularis	$\bar{X}$=	4.4	8.7	6.4
1	S.D.=	0.5	1.3	2.3
	S.E.=	0.17	0.54	0.61
	n =	9	6	15
Stephanocoenia michelini		4.7	9.8	6.4
15		1.3	1.7	2.8
		0.37	0.67	0.63
		14	7	21
Siderastrea radians		7.5	8.5	7.7
20		0.5	1.0	0.4
		0.22	0.50	0.15
		5	4	9

TABLE 3-8 Growth rates of Caribbean corals from the literature. Growth in mm/year.

Species	Growth rate	Locality	Author
Montastrea annularis	9.0 8.1	Key West	Agassiz (1890) *fide* Lewis *et al.* (1968)
Montastrea annularis	5.28 6.80 5.60	Florida Florida Bahamas	Vaughan (1915b) *fide* Lewis *et al.* (1968)
Montastrea annularis	10.7	Florida	Hoffmeister & Multer (1964)
Montastrea annularis	19.3 ± 8.4 25.0 ± 10.8	Barbados Jamaica	Lewis *et al.* (1968)
Montastrea annularis	17.0 ± 3.0	Florida 2-5m	Knutson *et al.* (1972)
Montastrea annularis	6.2 ± 0.36 8.2 ± 0.47 8.8 ± 0.50	Jamaica	Aller & Dodge (1974) Dodge *et al.* (1974)
Montastrea annularis	9.6	Belize 1m	Macintyre & Smith (1974)
Montastrea annularis	6.68 ± 2.0 4.79 ± 2.4 2.14 ± 0.4 1.70 ± 0.4 1.86 ± 0.6 1.54 ± 0.4 1.63 ± 0.4	Jamaica 10m 15m 27m 28m 30m 35m 45m	Dustan (1975)
Montastrea annularis	5.7 7.1	Florida 2-3m	Hein & Risk (1975)
Montastrea annularis	8.4	Florida 2.5m	Shinn (1976)
Montastrea annularis	10.15 ± 0.1	Barbados < 4m	Dodge *et al.* (1977)
Montastrea annularis	6.3	Belize	Highsmith (1981)

TABLE 3-8 (cont'd)

Species	Growth rate	Locality	Author
Montastrea annularis	7.90 ± 1.29	Puerto Rico 3-5m	Dodge (1981)
	9.10 ± 1.31		
	8.89 ± 1.68		
	8.61 ± 1.99		
	10.34 ± 1.55		
	9.12 ± 1.05		
	9.90 ± 2.95		
	9.05 ± 1.53		
	10.56 ± 2.80		
	10.07 ± 2.37		
	9.24 ± 1.84		
	10.02 ± 1.69		
Montastrea annularis	6.3	Florida forereef 8-10m	Hudson (1981)
	8.2	inshore 1-4m	
	11.2	midshore 22m	
Diploria strigosa	5.6	Florida 2-3m	Hein & Risk (1975)
Diploria strigosa	5.0	Florida 2.5m	Shinn (1976)
Porites astreoides	4.0	Cahuita <3m	Risk *et al.* (1980)
	6.0		
Porites astreoides	4.8	Belize	Highsmith (1981)
Siderastrea radians	3.7	Florida 2-3m	Hein & Risk (1975)
Siderastrea radians	5.0	Cahuita <3m	Risk *et al.* (1980)
	5.6		
	10.0		
	15.0		
Stephanocoenia sp.	5.0	Jamaica 25m	Moore & Krishnaswami (1974)

than the growth rate of the species at Florida at a depth between 2 and 3 m, 5.6 mm/year (Shinn, 1976). An unidentified species of *Stephanocoenia* from a depth of 25 m in Jamaica has a growth rate of 5.0 mm/year (Moore and Krishnaswami, 1974) which is not much lower than the growth rate of *Stephanocoenia michelini* at Cahuita at 4 m, 6.4 mm/year. The most studied coral in the Caribbean is *Montastrea annularis*; values found in the literature (Table 3-8) for this species range from 1.63±0.4 mm/year at 45 m in Jamaica (Dustan, 1975) to 25.0±10.8 mm/year, also in Jamaica, but in shallow waters (Lewis *et al.*, 1968). The value from Cahuita (Table 3-7) is 6.6±2.3 mm/year, which is equal to the value obtained by Dustan (1975) in Jamaica at 10 m, and to the value obtained by Dodge *et al.* (1974) at their station with highest values of resuspended sediments. This growth rate for *Montastrea annularis* at Cahuita (collected at a depth of 2 m) is low when compared to other shallow sample from the Caribbean (see Table 3-8). *Porites astreoides* was not measured here, but growth rate values from Cahuita are available elsewhere (Risk *et al.*, 1980), 4.0 and 6.0 mm/year. These values are similar to a value from Belize, 4.8 mm/year (Highsmith,1981). Unfortunaly, the depth of the sample from Belize is not given.

Table 3-7 has the growth rates of three corals from Cahuita. The samples are divided into "top": layers deposited less than ten years ago; "bottom": layers deposited more than 15 years ago; and "all": includes all measurements from top to bottom. The mean growth rate more than 15 years ago is significantly higher in sample 15 (test for difference of two means $t= 7.265$, $t_{0.05(2)19}= 2.093$) and in sample 1 ($t= 8.831$, $t_{0.05(2)13}= 2.160$) than the growth rate less than 10 years ago. In sample 20, the mean growth rate was higher more than 15 years ago, but not significantly at the confidence level of $\alpha= 0.05$ ($t= 1.972$; $t_{0.05(2)}= 2.365$).

The average growth rate of *Siderastrea radians* at Cahuita is about 5.3 mm/year. Some samples (01, 7, 8, 12, 18, 19 and 20) have average growth rates higher than 5.3 mm/year (Table 3-6 and 3-7). All but samples 7, 8 and 19 come from shallow waters, less than 2 m deep, where the amount of suspended and resuspended sediment was low (Tables 3-1 and 3-3). Sample 7 comes from 4 m of water but from an are with low amounts of sediments. The other two samples, 8 and 19 come from areas with high values of suspended sediments. Sample 19 was taken at 3 m of water and sample 8 at 5 m. Sample 8 shows a growth rate value just above average but still high for the depth and area of the reef where it comes from. The rest of the samples have low growth rates, and either come from areas of the reef with high sediment loads (samples 02, 4, 17) or from deep (4-5 m) areas (samples 3 and 6).

The highest growth rate value for Cahuita is 7.7±0.4 mm/year for sample 20, *Siderastrea radians*, which comes from shallow water (1 m) and where the amount of sediment was low. The second highest value, 6.4±0.9 mm/year, is from sample 01 (*Siderastrea radians*) which comes from shallow (1.5 m) and relatively clean waters. *Stephanocoenia michelini* (sample 15) also has a high growth rate (6.4±0.9 mm/year). This coral comes from deep water (4 m), from an area with high values of suspended sediments. This genus is probably adapted to low light intensities, since in Jamaica at 25 m, it has a growth rate of 5.0 mm/year (Table 3-8). The third highest value recorded is 6.1±2.3 mm/year (*Montastrea annularis*, sample 1). This sample comes from shallow water (2 m), near a patch reef on the lagoon where the amount of suspended sediments was low (Table 3-1).

The growth rate values of the two samples from Grand Cayman (GC-3, GC-5) are about twice as high as the values obtained from Cahuita at the same depth (Table 3-6). The amount of suspended sediments at Grand Cayman is much lower than at Cahuita (Table 3-2). No growth rate data from Grand Cayman are available in the literature.

3.3.2 Trapped Sediments

Scleractinian corals as they grow, will trap some of the sediments that are deposited on them (Fig. 3-3). The determination of the amount and composition of these trapped sediments can be used as an indication of the

FIGURE 3-3 *Diploria strigosa* from Cahuita with sediments in the valleys. Some of these sediments can be trapped in the skeleton. Depth 5 m.

environment where the corals lived (Barnard *et al.*, 1974). Samples from Cahuita and Grand Cayman were prepared and observed using the Scanning Electron Microscope. The corals from Cahuita have extraneous particles in their skeleton (Fig. 3-4), while the ones from Grand Cayman are clean (Fig. 3-5).

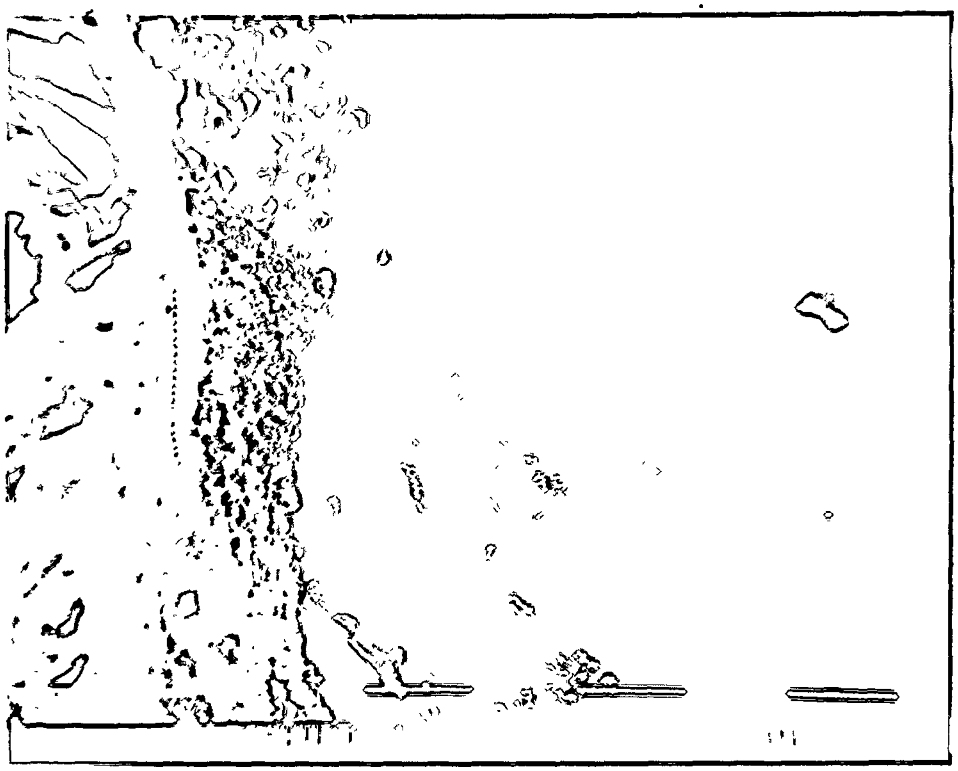
The amounts of trapped sediments were determined by the method described in Section 2.4.3. Table 3-9 and Table 3-10 show the values of trapped sediment in several species from Cahuita, and Table 3-11 the values from Grand Cayman. The amounts of trapped sediment from both reefs are significantly different (Mann-Whitney Test, $U= 165$, $U_{0.05(2)7,28} \doteq 146$), being higher at Cahuita than at Grand Cayman.

Sample 16 (Table 3-9) has a significant negative correlation between distance from the top of the coral head and the amount of trapped sediment ($r= -0.846$, $t_t= -3.17$, $t_{0.05(2)6}= 2.447$), that is, the amount of trapped sediments near the surface of the coral head is higher than farther down. No other sample shows this relation. Regressions calculated on the other samples have slopes almost equal to zero, indicating that the amount of trapped sediments is more or less constant throughout the coral. The higher values of the upper part of Sample 16 may represent organic matter that escaped dissolution.

Compared to other coral species of the reef, *Diploria strigosa* has higher values of trapped sediments

FIGURE 3-4 Scanning Electron Microscope photograph of coral *(Siderastrea)* from Cahuita. Note extraneous particles in the skeleton. Bars are 10 μm long.

FIGURE 3-5 Scanning Electron Microscope photograph of coral *(Siderastrea)* from Grand Cayman. The skeleton is clean. Bars are 10 μm long.



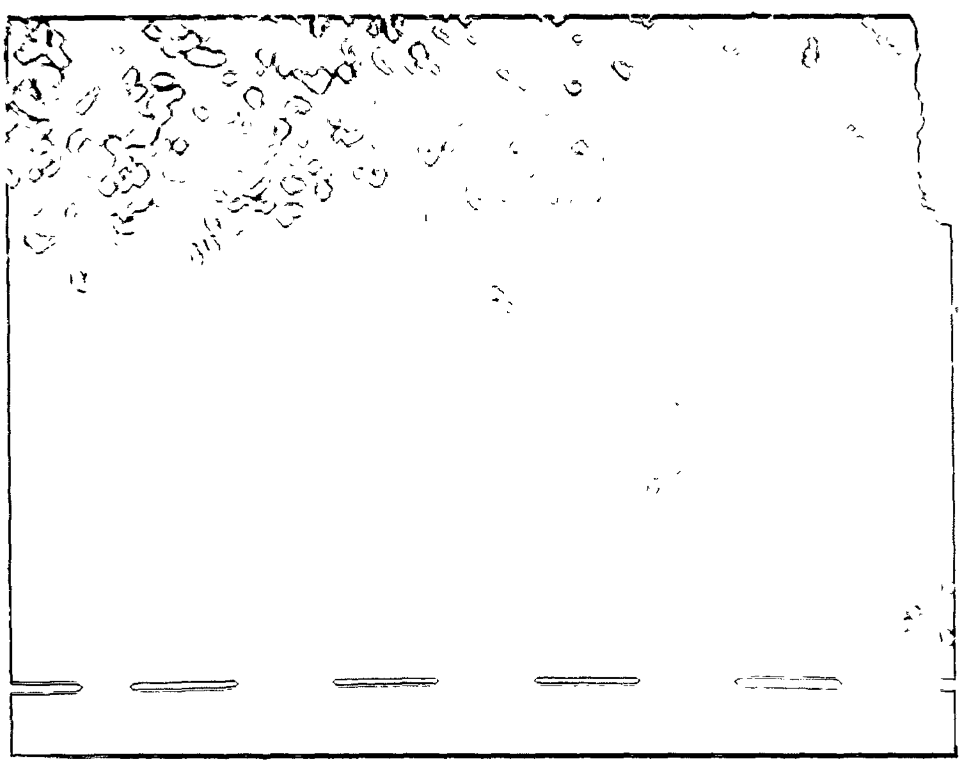


TABLE 3-9 Amount of trapped sediments in corals from Cahuita.

For location of coral samples see Figure 2-7. Location of subsamples in each coral head is in cm, measured from the top. Approximate year of formation is obtained using average growth rate of the species.

Species and sample number	Subsample (cm from the top)	Approximate year of deposition	% trapped sediment by weight of coral
Diploria strigosa	3	1973	0.2019
# 5	8 (bottom)	1963	0.2414
Siderastrea radians	2	1976	0.0582
# 8	5	1970	0.0443
	8	1964	0.0377
	12 (bottom)	1956	0.0440
Stephanocoenia michelini	2	1975	0.0259
# 15	8	1967	0.0405
	14	1963	0.0315
	20	1957	0.0200
	26	1951	0.0320
	32	1945	0.0213
Siderastrea radians	2	1975	0.2468
# 16	4	1971	0.1214
	8	1963	0.0611
	10	1959	0.0539

TABLE 3-9 (cont'd)

Species and sample number	Subsample (cm from the top)	Approximate year of deposition	% trapped sediment by weight of coral
Siderastrea radians	12	1955	0.0377
# 16	16	1947	0.0379
Siderastrea radians	1	1977	0.0140
# 17	2	1975	0.0268
	4	1971	0.0133
Siderastrea radians	1.5	1977	0.0168
# 18	3	1973	0.0407
	4	1971	0.0298
	5.5	1969	0.0231
Siderastrea radians	2	1976	0.0339
# 20	3	1974	0.0366
	5	1970	0.0284
	6	1968	0.0151
	8	1964	0.0210
	9.5	1961	0.0156
Siderastrea radians	1	1977	0.0920
# 21	2.5	1974	0.0550
	3.5	1972	0.0586
	5	1969	0.0618
	6	1967	0.0551
	7.5	1964	0.0369
	11	1955	0.0877

TABLE 3-10 Student t' test for replicate values of trapped sediments in a head of *Montastrea annularis* (Coral sample # 1, Fig. 2-7).

Location of subsamples, approximate year and values as described in Table 3-9.

Subsample (cm from the top)	Approximate year of deposition	Replicate I	Replicate II	Difference
2	1977	0.0745	0.0522	0.0223
5	1974	0.0492	0.0540	-0.0048
6	1972	0.0417	0.0302	0.0115
7	1971	0.0327	0.0458	-0.0131
8.5	1970	0.0462	0.0707	-0.0245
10	1968	0.0117	0.0273	-0.0156
11.5	1967	Lost	0.0313	--
13	1965	0.0018	0.0296	-0.0278
15.5	1963	0.0344	0.0333	0.0011
17	1960	0.0393	0.0648	-0.0255

$n = 9$ $\bar{d} = -0.008$ $t = -1.457$

D.F. $= n-1$ $Sd = 0.006$ $t_{0.05(2)8} = 2.306$

$= 8$ p 0.05

Therefore Replicate I is equal to Replicate II

(Table 3-9 and 3-11). The two species of *Siderastrea* from Grand Cayman (Table 3-11) have similar values of trapped sediments. All four coral samples from Grand Cayman were collected at approximately the same depth and area of the reef.

The Cahuita samples # 8, 16 and 21 (Table 3-9) come from 4-5 m of water, in the front part of the inner reef. Here the bottom is covered by a fine layer of sediments that goes into suspension easily. These samples have similar, high values of trapped sediments. Samples 17, 18 and 20 have lower values of trapped sediments. The first two corals were collected from shallow water on opposite ends of the inner reef crest; sample 20 came from a depth of 1 m at the edge of the inner reef crest (Fig. 2-7). In these shallow areas, circulation is good and most of the resuspended sediments are deeper. Sample 15, *Stephanocoenia michelini*, has low values of trapped sediments even though it comes from the same general area as samples 8, 16 and 21, which have higher values. This difference may be due to species differences.

Replicates drawn from one head of *Montastrea annularis*, sample 1 (Table 3-10) show no significant differences in trapped sediments ($t= -1.457$; $t_{0.05(2)8}= 2.306$).

Values of trapped sediment within a coral and between heads of the same general area are fairly constant. No correlation was found between amount of trapped sediment in different corals and year of deposition of the coral skeleton. In other words, specially high or low years of suspended

TABLE 3-11 Amount of trapped sediments in corals from Grand Cayman. For location of coral samples see Figure 2-15. Subsamples and year of deposition as in Table 3-9.

Species and sample number	Subsample (cm from the top)	Approximate year of deposition	% trapped sediment by weight of coral
Diploria strigosa	2	--	0.0111
G.C. 1	3.5	--	0.0170
	5	--	0.0159
Diploria strigosa	2	--	0.0114
G.C. 2	6	--	0.0218
	10	--	0.0063
Siderastrea siderea	2	1977	0.0288
G.C. 3	7	1970	0.0172
Siderastrea radians	5	1974	0.0217
G.C. 5	10	1969	0.0288

sediments are not observed in these samples.

3.4 Coral Community

3.4.1 Transect Data

Transects were laid out parallel to the main reef trend at determined depths. A nylon rope was stretched over the corals, and the distance covered by each species was recorded.

Sixteen transects were run at Cahuita covering a total of 201 m. These were run between depths of 1 to 5 m. At Grand Cayman, seven transects were made, covering 52 m at depths between 5 and 16 m. Table 3-12 summarizes part of the information from these transects, which includes: main species, percentages of dead and live coral, and substrate and species diversity (Shannon-Weaver Index). Additional data of the transects at Cahuita reef are given in Appendix III. Table 3-13 summarizes the same information from the Grand Cayman transects, and Appendix IV provides additional data.

At Cahuita, live coral coverage is characteristically low (4-50%, Fig. 3-6), in the form of isolated patches among large areas covered by dead coral (Fig. 3-7). Three transects, 1, 11 and 12, from the reef front run between 4-5 m of water (Fig. 3-8), differ from the rest in that the percentage of live coral is very high (77-80%). There, *Agaricia agaricites* is the dominant species (Fig. 3-9). *Agaricia* occurs nearly exclusively in a similar setting at

TABLE 3-12 Transects from Cahuita.

Transect #	Depth in metres	Main Species	% Dead coral	% Live coral	Substrate diversity	Species diversity
1	5	*Agaricia agaricites* (Pallas)	20	80	0.946	0.555
2	3	*Siderastrea radians* (Pallas)	73	27	0.969	1.434
3	3	*Siderastrea radians* (Pallas)	50	50	1.278	1.161
4	2	*Agaricia agaricites* (Pallas)	69	31	1.107	1.602
5	2	*Porites astreoides* Lesueur	71	29	1.024	1.495
6	4	*Agaricia agaricites* (Pallas)	59	41	1.125	1.094
7	4	*Siderastrea radians* (Pallas)	46	54	1.178	0.900
8	3	*Siderastrea radians* (Pallas)	80	20	0.725	1.124
9	2	*Porites porites* (Pallas)	72	28	0.782	0.677
10	1	*Acropora palmata* Lamarck	69	31	0.926	0.963
11	5	*Agaricia agaricites* (Pallas)	20	80	0.524	0.038
12	4	*Agaricia agaricites* (Pallas)	23	77	0.897	0.464
13	3	*Porites porites* (Pallas)	63	37	0.896	0.639
14	2	*Porites porites* (Pallas)	75	25	0.772	0.838
15	1.5	*Porites porites* (Pallas)	96	4	0.216	1.213
16	3	*Agaricia agaricites* (Pallas)	67	33	0.994	1.077

TABLE 3-13 Transects from Grand Cayman.

Transect #	Depth in metres	Main Species	% Dead coral	% Live coral	Substrate diversity	Species diversity
1	7	*Acropora cervicornis* (Lamarck)	33	67	1.238	0.903
2	16	*Acropora cervicornis* (Lamarck)	38	62	1.483	1.326
3	13	*Montastrea annularis* (Ellis & Solander)	40	60	1.565	1.483
4	5	*Montastrea annularis* (Ellis & Solander)	24	76	1.384	1.096
5	15	*Acropora cervicornis* (Lamarck)	38	62	1.632	1.557
6	15	*Montastrea annularis* (Ellis & Solander)	55	45	1.494	1.596
7	13	*Acropora cervicornis* (Lamarck)	28	72	1.844	1.725

FIGURE 3-6 Percentage of live coral in each of the 16 transects from Cahuita. For location of transects, see Figure 2-10.

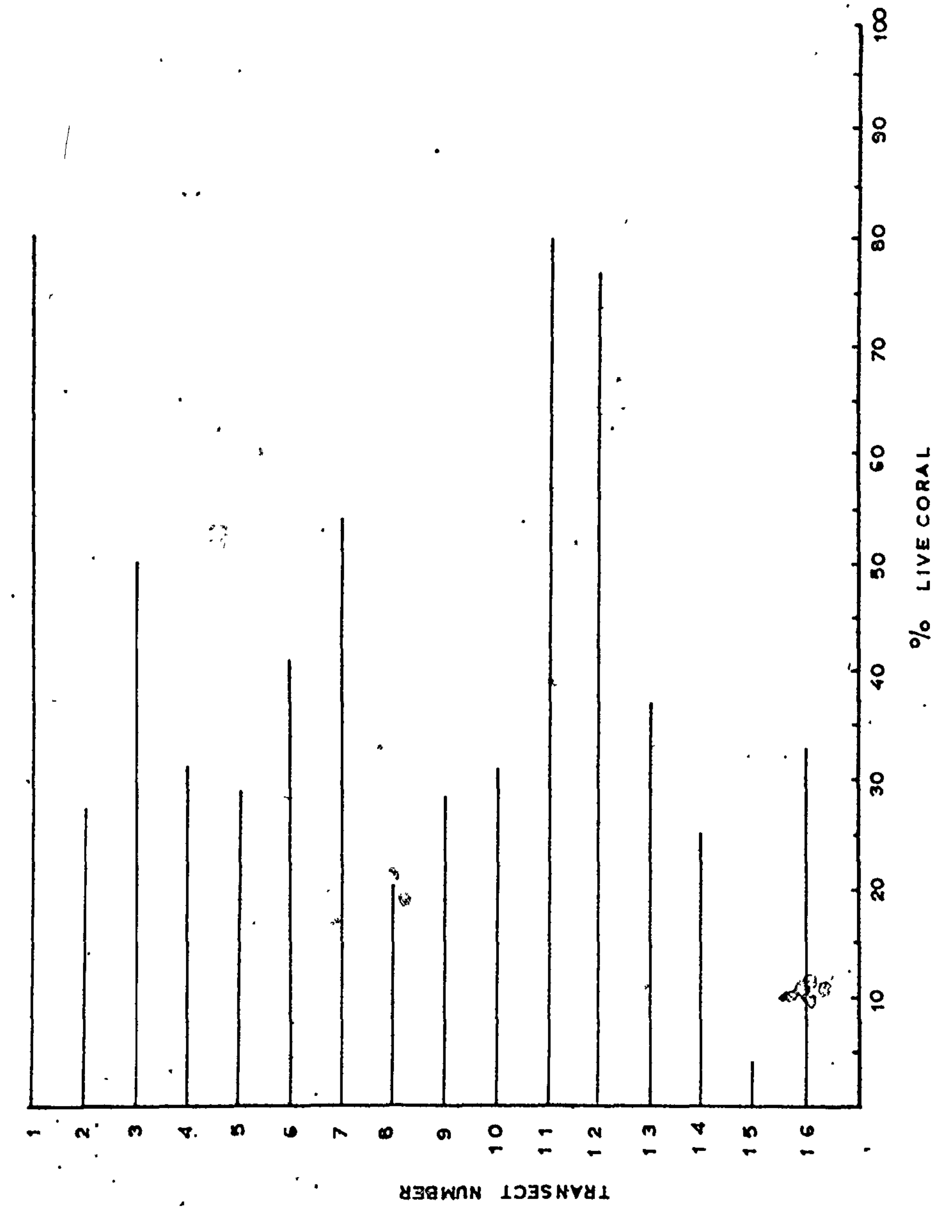

% LIVE CORAL
10
20
30
40
50
60
70
80
90
100
TRANSECT NUMBER
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

FIGURE 3-7 Picture of the bottom on the inner crest, Cahuita. Arrow shows isolated heads of live coral, the rest is substrate covered with sediments or algae. Area photographed is 2 m across the centre.

FIGURE 3-8 Transect across the inner reef, Cahuita.

See Figure 1-2 for location.

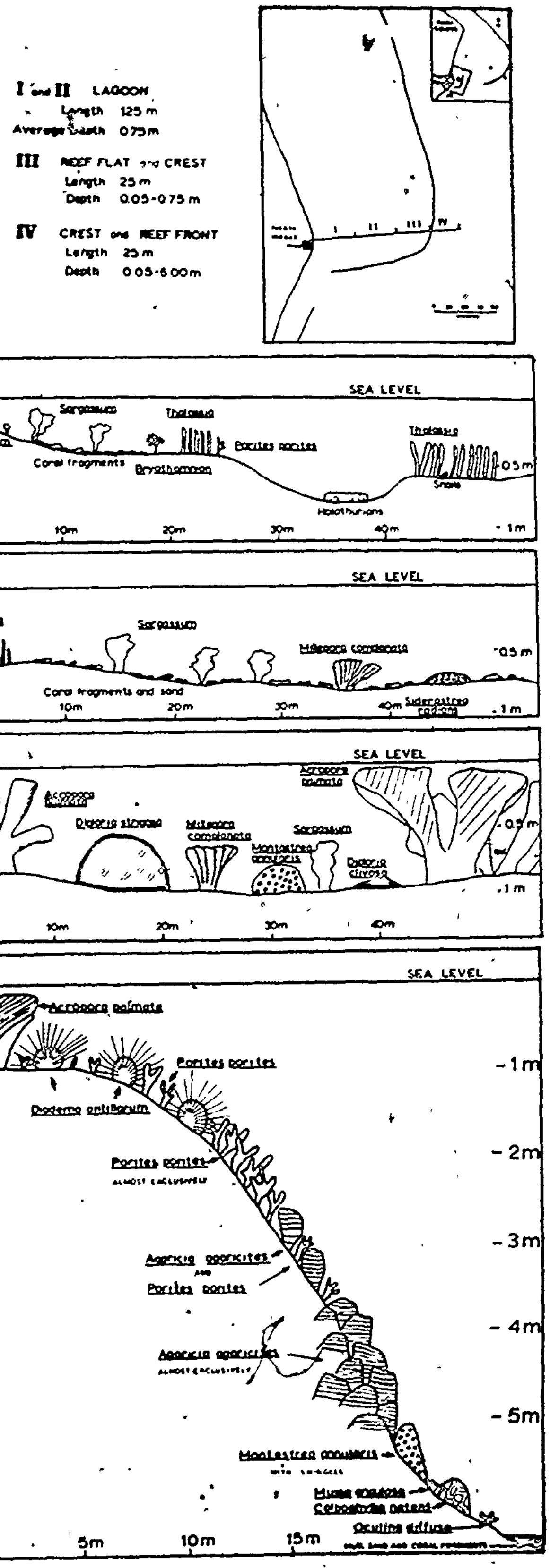

I and II LAGOON
Length 125 m
Average Depth 0.75 m
III REEF FLAT and CREST
Length 25 m
Depth 0.05-0.75 m
IV CREST and REEF FRONT
Length 25 m
Depth 0.05-6.00 m
BEACH
SEA LEVEL
Sargassum
Thalassia
Porites porites
Coral fragments
Holothurians
I
10m
20m
30m
40m
-1m
SEA LEVEL
Thalassia
Sargassum
Millepora complanata
Coral fragments and sand
II
10m
20m
30m
40m
-1m
SEA LEVEL
Acropora palmata
Diploria strigosa
Millepora complanata
Sargassum
Diploria clivosa
III
10m
20m
30m
40m
-1m
SEA LEVEL
Acropora palmata
Porites porites
Diadema antillarum
Porites porites
Agaricia agaricites
Porites porites
Agaricia agaricites
Montastrea annularis
Oculina diffusa
-1m
-2m
-3m
-4m
-5m
IV
5m
10m
15m

FIGURE 3-9 *Agaricia agaricites* occurs almost exclusively at Cahuita between 3.5 and 5 m. Area photographed is 3 m across the centre.

Sardinga Point, San Blas, Panamá (Robertson and Glynn, 1977, p. 5).

At Grand Cayman the coral community is characterized by a high percentage (45% or more) of live coral (Fig. 3-10), but these values are not as high as those given by transects 1, 11 and 12 from Cahuita. This is due to the fact that no monospecific stands of corals with a very high percentage of live coral were noted at Grand Cayman. Transects made at Grand Cayman over dense coverage of corals (Fig. 3-11) have about 25% of dead coral. Species diversity is relatively lower in shallow water (5-7 m) than in deeper water (13-15 m) (Table 3-13).

Figure 3-12 depicts a transect perpendicular to the shore on the west end of Grand Cayman. There is no lagoon on this side of the island (Rigby and Roberts, 1976). The equivalent of the reef crest would be at the shore and the rest of the transect would be the reef front. Only one dive was made between 18 and 27 metres. At 18 m there is a band of sand 5 to 10 m wide with a slight slope. At 20 m the coverage of coral is very dense and diversity very high. Around 27 m there is a drop-off, here the slope is pronounced (45^0). At this depth, different species and deep-water morphologies were observed, for example *Montastrea annularis* growing in shingles.

FIGURE 3-10 Percentage of live coral in each of the 7 transects from Grand Cayman. For location of transects, see Figure 2-16.

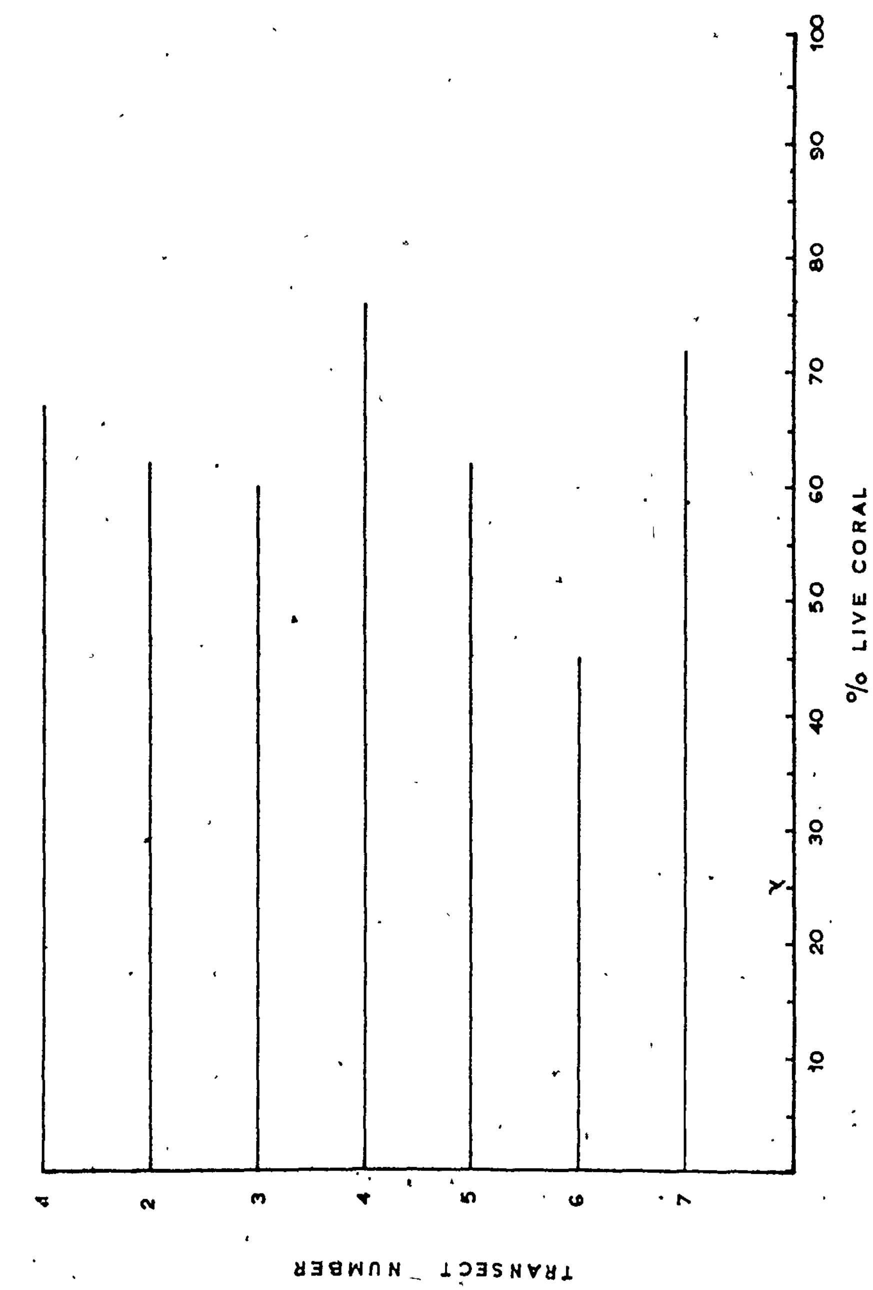

% LIVE CORAL
10
20
30
40
50
60
70
80
90
100
TRANSECT NUMBER
1
2
3
4
5
6
7

FIGURE 3-11 Photograph of the reef at Grand Cayman at a depth between 5 and 6 metres. The two most prominent species here are *Acropora cervicornis* -the branching coral- and *Montastrea annularis* -the knobby coral-. Area photographed is 6 m on the lower part.

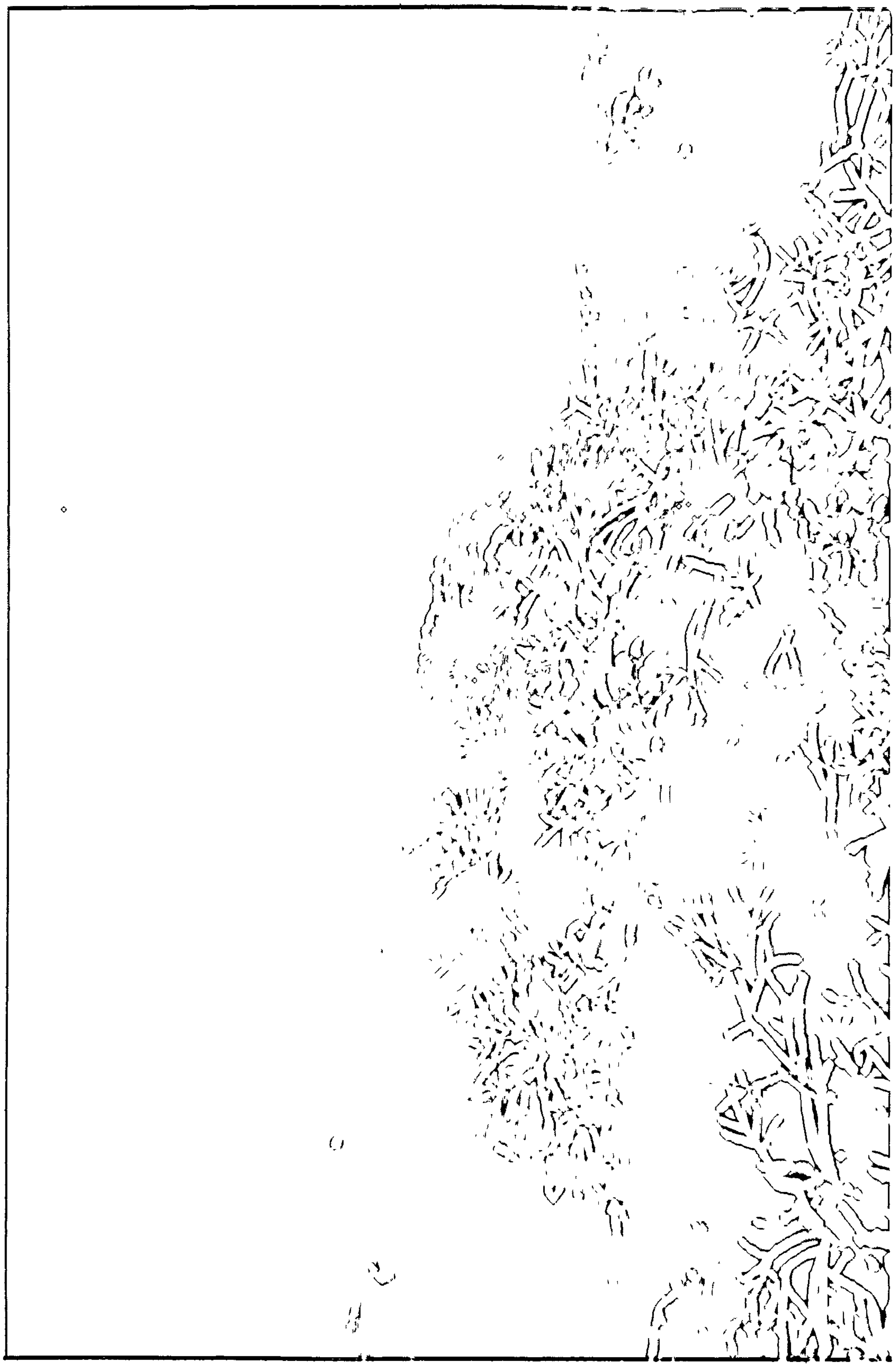
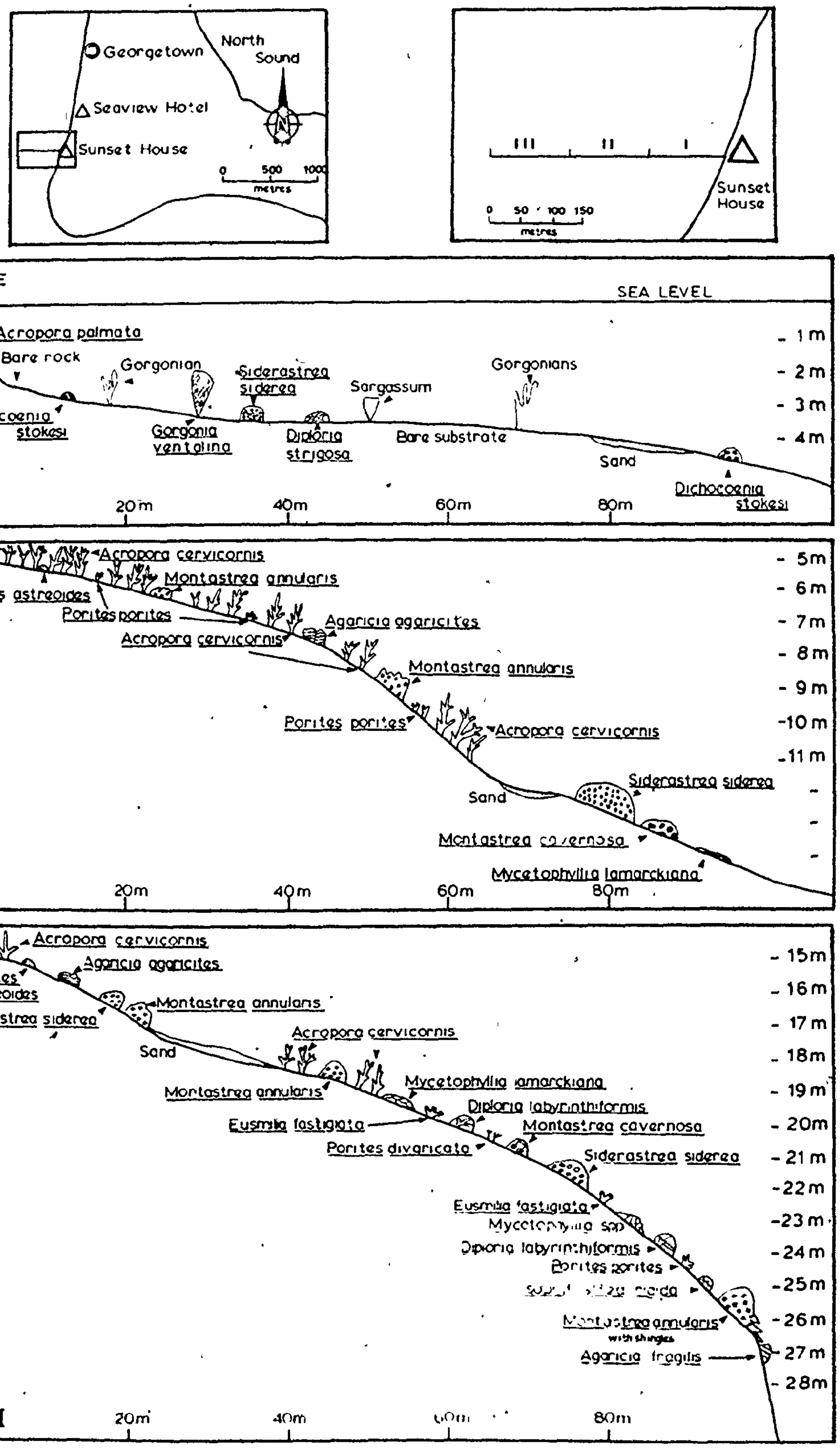


FIGURE 3-12 Transect perpendicular to the coast on the west end of Grand Cayman. See Figure 1-4 for location.


Georgetown
North Sound
Seaview Hotel
Sunset House
0 500 1000
metres
N
III II I
0 50 100 150
metres
Sunset House
SHORE
SEA LEVEL
Acropora palmata
Bare rock
Gorgonian
Siderastrea siderea
Sargassum
Gorgonians
Dichocoenia stokesi
Gorgonia ventalina
Diploria strigosa
Bare substrate
Sand
Dichocoenia stokesi
- 1 m
- 2 m
- 3 m
- 4 m
I
20m
40m
60m
80m
Acropora cervicornis
Montastrea annularis
Porites astreoides
Porites porites
Agaricia agaricites
Acropora cervicornis
Montastrea annularis
Porites porites
Acropora cervicornis
Siderastrea siderea
Sand
Montastrea cavernosa
Mycetophyllia lamarckiana
- 5m
- 6m
- 7m
- 8m
- 9m
-10m
-11m
II
20m
40m
60m
80m
Acropora cervicornis
Agaricia agaricites
Porites astreoides
Montastrea annularis
Siderastrea siderea
Sand
Acropora cervicornis
Montastrea annularis
Mycetophyllia lamarckiana
Diploria labyrinthiformis
Eusmilia fastigiata
Montastrea cavernosa
Porites divaricata
Siderastrea siderea
Eusmilia fastigiata
Mycetophyllia spp
Diploria labyrinthiformis
Porites porites
Montastrea annularis
with shingles
Agaricia fragilis
- 15m
- 16m
- 17m
- 18m
- 19m
- 20m
- 21m
-22m
-23m
-24m
-25m
-26m
-27m
- 28m
III
20m
40m
60m
80m

3.4.2 Species Abundance and Colony Sizes

The percentage coverage of the species at Cahuita and Grand Cayman are given in Table 3-14. From the transects, it can be seen that at Cahuita one species is abundant while the rest are rare (Fig. 3-13). If all the species of Scleractinian corals that were observed (including those not measured) during the study period are considered, the pattern where few species are numerically dominant is even more apparent (Table 3-15). This type of distribution is common in natural populations (Margalef, 1974). However, in a highly diverse system, such as Grand Cayman (Fig. 3-13, Table 3-16), generally several species are abundant, not just one.

Of the eighteen species encountered on the transects, six are common to both reefs. These are: *Agaricia agaricites*, *Porites porites*, *Porites astreoides*, *Siderastrea radians*, *Montastrea annularis* and *Acropora cervicornis*. Only the first four are found in sufficient amounts as to enable comparisons of colony sizes from both reefs (Table 3-17); *P. porites* is a branching coral so this type of comparison cannot be made here. *Agaricia agaricites*, *Porites astreoides* and *Siderastrea radians* are larger at Cahuita than at Grand Cayman. The trend seems to extend to other species that were not recorded in the transects. A larger size is indicative of older age (see Section 3.3.1). Few young specimens of the most common species

TABLE 3-14 Percentage of each species measured.
These values represent a total of 16 transects from Cahuita and 7 from Grand Cayman.

CAHUITA		GRAND CAYMAN	
Species	Percentage	Species	Percentage
1. *Agaricia agaricites*	54.61	1. *Acropora cervicornis*	41.48
2. *Siderastrea radians*	15.58	2. *Montastrea annularis*	22.90
3. *Porites porites*	13.04	3. *Agaricia agaricites*	16.75
4. *Porites astreoides*	6.49	4. *Porites porites*	6.94
5. *Diploria strigosa*	3.44	5. *Montastrea cavernosa*	2.96
6. *Acropora palmata*	3.15	6. *Diploria labyrinthiformis*	2.93
7. *Millepora complanata*	2.44	7. *Porites astreoides*	1.96
8. *Diploria clivosa*	0.74	8. *Porites divaricata*	1.41
9. *Montastrea annularis*	0.43	9. *Eusmilia fastigiata*	0.86
10. *Acropora cervicornis*	0.06	10. *Mycetophyllia lamarckiana*	0.73
		11. *Siderastrea radians*	0.49
		12. *Millepora alcicornis*	0.34
		13. *Siderastrea siderea*	0.12
		14. *Agaricia fragilis*	0.12

FIGURE 3-13 Percentage of each species measured at Cahuita and Grand Cayman. These values represent the total of 16 transects from Cahuita and 7 from Grand Cayman. Species numbered as in Table 3-14.

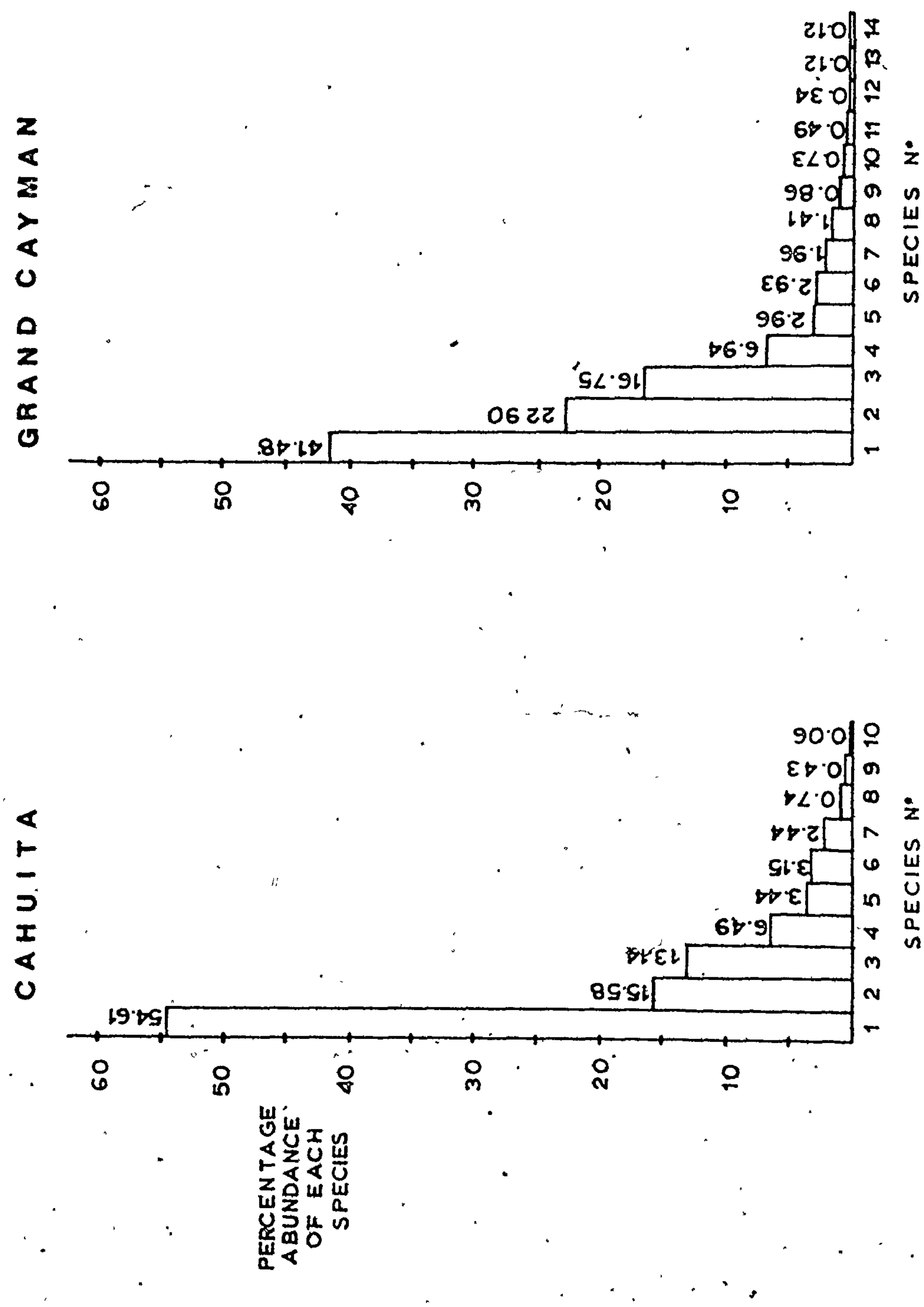

CAHUITA
GRAND CAYMAN
PERCENTAGE ABUNDANCE OF EACH SPECIES
SPECIES N°
60 50 40 30 20 10
1 2 3 4 5 6 7 8 9 10
54.61 15.58 13.14 6.49 3.44 3.15 2.44 0.74 0.43 0.06
1 2 3 4 5 6 7 8 9 10 11 12 13 14
41.48 22 90 16.75 6.94 2.96 2.93 1.96 1.41 0.86 0.73 0.49 0.34 0.12 0.12

TABLE 3-15 Coral species from Cahuita and their abundance.

Species	Very abundant[1]	Locally abundant[2]	common[3]	rare[4]
Acropora cervicornis				X
Acropora palmata	X			
Agaricia agaricites	X			
Agaricia fragilis				X
Astrangia solitaria				X
Cladocora arbuscula				X
Colpophyllia breviserialis				X
Colpophyllia natans			X	
Dichocoenia stellaris				X
Dichocoenia stokesi				X
Diploria clivosa	X			
Diploria strigosa	X			
Eusmilia fastigiata				X
Favia fragum				X
Helioseris cucullata				X
Isophyllia multiflora				X
Isophyllia sinuosa				X
Madracis decactis				X
Madracis mirabilis				X
Manicina areolata				X
Montastrea annularis			X	

TABLE 3-15 (cont'd)

Species	Very abundant[1]	Locally abundant[2]	common[3]	rare[4]
Montastrea cavernosa			X	
Mussa angulosa				X
Mycetophyllia danaana				X
Mycetophyllia lamarckiana				X
Oculina diffusa		X		
Porites astreoides		X		
Porites divaricata				X
Porites furcata			X	
Porites porites		X		
Siderastrea radians	X			
Siderastrea siderea		X		
Solenastrea bournoni				X
Stephanocoenia michelini				X

TOTAL SPECIES : 34

Very abundant :	5 (15%)	Locally abundant:	3	(9%)
Common:	4 (12%)	Rare:	22	(64%)

1: Very abundant: present all over the reef in large amounts.
2: Locally abundant: not found all over the reef but in large amounts where it is found.
3: Common: found all over the reef but not abundantly.
4: Rare: not widely distributed and only found in small amounts.

TABLE 3-16 Coral species observed at Grand Cayman and their abundance.

Species	Very abundant[1]	Locally abundant[2]	common[3]	rare[4]
Acropora cervicornis	X			
Acropora palmata	X			
Acropora prolifera				X
Agaricia agaricites	X			
Agaricia fragilis			X	
Agaricia sp				X
Colpophyllia natans	X			
Dichocoenia stokesi	X			
Diploria clivosa		X		
Diploria labyrinthiformis	X			
Diploria strigosa		X		
Eusmilia fastigiata		X		
Favia fragum				X
Helioseris cucullata				X
Isophyllastrea rigida				X
Isophyllia sinuosa				X
Madracis decactis		X		
Madracis mirabilis		X		
Meandrina meandrites				X
Montastrea annularis	X			

TABLE 3-16 (cont'd)

Species	Very abundant[1]	Locally abundant[2]	common[3]	rare[4]
Montastrea cavernosa		X		
Mussa angulosa				X
Mycetophyllia danaana			X	
Mycetophyllia ferox				X
Mycetophyllia lamarckiana			X	
Porites astreoides		X		
Porites divaricata		X		
Porites furcata			X	
Porites porites	X			
Scolynia lacera				X
Siderastrea radians		X		
Siderastrea siderea	X			

TOTAL SPECIES : 32

Very abundant :	9	(28%)	Locally abundant :	8	(25%)
Common :	4	(13%)	Rare :	11	(34%)

1: Very abundant: present all over the reef in large amounts.
2: Locally abundant: not found all over the reef but in large amounts where it is found.
3: Common: found all over the reef but not abundantly.
4: Rare: not widely distributed and only found in small amounts.

TABLE 3-17 Average head size of three species in common between Cahuita and Grand Cayman.

$\bar{X}$ = average; S.D. = standard deviation; S.E. = standard error; n = number of heads measured.

Species		CAHUITA	GRAND CAYMAN
Agaricia agaricites	$\bar{X}$ =	21.0 cm	6.6 cm
	S.D. =	3.0 cm	2.1 cm
	S.E. =	1.11 cm	1.09 cm
	n =	105	76
Porites astreoides		9.3 cm	7.0 cm
		1.9 cm	1.8 cm
		1.10 cm	1.22 cm
		48	8
Siderastrea radians		26.6 cm	4.6 cm
		2.4 cm	2.1 cm
		1.17 cm	1.52 cm
		32	3

at Cahuita were observed. The opposite case is evident at Grand Cayman where the size of the colonies is smaller, probably because of interspecific competition.

3.4.3 Diversity

Species diversity was calculated to evaluate the effect of environmental conditions on the reef community. The values of diversity, evenness and richness for the reef at Cahuita, Costa Rica, are given in Tables 3-18 and 3-19, (see Zar, 1974 for calculations of linear regression). There is a significant correlation ($r = -0.869$; $t_t = -6.586$; $t_{0.05(2)14} = 2.145$) between the Shannon-Weaver's diversity index and Simpson's index. Pielou's and Heip's indices of evennes also show a very significant correlation ($r = 0.977$, $t_t = 17.259$).

The diversity indices consider two aspects, the number of species present (species richness or species abundance) and their distribution in the community (species evenness or apecies equitability). In this case (Table 3-18), the Simpson's diversity index values reflect more closely the species evenness ($r = -0.830$, $t_t = -5.15$) than the species richness ($r = -0.690$, $t_t = -3.302$); while the Shannon-Weaver's index reflects closer the species richness ($r = 0.83$, $t_t = 5.15$) than the species evenness ($r = 0.67$, $t_t = 3.126$).

The values of diversity, evenness and richness for the reef at Grand Cayman are given in Tables 3-19 and 3-20. There is a very significant correlation ($r = -0.96$; $t_t = -7.929$;

TABLE 3-18 Values of diversity, evenness and richness of each transect from Cahuita Reef, Costa Rica.

Formulae to calculate these indices are given in Table 2-1.
The transects are numbered in the same way as in Appendix III.

Transect number	H'	Simpson	Evenness	H_{max}	Heip	Richness	# Species	Distance (cm)
1	0.555	0.720	0.400	1.386	0.247	0.404	4	1662
2	1.434	0.282	0.800	1.792	0.639	0.743	6	833
3	1.161	0.344	0.838	1.386	0.731	0.474	4	563
4	1.602	0.222	0.894	1.792	0.792	0.772	6	651
5	1.495	0.241	0.929	1.609	0.865	0.666	5	406
6	1.094	0.459	0.680	1.609	0.496	0.644	5	498
7	0.900	0.460	0.819	1.099	0.730	0.348	3	314
8	1.124	0.378	0.811	1.386	0.692	0.566	4	200
9	0.677	0.514	0.977	0.693	0.968	0.177	2	280
10	0.963	0.407	0.876	1.099	8.810	0.348	3	315
11	0.038	0.987	0.055	0.693	0.039	0.149	2	805
12	0.464	0.710	0.669	0.693	0.590	0.150	2	770
13	0.639	0.551	0.922	0.693	0.894	0.169	2	370
14	0.838	0.515	0.762	1.099	0.656	0.362	3	250
15	1.213	0.327	0.875	1.386	0.788	0.271	4	40
16	1.077	0.343	0.980	1.099	0.968	0.401	3	147

TABLE 3-19 Values of diversity, evenness and richness for the whole reef.

Formulae for these indices are given in Table 2-1. The diversity values were tested for difference following the procedure outlined in Zar (1974, p. 115).

	CAHUITA	GRAND CAYMAN
H'	1.443	1.670
Simpson	0.346	0.260
Evenness	0.627	0.633
H_{max}	2.302	2.639
Heip	0.359	0.332
Richness	1.000	1.606
# Species	10	14
Total distance (cm)	8104	3271

Test for difference between the diversity indices of Cahuita and Grand Cayman.

H_o = the diversity of Cahuita is the same as the diversity of Grand Cayman.

H_a = the diversity of Cahuita and Grand Cayman are different.

t = 10.489 t 0.01(2), 2 = 9.925

Therefore, reject H_o. The two indices are different.

TABLE 3-20 Values of diversity, evenness and richness of each transect from Grand Cayman.

Formulae to calculate these indices are given in Table 2-1. The transects are numbered in the same way as in Appendix IV.

Transect number	H'	Simpson	Evenness	H_{max}	Heip	Richness	# Species	Distance (cm)
1	0.903	0.490	0.651	1.386	0.489	0.484	4	494
2	1.326	0.327	0.740	1.792	0.553	0.787	6	573
3	1.483	0.272	0.675	2.197	0.426	1.278	9	523
4	1.096	0.380	0.681	1.609	0.498	0.604	5	747
5	1.557	0.263	0.749	2.079	0.535	1.250	8	270
6	1.596	0.198	0.726	2.197	0.492	1.341	9	390
7	1.725	0.235	0.785	2.197	0.576	1.425	9	274

$t_{0.05(2)5}$= 2.571) between Shannon-Weaver's diversity index and Simpson's index. Pielou's and Heip's indices of evenness also show a significant correlation (r= 0.81; t_t= 3.048). In Grand Cayman, both the Shannon-Weaver and the Simpson diversity indices are significantly correlated with the species richness (r= 0.97; t_t= 8.820 and r= -0.93, t_t= -5.929, respectively), but both are less related to the species evenness (r= 0.80, t_t= 2.973 for Shannon-Weaver, and r= -0.70, t_t= -2.213 for Simpson).

At Cahuita there is a significant inverse relation between the live coral coverage and diversity (r= -0.69; t_t= -3.567; $t_{0.05(2)14}$= 2.145); that is, the higher the percentage of live coral, the lower the diversity (Table 3-12). There is also a significant inverse relation between depth of the transect and diversity (r= -0.57; t_t= -2.596). The deeper transects (4-5 m) are less diverse than the shallower (1-2 m) ones (Table 3-12). The direct relation between percentage of live coral and depth is highly significant (r= 0.83; t_t= 5.643). The greater the depth, the higher the percentage of live coral and the lower the diversity. No significant relations were found between substrate diversity and percentage of dead coral or depth of transect.

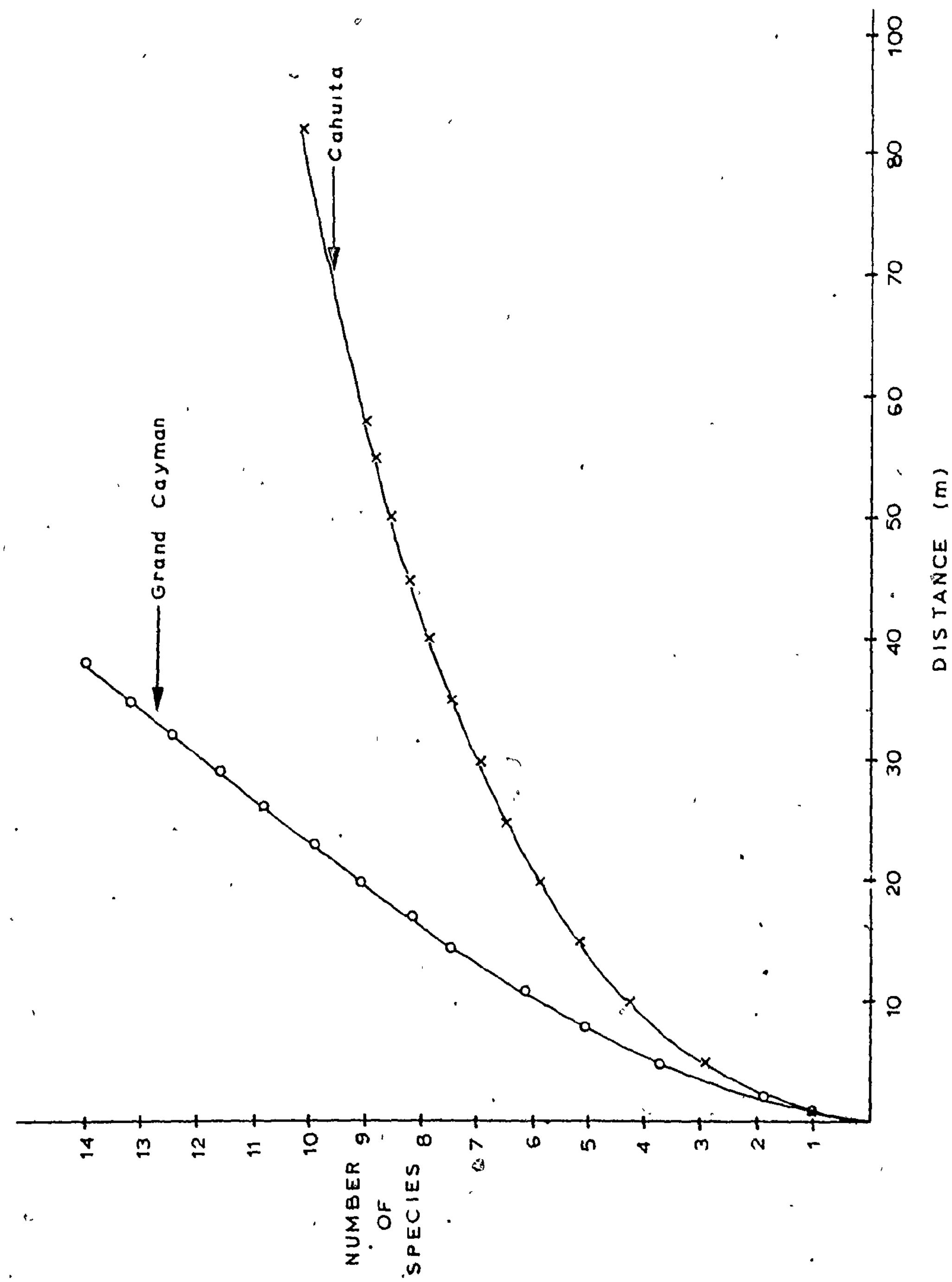
At Grand Cayman (Table 3-13) diversity increases with depth (depth vs. H'; r= 0.76; t_t= 2.615; $t_{0.05(2)5}$= 2.571). The shallower transects (5 and 7 m) have lower diversity than the transects between 13 and 16 m. None of the other relations (percentage of live coral vs. depth; percentage of dead coral vs. substrate diversity; percentage of live coral vs. diversity) are significant at the $\alpha = 0.05$ level for the seven transects made at Grand Cayman.

The reefs from Cahuita and Grand Cayman are compared as a whole in Table 3-19. The test for difference between Shannon-Weaver's diversity indices proposed by Hutcheson (1970) and described in Zar (1974) was used. The diversity indices are significantly different, being higher for Grand Cayman (Table 3-19).

Rarefaction curves are very convenient in characterizing and comparing the diversity of communities (Tipper, 1979). The rarefaction method allows comparison of different sample sizes. Taking into consideration the drawbacks of this method and applying more accurate approximations, the diversity of the reef at Cahuita was compared to the diversity of the reef at Grand Cayman (Fig. 3-14).

The two-sided Smirnov test (T') is suggested by Tipper (1979) as a simple and direct way to compare rarefaction curves. This test was applied to the curves on Figure 3-14 (T'= 0.414). With a significance level $\alpha = 0.05$, the quantile for the two-sided Smirnov test is approximately 0.5 (Conover, 1971, Table 17). Hence, at this level of significance, the two curves are not different. At a significant level of

FIGURE 3-14 Rarefaction curves for Cahuita and Grand Cayman reefs. Points calculated using the formula given in Heck *et al.* (1975) and in Tipper (1979).


Grand Cayman
Cahuita
NUMBER OF SPECIES
14
13
12
11
10
9
8
7
6
5
4
3
2
1
DISTANCE (m)
10
20
30
40
50
60
70
80
100

$\alpha = 0.1$ ($T_{0.1(2)_{7,5}} = 0.4$), the two curves are different. Significant differences were noted when other tests (Eason *et al.*, 1980) were applied. The differences between the tests and the difference of the curves at a slightly lower level of significance, probably reflect the conservative characteristic of the Smirnov test (Conover, 1971; Tipper, 1979).

3.5 Oceanographic Setting

3.5.1 Currents

Current speed and direction over the reef can give some insight about the source and trajectory of sediments. Two drogues were used for this purpose. Direction and speed were calculated from bearings taken from shore. Average speed of the two drogues is recorded in Table 3-21, together with wave and wind conditions during the run. The trajectories of the drogues were erratic (Fig. 3-15). Apparently, the direction of the drogues is controlled by the prevailing winds and currents in the reef and around coral patches.

A general direction of the currents over the reef was determined after analysing all the data (Fig. 3-16). The currents flow roughly from the north-west to the south-east. Their speed seems to depend upon the prevailing winds.

Currents along the coast north of the reef were not measured, because the water there is exceptionally rough. However, from LANDSAT photographs (Fig. 3-17), and from

TABLE 3-21 Dates, wave and wind condition, and average speed of drogues at Cahuita Reef.

First value each day corresponds to drogue 1, which was always set farther from shore. The second value corresponds to drogue 2, set nearshore.

Date	Waves	Wind	Speed
9-VI-1979	Calm	Very little	4 m/min 4 m/min
10-VI-1979	Calm	Very little	2 m/min 3 m/min
29-VI-1979	Very rough	Some wind away from the coast	10 m/min 4 m/min
30-VI-1979 Morning	Very rough	Very windy	19 m/min
30-VI-1979 Afternoon	Very rough	Windy	11 m/min 7 m/min
10-VII-1979	Rough	Some wind	5 m/min 6 m/min
11-VII-1979	Rough	Windy	8 m/min 10 m/min

FIGURE 3-15 Representative example of the erratic course followed by the drogues through the reef at Cahuita. A and B are fixed points on the beach from which the drogues were tracked. Run, morning of the 11-VII-1979.

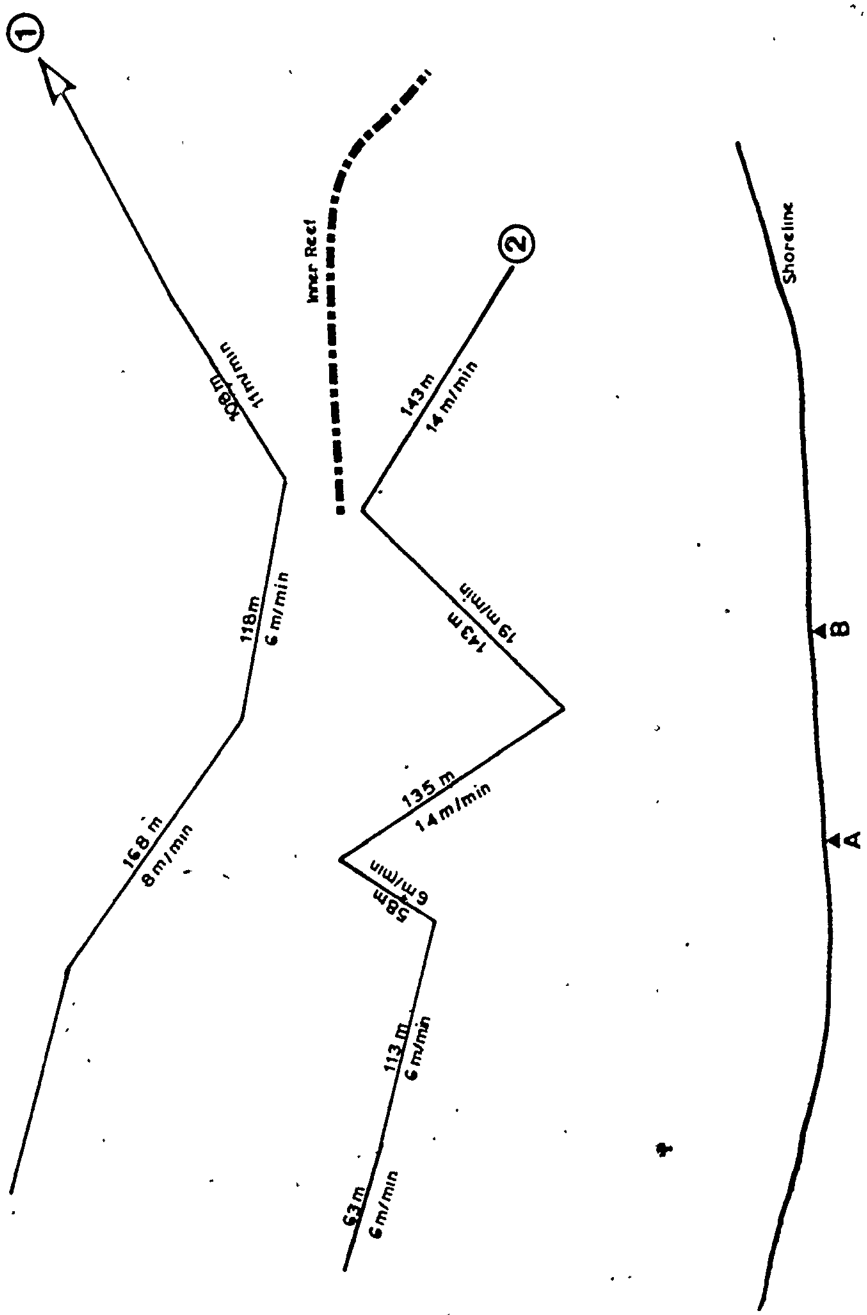

1
2
Inner Reef
Shoreline
B
A
108 m
11 m/min
118m
6 m/min
168 m
8 m/min
143 m
14 m/min
143 m
19 m/min
135 m
14 m/min
58m
6 m/min
113 m
6 m/min
63 m
6 m/min

FIGURE 3-16 General direction of the currents over the reef at Cahuita.

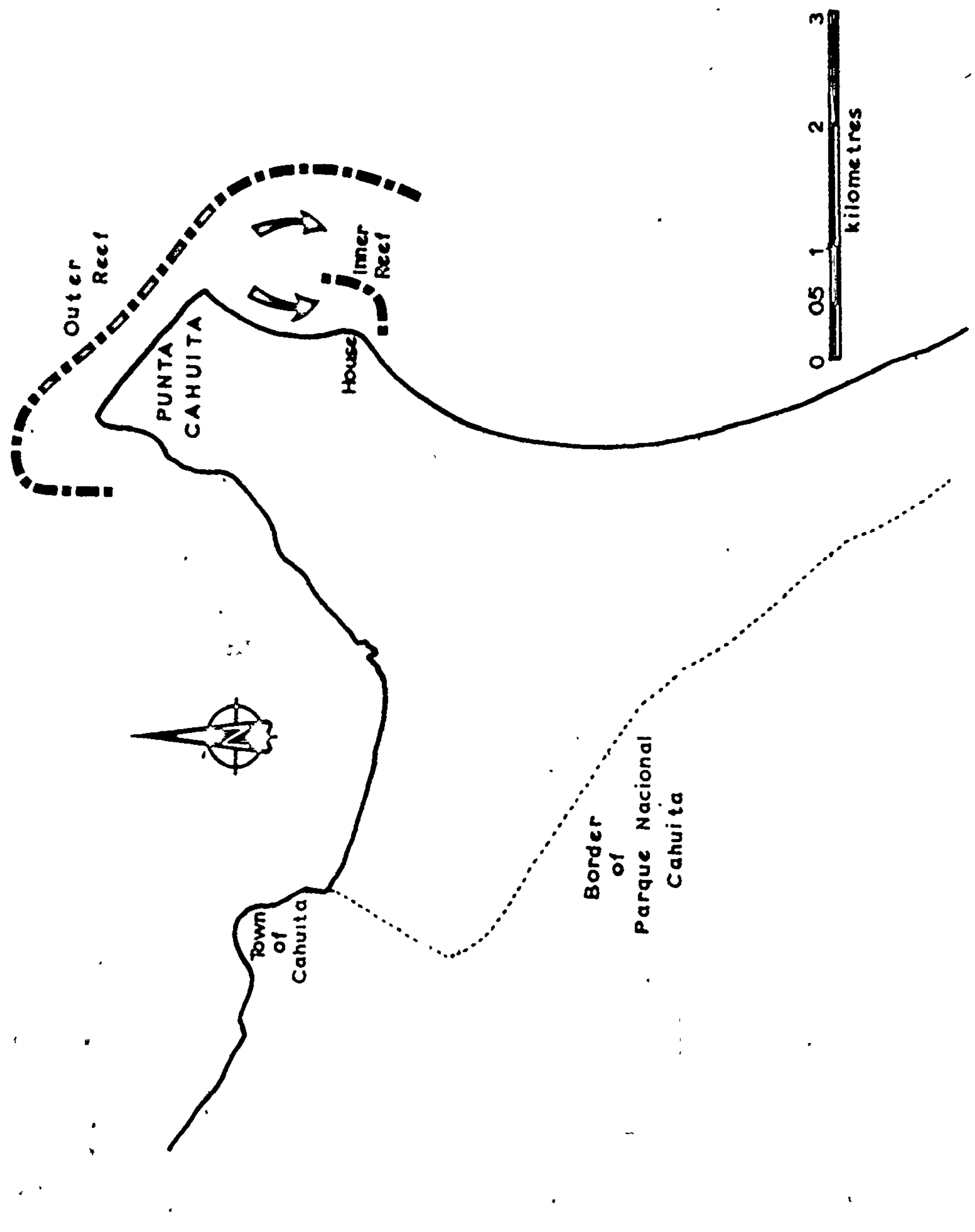
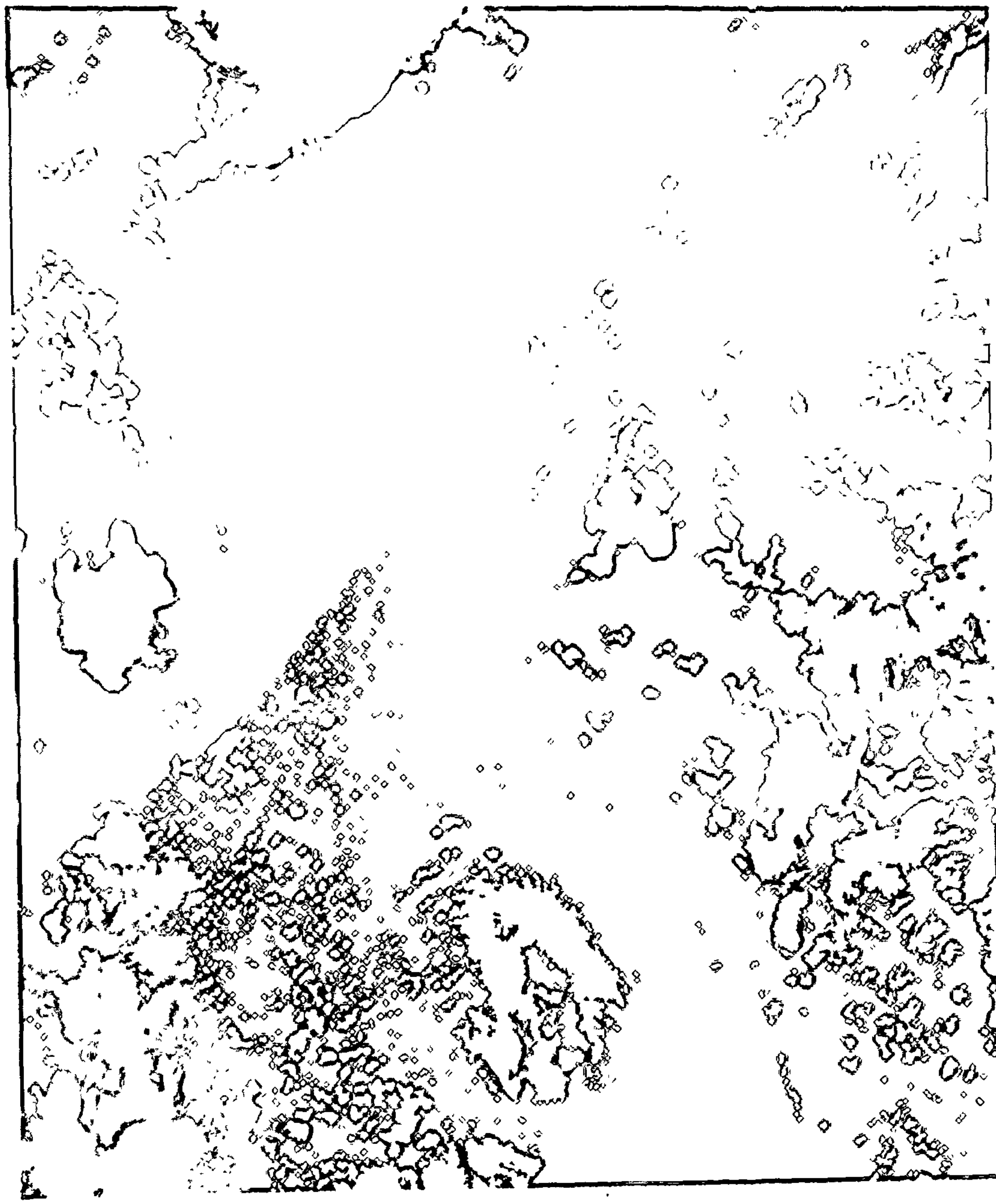

Outer Reef
Inner Reef
PUNTA CAHUITA
House
Town of Cahuita
Border of Parque Nacional Cahuita
0 0.5 1 2 3
kilometres

FIGURE 3-17 LANDSAT photograph of the Atlantic coast of Costa Rica. The arrow shows the Cahuita reef. Note the plume of the rivers directed towards the south-east.



observations of the river mouths on the Atlantic coast (Risk *et al.*, 1980), it is evident that they flow from the northwest to the southeast. An eddy system moving from west to east is created along the north coast of southern Central America by the main east-west currents prevailing in the Caribbean (Collier, 1964, fig. 2).

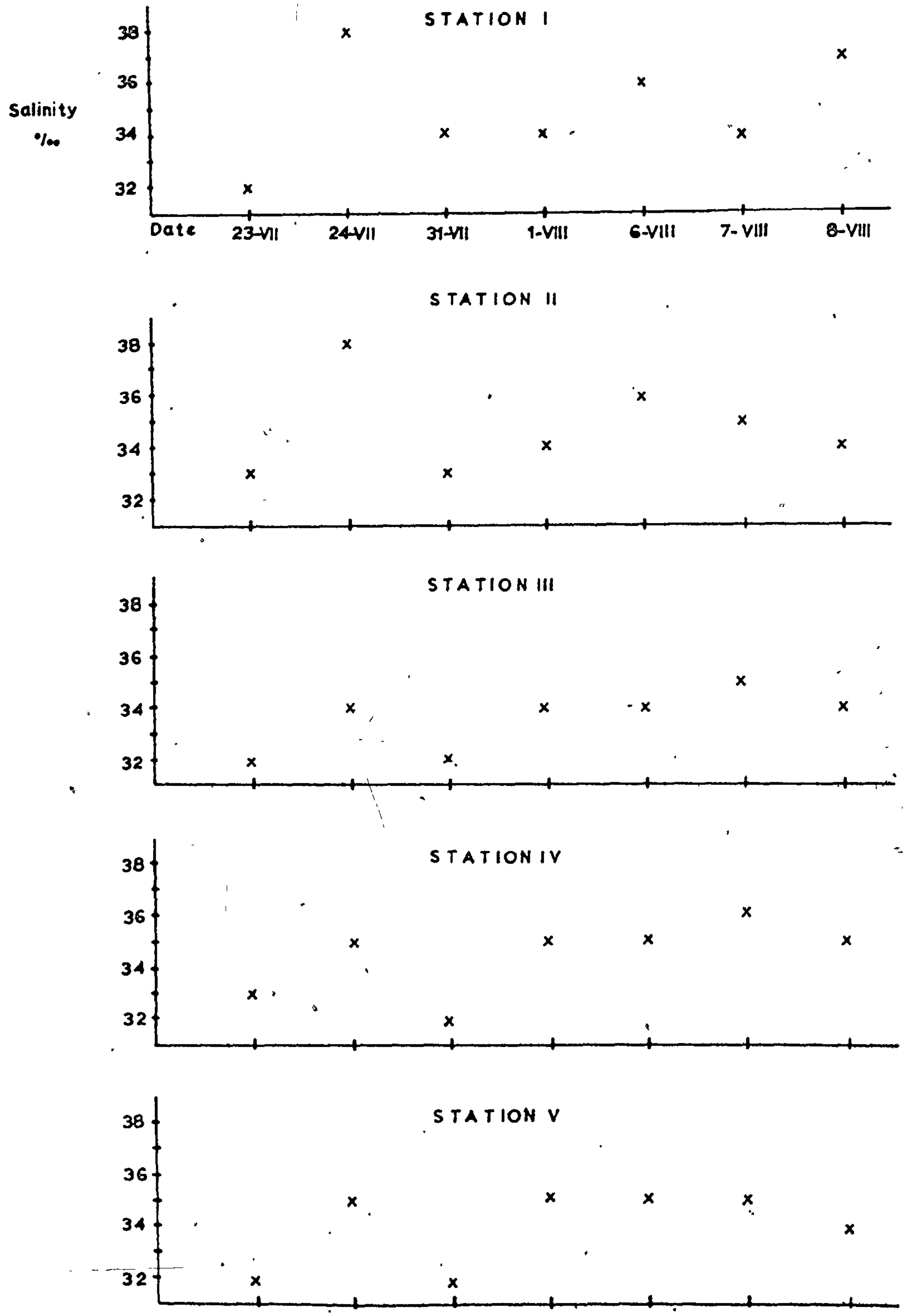
3.5.2 Salinity

Salinity was measured with a Hand Refractometer during July and August, 1980. The values obtained range from a low of 32 o/oo (o/oo: parts per thousand), after heavy rains to a high of 38 o/oo, with an average around 34 o/oo (Fig. 3-18). Measurements made by Wellington (1974) from October, 1972 to January, 1973, range from a low of 31.5 o/oo to a high of 36.5 o/oo, the average being around 34 o/oo. These values are within the salinity tolerances of Scleractinian corals, that is, 27 to 40 o/oo (Wells, 1956, 1957). Thus, even after a period of heavy rains or under intense radiation, salinity at Cahuita stays within the limits of tolerance by corals.

3.5.3 Temperature

Wellington (1974) made temperature readings for the study area during his research; the values he obtained range from a low of 27^{0}C to a high of 30^{0}C, with an average value of 28^{0}C. Measurements for this study during December 1979 and the summer of 1980 gave an average of 28^{0}C as well.

FIGURE 3-18 Salinity values on different parts of the reef. For location see Figure 2-12. Salinity was determined with a Hand Refractometer.


STATION I
Salinity
°/oo
38
36
34
32
Date
23-VII
24-VII
31-VII
1-VIII
6-VIII
7- VIII
8-VIII
STATION II
STATION III
STATION IV
STATION V

Tolerance limits for hermatypic Scleractinian corals are between 18°C and 36°C (Smith, 1976; Glynn, 1977). The range of temperature within which they grow best is between 25°C and 29°C (Wells, 1956). The water temperature at Cahuita is then, optimum for coral growth.

3.6 Geochemical Analysis

X-ray diffraction was used to analyse sediment samples from Cahuita and from Grand Cayman. The suites of minerals present in each type of sample are given in Table 3-22. The mineral suites of the samples from Cahuita consist mainly of clays and the typical reef minerals, and are very similar to the river samples (Fig. 3-19). The minerals at Grand Cayman are aragonite, calcite and quartz. Halite was the only mineral detected in the coral dissolved residue from Grand Cayman. This is probably a product of not enough rinsing of the filters.

Analysis of trapped sediments in corals from Cahuita at different depths in the heads do not show any changes. The sediments present on the reef fifteen years ago (probable age of deeper sample) is the same as the sediments present two or three years ago.

Suspended sediment samples taken on the northern part of the reef during the storm of the 6-VIII-1980 (see Section 3.1) have an XRD trace almost exactly that of the river. This possibly indicates the transport of fresh sediments from

TABLE 3-22 Mineral suite present in each type of sample, from Cahuita and Grand Cayman. Determinations by X-ray diffraction and visual observations*.

SAMPLE	MINERALS[1]
Trapped sediments in corals from Cahuita	F-Q-M-K-I
Trapped sediments in corals from Grand Cayman	H
Bottom sediments from Cahuita	A-C*-Q-F-M-K-I
Bottom sediments from Grand Cayman	A*-C*-Q
Suspended sediments from Cahuita	A-Q-M-F
Suspended sediments from Grand Cayman	N.D[2]
Suspended sediments from Rio La Estrella	Ma-F-Q-I-M-K
Resuspended sediments in Trap #3	A-Q-M-F

---

[1]Minerals: F- Feldspar; Q- Quartz; M- Montmorillonite; K- Kaolinite; I- Illite; H- Halite; A- Aragonite; C- Calcite; Ma- Magnetite.

[2]N.D.- Not Determined, quantities too low for determination.

the river mouth to the reef. Samples from the reef at other times are different in the minor peaks, but similar in most of the main minerals.

The climate at Cahuita is humid and hot. Under these conditions, illite, feldspar and montmorillonite should degrade to kaolinite and then to gibbsite. Gibbsite was not found. Illite and kaolinite were found in the bottom sediments and trapped in corals from Cahuita, and in the river samples (Table 3-22). Feldspar and montmorillonite were found in all the samples from Cahuita, and the river. Magnetite was identified in several of the river samples.

The presence of illite, feldspar and montmorillonite could be explained by the short distance between the volcanic mountains and the sea.

FIGURE 3-19 X-ray diffractograms of Cahuita Reef and Rio La Estrella sediments.

RS = River Sediments

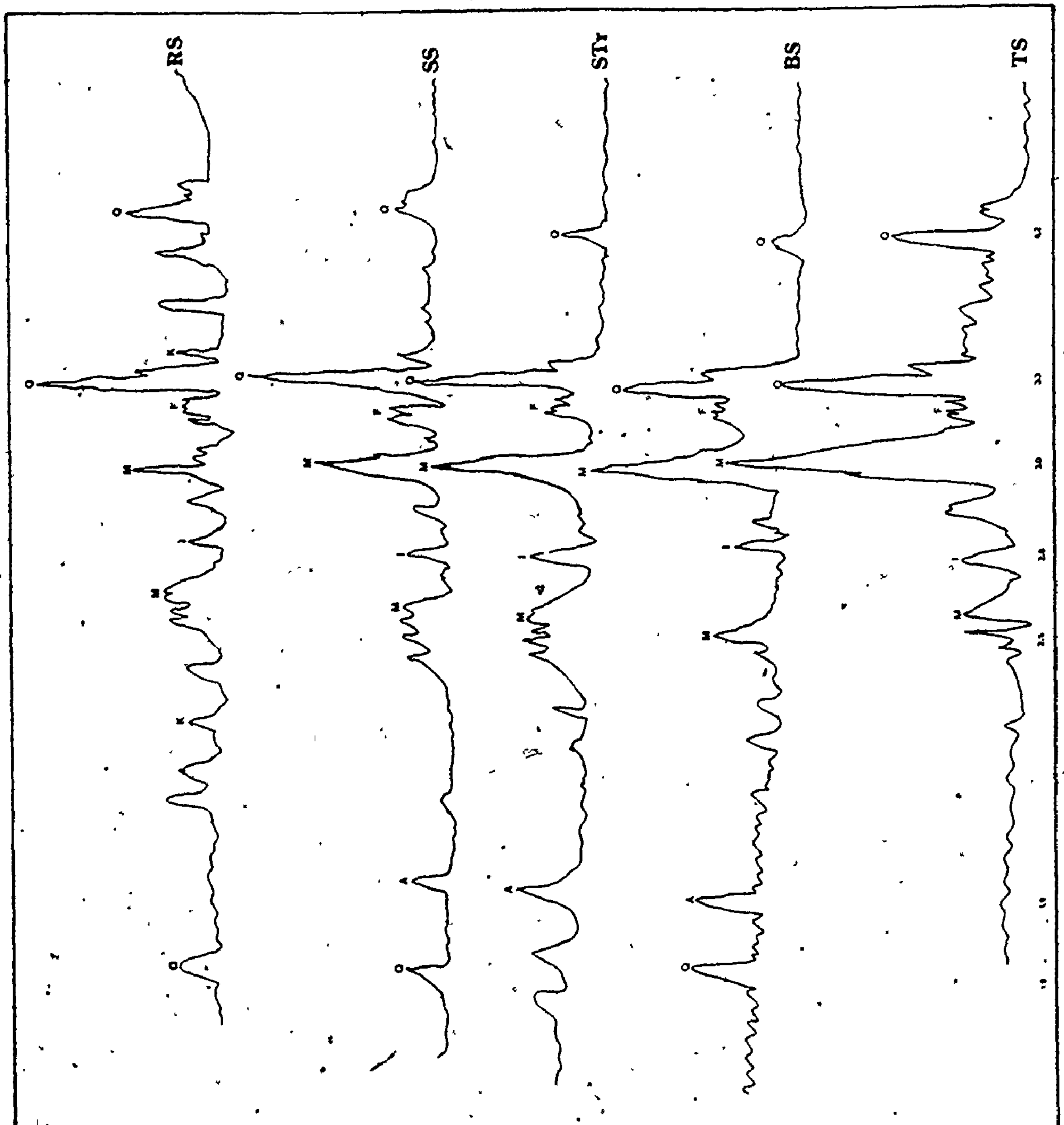
SS = Suspended Sediments

STr = Sediments Trap # #, 50 cm from the bottom

BS = Bottom Sediments

TS = Sediments Trapped in the coral skeleton

The letters Q, F, M, I, and A refer to the minerals quartz, feldspar, montmorillonite, illite and aragonite, respectively.


RS
SS
STr
BS
TS

CHAPTER 4

DISCUSSION

The environmental conditions at Cahuita Reef, that is, salinity (Section 3.5.2), temperature (Section 3.5.3) and solar radiation, are ideal for coral growth (Wells, 1956; 1957). However, one important parameter, the amount of suspended sediments (7.4 mg/l, range 0.1 to 212.7 mg/l) is higher in Cahuita than in any other reef studied in the Caribbean (Glynn, 1973; Rogers, 1977; personal observations). The values of resuspended sediments at Cahuita 50 cm from the bottom are much higher (30 to 360 mg/cm^2/day) than the values reported for Jamaica (0.45 to 1.1 mg/cm^2/day; Dodge *et al.*, 1974; Aller and Dodge, 1974) or from Puerto Rico (1 to 21 mg/cm^2/day; Rogers, 1977). Values of resuspended sediments from stressed reefs in Kaneohe Bay, Hawaii (Maragos, 1972 *fide* Rogers, 1977) are as high or higher than at Cahuita (35 to 41,096 mg/cm^2/day).

How do the sediments affect the individual corals? And, how do they affect the coral community structure?

Sediments can affect the corals in several ways: 1) energy drain; 2) blocking the light necessary for the photosynthesis of the symbiotic zooxanthellae; and

3) interference with feeding.

1.- Energy drain

Corals can remove sediments that deposit on them by several mechanisms: a) tentacular action; b) ciliary movement; c) distension of the body, and d) mucus entanglement (Hubbard and Pocock, 1972; Hubbard, 1973; Bak and Elgershuizen, 1976). All these mechanisms require energy, energy that can not be used for growing, reproduction or repairing wounds.

2.- Blocking of light

It has been proven that the symbiotic zooxanthellae aid the corals in the formation of their carbonate skeletons. How do they contribute to this is at present reason for discussion (Goreau, 1959b; Simkiss, 1964a; 1964b; Muscatine and Cermichiari, 1969; Lewis and Smith, 1971; Pearse and Muscatine, 1971; Taylor 1977; Muscatine and D'Elia, 1978; Muscatine *et al.*, 1979). Rogers (1979) gives experimental evidence demonstrating that the lack of light reaching the corals because of suspended sediments has a more profound effect on some coral species than the sediments *per se*.

3.- Interference with feeding

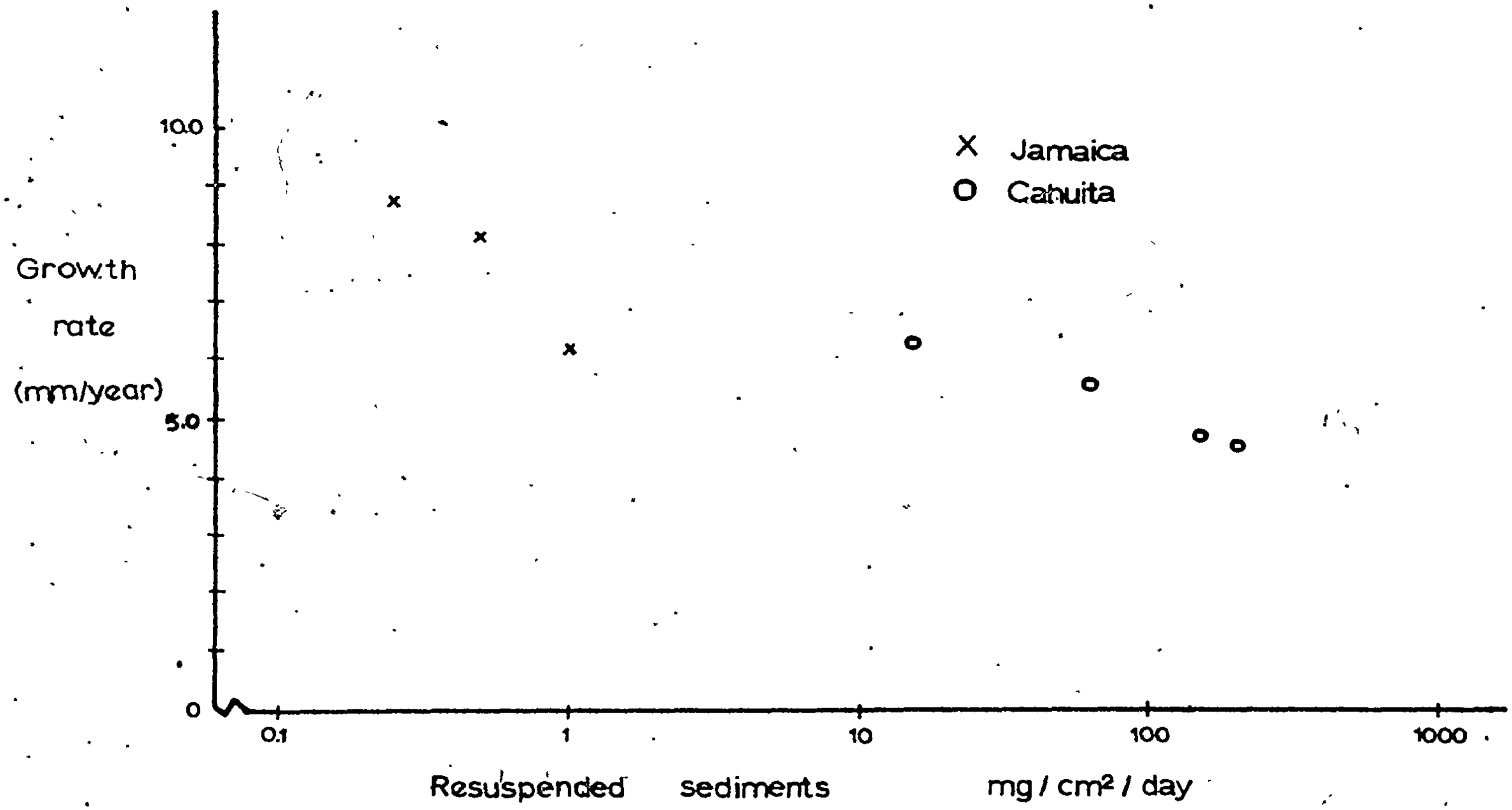
The corals remove zooplankton from the water column. The more suspended sediments present, the harder it will be for the corals to feed themselves. This last factor may not be critical, since it has been shown that the dependence on plankton of most corals is small or non-existant (Johanness *et al.*, 1970; Johannes, 1974; Johannes and Tepley, 1974).

The effect of the energy drain, blocking of light and interference with feeding will result in a lowering of the growth rates (Dodge *et al.*, 1974; Aller and Dodge, 1974; Dodge and Vaisnys, 1977), reduction in the regeneration capacity (Bak *et al.*, 1977; Bak and Steward-Van Es, 1980), and, in extreme cases, death of the corals (Dodge and Vaisnys, 1977; Bak, 1978; Thompson, 1979) and skeletal deterioration (Rogers, 1977; 1979).

The growth rates of the corals from Cahuita are lower (5.3 mm/year, range 3.7±0.8 to 7.7±0.4 mm/year) than at Grand Cayman (12.4 mm/year, average of two corals) and other areas of the Caribbean (see Table 3-8). Figure 4-1 shows the average growth rates of corals and the amount of resuspended sediments in Discovery Bay, Jamaica (Dodge *et al.*, 1974; Aller and Dodge, 1974), and in Cahuita. There is a significant correlation between the growth rate and the log of the amount of resuspended sediments ($r = -0.77$, $t_t = -2.75$, $t_{0.05(2)7} = 2.365$).

The amount of trapped sediments in the coral skeletons is higher at Cahuita (0.0533±0.0510 %/wt.), than in Grand Cayman (0.0180±0.0074 %/wt.), and the growth rates of the

FIGURE 4-1 Resuspension of bottom sediments (50 cm from the bottom, in $mg/cm^2/day$) *versus* growth rate in mm/year. Data from Jamaica in Dodge *et al.* (1974) and Aller and Dodge (1974).


Jamaica
Cahuita
Growth rate (mm/year)
10.0
5.0
0
0.1
1
10
100
1000
Resuspended sediments mg / cm² / day

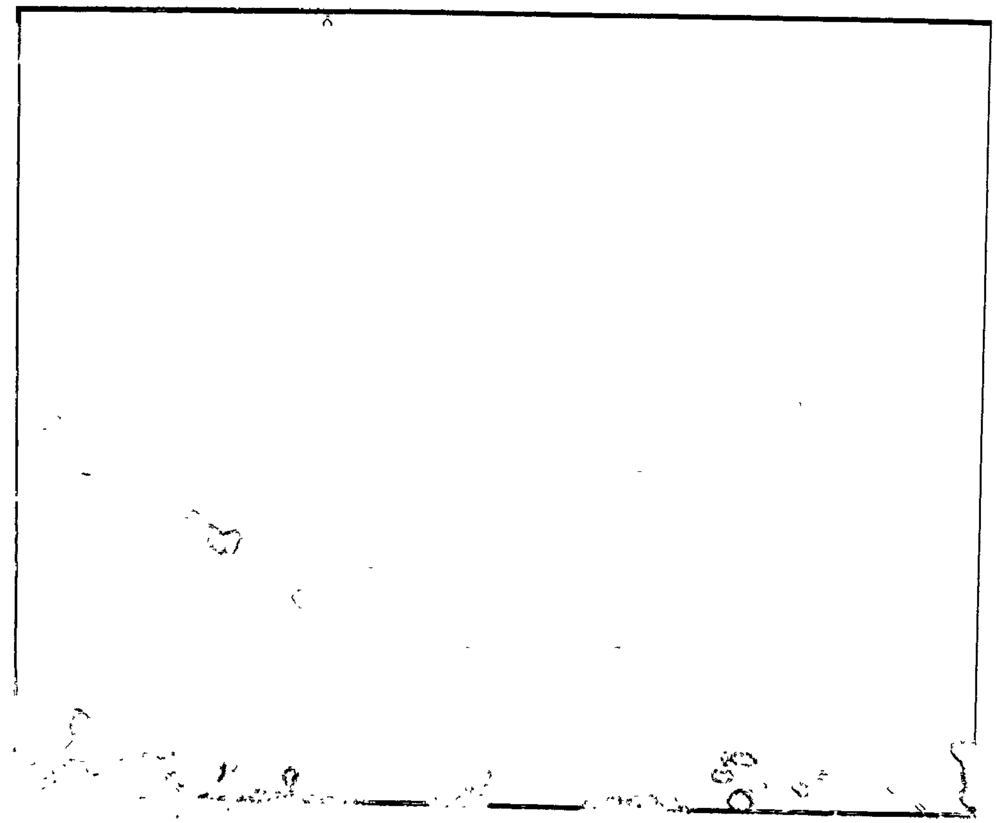
corals at Cahuita are lower than at Grand Cayman. There was no significant correlation between the amount of trapped sediments in the Cahuita corals and their growth rates. This is probably due to the fact that the sediments are trapped when the polyp is damaged. If the damage is localized, the growth rate of the whole colony will not be affected much.

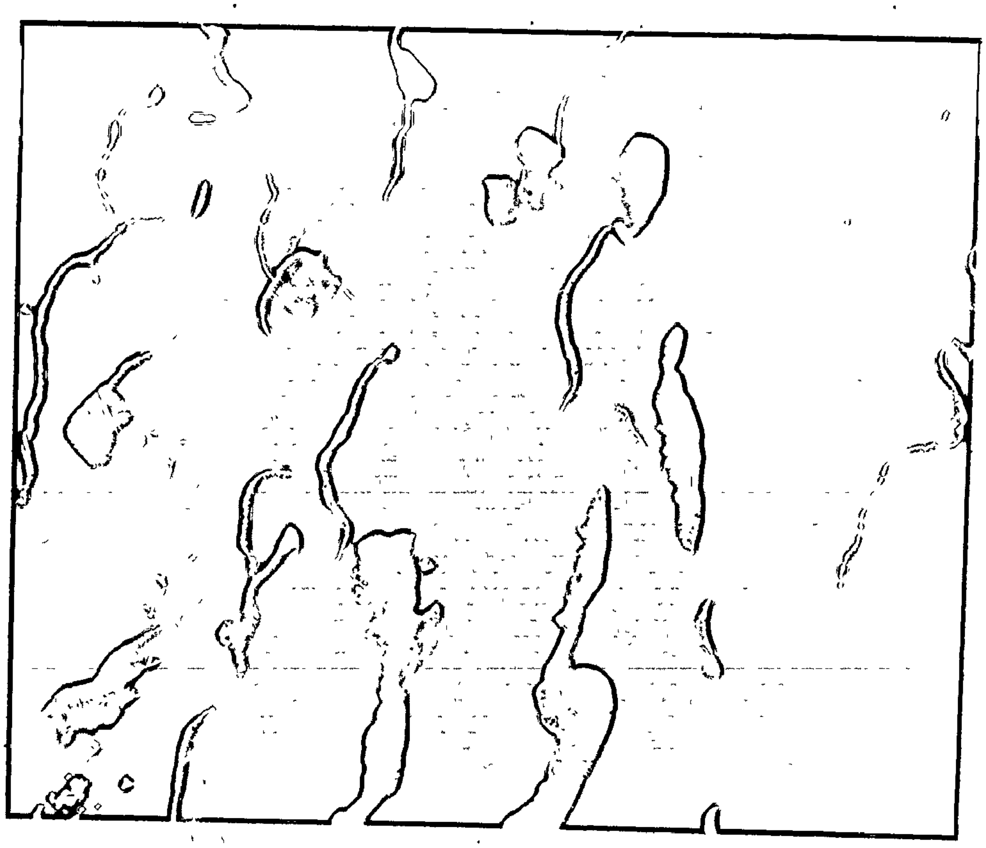
The sediments in the water column scatter and absorb light, so the amount of radiant energy reaching the corals is reduced in a turbid environment. Two species of corals, *Montastrea annularis* and *Porites astreoides*, respond to the low light levels at Cahuita by having, in less than 5 m, the deep-water morphology ("shingles", Fig. 4-2) normally observed under 20 m in other reefs (Goreau, 1959a, Dustan, 1975; Graus and Macintyre, 1976).

Sediments in a reef environment also have effects on the community structure. Hierarchies of coral's ability to withstand sediments can be erected from the work of Hubbard and Pocock (1972), Hubbard (1973), and Bak and Elgershuizen (1976). The community structure at Cahuita corals reflects this hierarchy (Table 4-1). The most abundant species at Cahuita have good or very good ability to reject sediments. There are some exceptions though, for example, *Manicina areolata* is one of the best sediment rejectors but it is rarely found at Cahuita. On the other hand, *Porites astreoides* is bad at rejecting sediments but it is very

FIGURE 4-2 *Montastrea annularis* at only 4 m showing a typical deep-water morphology (shingles). This is normally observed under 20 m in other reefs. Area photographed is about 1 m across the centre. Cahuita Reef.

FIGURE 4-3 *Agaricia agaricites* with its fronds vertically oriented, a position more resistant to siltation. Area photographed is about 30 cm across the centre. Cahuita Reef.





abundant on the reef crest, whereas in other Caribbean reefs it is mostly found on the back or reef front. Possibly the wave action has a positive effect on removing sediments.

Montastrea annularis is the main frame-building coral in the Caribbean (Goreau, 1959a), but it is not abundant at Cahuita. This species is a poor sediment remover (Bak and Elgershuizen, 1976) and was deeply affected by sediments though not as much as by shading (Rogers, 1977; 1979). Rogers (*op.cit.*) found that *Acropora cervicornis* is resistant to sediments, but weakens until deterioration of the skeleton by shading. Maybe this is why they are so rare at Cahuita.

Montastrea cavernosa was found to be the main reef-building coral in a turbid reef off the west coast of Puerto Rico (Loya, 1976). This coral has a good ability to reject sediments (Table 4-1), but it is not abundant at Cahuita. This species depends largely on zooplankton for its nutrition (Porter, 1974), and large amounts of suspended sediments must hinder feeding. *Agaricia agaricites* growing in vertical fronds can withstand higher sedimentation rates than in any other orientation (Bak and Elgershuizen, 1976; Bak, 1978). *Agaricia agaricites* covered extensive areas of the reef at Cahuita (Fig. 3-9) and it was almost always vertically oriented (Fig. 4-3).

Another effect of the sediments on the coral community is the reduction of live coral and species diversity. It has

TABLE 4-1 Abundance and ability to reject sediments of some coral species at Cahuita.

Species	Abundance	Ability to reject sediments*
Acropora palmata (Lamarck)	1	vertical branches - very good horizontal branches- bad
Agaricia agaricites (Pallas)	1	vertical fronds - very good horizontal fronds - bad
Colpophyllia natans (Muller)	3	very good
Diploria strigosa (Dana)	1	good
Manicina areolata (Linnaeus)	4	very good
Montastrea annularis (Ellis & Solander)	3	bad
Montastrea cavernosa (Linnaeus)	3	good
Porites astreoides Lesueur	2	bad
Porites porites (Pallas)	2	good
Siderastrea siderea (Ellis & Solander)	2	good

* After Bak and Elgershizen, 1976

1- Very abundant 2- Locally abundant 3- Common 4- Rare
(Definition of 1, 2, 3 and 4 as in Table 3-15)

been observed that where turbidity is higher, the percentage of live coral coverage is lower (Roy and Smith, 1971; Loya, 1976). At Cahuita, the percentage of live coral (40%, 7.4 mg/l suspended sediments) is lower than at Grand Cayman (63%, 2.0 mg/l). At Fanning Island (Roy and Smith; 1971) live coral covers 31% of the turbid area (3.5 mg/l carbonate sediment) and 62% of the clear-water area (1.0 mg/l). Loya (1976) found off the west coast of Puerto Rico, that where turbidity was high (5.5 FTU, Formazin Turbidity Units) live coral coverage was only 30%, while in clear water (1.5 FTU) it was 79%.

An inverse relation exists between the amount of suspended sediments and the coral species diversity. At Cahuita, diversity (H') is 1.443 (range 0.038 to 1.602, 7.4 mg/l suspended sediments) while at Grand Cayman it is H' = 1.670 (range 1.238 to 1.844, 2.0 mg/l suspended sediments). Porter (1972) hypothesized that sedimentation in the back shelf region of the reef at San Blas, Panamá was partially responsible for the lower species diversity of this area. In reefs off the west coast of Puerto Rico (Loya, 1976) diversity was lower (H'= 1.830) where turbidity was higher (5.5 FTU), and higher (H'= 2.196) where turbidity was lower (1.5 FTU).

Large concentrations of suspended sediments will reduce the live coral coverage and the species diversity in several ways: 1) death of colonies smothered under the sediments; 2) death of part of the colony that fails to recover from a wound; 3) complete or partial death due to low ilumination; 4) selective elimination of species that are not able to remove sediments and dominance of species with a good ability to reject sediments; and 5) inability of the coral planulae (motile larval stage) to settle in areas of high sedimentation (this will be further discussed below).

Points 1, 2, and 3 explain how the live coral coverage will be reduced in a turbid environment. Points 4 and 5 explain how the coral diversity will be lowered. Diversity has two components, the number of species and their evenness of distribution. Selective elimination of species by sediments will reduce the number of different species and will increase the unevenness between the amount of members of each species.

Many researchers have hypothesized that coral planulae (larval stage) will not settle, or will suffer a high mortality in areas with large amounts of sediments (Stephenson *et al.*, 1958; Yonge, 1963; Loya and Slobodkin, 1971; Roy and Smith, 1971; Maragos, 1972 *fide* Loya, 1976; Rogers, 1977; Sammarco, 1980). It can be supposed that in an area where recruitment of larvae is high, small colonies will be common between the larger colonies and on newly exposed areas. At Cahuita it seems that there is very little recruitment of corals. Few small individuals were observed. The average size of the adult colonies from Cahuita is larger than at Grand Cayman (Table 3-17) and larger than in Puerto Rico (Loya, 1976). A larger size of coral indicates an older age, and more so if the growth rate is lower, as it is in Cahuita. This means that in Cahuita, corals are old, with few young ones growing. The small colonies observed at Cahuita were usually the product of partial death, as described from Barbados by Lewis (1974).

It is argued that colony sizes in turbid waters have to be small because sediment rejection is not directional (Dodge *et al.*, 1974; Dodge, 1978). Sediments are moved to the edge of the colony in a random way. If the colony is small, moving the sediments in any direction, will take them to the edge more or less rapidly. In a large colony this will not be very efficient. Loya (1976) found in Puerto Rico that the reef with turbid water had smaller colonies. In contrast to this, Maragos (1974a, 1974b *fide* Loya, 1976) found that individual colonies were larger in turbid areas than in the clear area of the Fanning lagoon. At Cahuita, the colonies are larger than at Grand Cayman or Puerto Rico. Some of the very large colonies have dead centres, probably the product of accumulation of sediments that could not be moved to the edge. This can also happen when the colonies are exposed to the air due to low-water levels (Scatterday, 1977), however, this does not seem to be the case at Cahuita.

Is the reef at Cahuita deteriorating or is it growing? Unfortunately, there are no old records of the reef to be used as comparison. Wellington's (1974) description of the reef is very similar to what we see today. Some people of the area say that the coral coverage has actually increased in the past ten years. Several observations however, indicate that the reef at Cahuita is deteriorating:

1) Hemispherical masses of dead *Mussa angulosa*, a long, solitary coral, were observed with the individuals still in place. It would be expected that these hemispherical aggregates would dismember quickly since the corals are not cemented.

2) The hydrozoan *Millepora complanata* is very abundant at Cahuita. It has been observed that reefs with good coral growth and high diversity of species do not show great quantities of hydrozoans, but in areas where the reef is predominantly dead the hydrozoans tend to be abundant (Mergner, 1977).

3) Experiments with the echinoid *Diadema antillarum* have demonstrated that it is important in controlling the distribution and abundance of coral spat (Sammarco, 1980); its long spines also cause damage to adult corals. *Diadema* is moderately to very abundant in some areas of the reef at Cahuita (Valdez and Villalobos, 1978; personal observations).

4) Parts of the outer reef have well developed

buttresses, indicating good coral growth in the past. Now these areas are covered by algae and some isolated corals (Risk *et al.*, 1980).

Analysis of sediments trapped in the coral skeletons could help to determine quickly the effect of sediments on reef environments. Qualitative and quantitave determinations of the trapped sediments in the coral will give an indication of the extent of the problem and of the origin of the sediments. Corals living in clear water trap little or no sediments; corals living in turbid waters will trap some sediments in their skeletons. Aragonite, calcite and quartz are the main sediments that will be found in reef environments; the presence of other minerals will indicate an allocthtonous source. For example, the clay minerals detected in Cahuita corals are also found coming down the Río La Estrella.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The coral reef at Cahuita, Costa Rica can be characterized as follows:

1.- High concentration of supended sediments, 7.4 mg/l (range 0.1 to 212.7 mg/l).

2.- High rates of resuspension of bottom sediments: 30 to 360 $mg/cm^2/day$ (at 50 cm from the bottom).

3.- The percentage of carbonate material in the bottom sediments is relatively low: 66.6% (range 26.2 to 97.2).

4.- Growth rates of the coral are low: 5.3 mm/year (range 3.7±0.8 to 7.7±0.4 mm/year).

5.- The percentage of live coral coverage is low: 40% (range 4 to 80%).

6.- Low coral diversity: H'= 1.443 (range 0.038 to 1.602).

7.- Coral colonies are generally larger than in other areas studied, implying low recruitment of coral planulae.

Stress is defined by Rogers (1977) "as a factor which disrupts the normal energy flow in a system either by increasing energy drains, removing structure, or diverting or blocking energy inputs. Stresses may be classified as chronic or acute". The sediment problem at Cahuita must be classified as chronically acute, but even so, it is possible that the reef can survive and even grow. There are many different species living there (Appendix I), plus there are areas with enough live coral to supply larvae for resettlement of dead areas. If the input of sediments to the reef from Río La Estrella is reduced below the output of sediments to the bay by currents, the reef might have a chance to survive. Even then, the effect of sediments at Cahuita will be felt for a long time, since the main problem now is resuspension of bottom sediments.

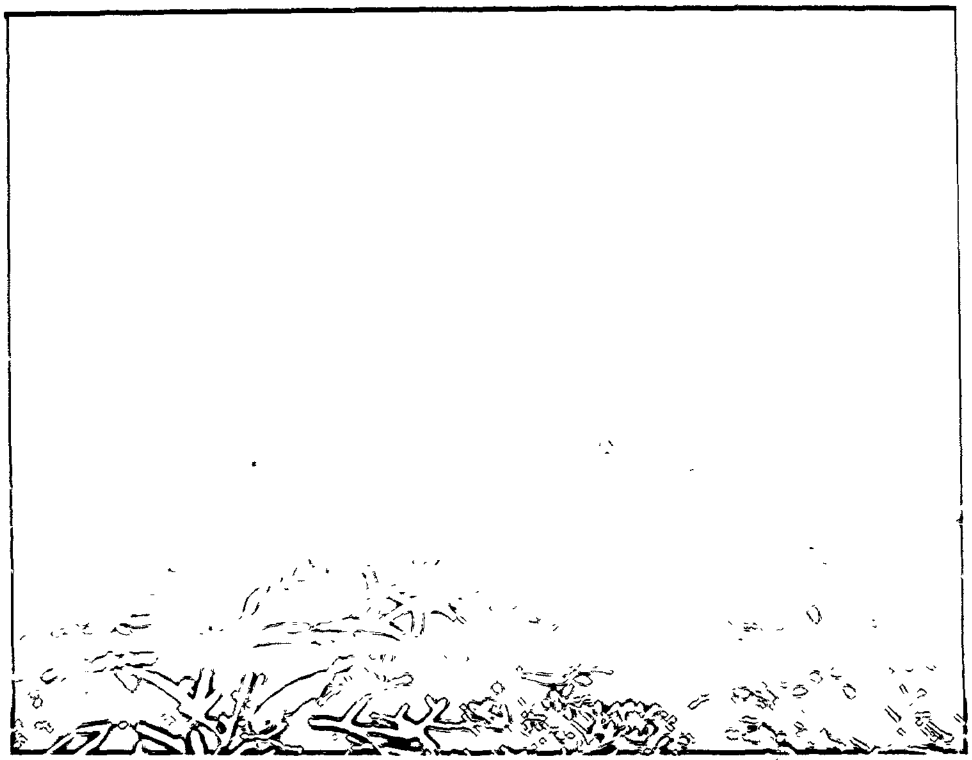
The problem of terrigenous sediments in reef environments is bound to increase as new areas in the tropics are developed (Johannes, 1972; 1975). Care must be taken so that these highly productive and diverse living reefs (Fig. 5-1) are not converted into dead, unproductive ecosystems (Fig. 5-2).

With only a limited number of observations and analyses, it can be determined if a reef is or has been under stress due to siltation. Growth rates of corals will decrease as the amount of sediment increases, the amount of trapped sediments in the coral skeleton will increase, and live coral coverage as well as diversity will be reduced.

At Cahuita, the substrate is covered mainly by algae

FIGURE 5-1 Grand Cayman coral reef.

FIGURE 5-2 Part of the reef at Cahuita, Costa Rica. Most of the corals are dead and the substrate covered by algae and sediments.



and/or sediments. The species composition will be mostly controlled by the amount of sediments present; species with a good ability to reject sediments will be abundant while poor rejectors will be rare or absent. The morphology of some corals will also change in response to high sediment loads. This change can be in response to the sediment *per se*, i.e.: *Agaricia agaricites* growing in vertical fronds; or to low light intensities, i.e.: *Montastrea annularis* and *Porites astreoides* growing in shingles, increasing the area to receive light, but orienting themselves at a steep angle to avoid the sediments. At Cahuita it was also noticeable that the size of the coral colonies was larger than in other reefs, and that there were few small colonies, indicating a low recruitment. The analysis of trapped sediments in coral skeletons can be used to determine if siltation is a problem. X-ray diffraction will indicate the type of sediments present in the corals, shedding some light on their origin.

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Appendix I

Systematic list of Cahuita Scleractinian and other Cnidarians.

Class ANTHOZOA Ehrenberg, 1834

Subclass ZOANTHARIA de Blainville, 1830

Order SCLERACTINIA Bourne, 1900

Suborder ASTROCOENIINA Vaughan & Wells, 1943

Family *ASTROCOENIIDAE* Koby, 1890

Subfamily *ASTROCOENIINAE* Koby, 1890

1. *Stephanocoenia michelini* Milne-Edwards & Haime

Family *POCILLOPORIDAE* Gray, 1842

2. *Madracis decactis* (Lyman)
3. *Madracis mirabilis* sensu Wells

Family *ACROPORIDAE* Verril, 1902

4. *Acropora cervicornis* (Lamarck)
5. *Acropora palmata* (Lamarck)

Suborder FUNGIINA Verrill, 1865

Superfamily AGARICIICAE Gray, 1847

Family *AGARICIIDAE* Gray, 1847

6. *Agaricia agaricites* (Pallas)
   forma *agaricites*
   forma *danai*
   forma *purpurea*
7. *Agaricia fragilis* Dana
8. *Helioseris cucullata* (Ellis & Solander)

Family *SIDERASTREIDAE* Vaughan & Wells, 1943

9. *Siderastrea radians* (Pallas)
10. *Siderastrea siderea* (Ellis & Solander)

Superfamily PORITICAE Gray, 1842

Family *PORITIDAE* Gray, 1842

11. *Porites astreoides* Lesueur
12. *Porites divaricata* Lesueur
13. *Porites furcata* Lamarck
14. *Porites porites* (Pallas)

Suborder FAVIINA Vaughan & Wells, 1943

Superfamily FAVIICAE Gregory, 1900

Family FAVIIDAE Gregory, 1900

Subfamily FAVIINAE Gregory, 1900

15. *Colpophyllia breviserialis* Milne-Edwards & Haime
16. *Colpophyllia natans* (Müller)
17. *Diploria clivosa* (Ellis & Solander)
18. *Diploria strigosa* (Dana)
19. *Favia fragum* (Esper)
20. *Manicina areolata* (Linnaeus)

Subfamily MONTASTREINAE Vaughan & Wells, 1943

21. *Cladocora arbuscula* (Lesueur)
22. *Montastrea annularis* (Ellis & Solander)
23. *Montastrea cavernosa* (Linnaeus)
24. *Solenastrea bournoni* (Milne-Eduards & Haime)

Family RHIZANGIIDAE d'Orbigny, 1851

25. *Astrangia solitaria* (Lesueur)

Family OCULINIDAE Gray, 1847

Subfamily OCULININAE Gray, 1847

26. *Oculina diffusa* Lamarck

Family MEANDRINIDAE Gray, 1847

Subfamily DICHOCOENIINAE Vaughan & Wells, 1943

27. *Dichocoenia stellaris* Milne-Edwards & Haime
28. *Dichocoenia stokesi* Milne-Edwards & Haime

Family MUSSIDAE Ortmann, 1890

29. *Isophyllia multiflora* (Verril)
30. *Isophyllia sinuosa* (Ellis & Solander)
31. *Mussa angulosa* (Pallas)
32. *Mycetophyllia danaana* Milne-Eduards & Haime
33. *Mycetophyllia lamarckiana* Milne-Edwards & Haime

Suborder CARYOPHYLIINA Vaughan & Wells, 1943

Superfamily CARYOPHYLIICAE Gray, 1847

Family CARYOPHYLIIDAE Gray, 1847

Subfamily *EUSMILIINAE* Milne-Edwards & Haime, 1857

34. *Eusmilia fastigiata* (Pallas)

forma *fastigiata*

Other important Cnidarians from Cahuita.

Class HYDROZOA

Order MILLEPORINA Hickson, 1901

Family *MILLEPORIDAE* Fleming, 1828

Millepora complanata Lamarck

Order STYLASTERINA Hickson & England, 1905

Family *STYLASTERIDAE* Gray, 1847

Subfamily *STYLASTERINAE* Gray, 1847

Stylaster roseus (Pallas)

Class ANTHOZOA Ehrenberg, 1834

Subclass OCTOCORALLIA Haeckel, 1866

Order GORGONACEA Lamouroux, 1816

Suborder HALOXONIIA Stüder, 1887

Family *GORGONIIDAE* Lamouroux, 1812

Gorgonia flabellum Verrill

Appendix II

List of coral species and other Cnidarians from Grand Cayman.

Acropora cervicornis
Acropora palmata
Acropora prolifera
Agaricia agaricites
Agaricia fragilis
*Agaricia novilis**
Colpophyllia natans
*Dendrogyra cylindrus**
Dichocoenia stokesi
Diploria clivosa
Diploria labyrinthiformis
Diploria strigosa
Eusmilia fastigiata
Favia fragum
Helioseris cucullata
Isophyllastrea rigida
Isophyllia sinuosa
Madracis decactis
Madracis mirabilis
Meandrina meandrites
Montastrea annularis
Montastrea cavernosa
Mussa angulosa
Mycetophyllia danaana
Mycetophyllia ferox
Mycetophyllia lamarckiana
Porites astreoides
Porites divaricata
Porites furcata
Porites porites
Scolymia lacera
Siderastrea radians
Siderastrea siderea

* from Rigby and Roberts (1976)

Other important Cnidarians.

Millepora alcicornis
Millepora complanata
Stylaster roseus
Gorgonia flabellum
Gorgonia ventalina

Appendix III

Species and distance covered (cm) in each transect.

(For location of transects see Figure 2-10).

CAHUITA

Transect 1

Species	Distance
Agaricia agaricites	1398
Siderastrea radians	163
Porites astreoides	96
Millepora complanata	5
Dead	421
Total	2088

Transect 2

Species	Distance
Siderastrea radians	319
Agaricia agaricites	275
Diploria strigosa	104
Porites astreoides	79
Millepora complanata	43
Porites porites	13
Dead	2260
Total	3093

Transect 3

Species	Distance
Siderastrea radians	258
Diploria strigosa	175
Agaricia agaricites	109
Porites astreoides	21
Dead	555
Total	1118

Transect 4

Species	Distance
Agaricia agaricites	196
Porites astreoides	156
Siderastrea radians	152
Acropora palmata	79
Millepora complanata	45
Diploria clivosa	23
Dead	1474
Total	2125

Transect 5

Species	Distance
Porites astreoides	140
Agaricia agaricites	98
Porites porites	77
Millepora complanata	65
Acropora palmata	26
Dead	1018
Total	1424

Transect 6

Species	Distance
Agaricia agaricites	324
Siderastrea radians	75
Porites porites	43
Diploria clivosa	37
Porites astreoides	19
Dead	718
Total	1216

Transect 7

Species	Distance
Siderastrea radians	191
Agaricia agaricites	89
Porites porites	34
Dead	265
Total	579

Transect 8

Species	Distance
Siderastrea radians	105
Porites porites	60
Agaricia agaricites	20
Porites astreoides	15
Dead	800
Total	1000

Transect 9

Species	Distance
Porites porites	165
Agaricia agaricites	115
Dead	720
Total	1000

Transect 10

Species	Distance
Acropora palmata	150
Agaricia agaricites	130
Porites porites	35
Dead	685
Total	1000

Transect 11

Species	Distance
Agaricia agaricites	800
Porites porites	5
Dead	195
Total	1000

Transect 12

Species	Distance
Agaricia agaricites	635
Porites porites	135
Dead	230
Total	1000

Transect 13

Species	Distance
Porites porites	245
Agaricia agaricites	125
Dead	630
Total	1000

Transect 14

Species	Distance
Porites porites	170
Agaricia agaricites	50
Millepora complanata	30
Dead	750
Total	1000

Transect 15

Species	Distance
Porites porites	20
Millepora complanata	10
Agaricia agaricites	5
Acropora cervicornis	5
Dead	960
Total	1000

Transect 16

Species	Distance
Agaricia agaricites	57
Porites porites	55
Montastrea annularis	35
Dead	295
Total	442

Appendix IV

Species and distance covered (cm) in each transect.

(For location of transects see Figure 2-16).

GRAND CAYMAN

Transect 1

Species	Distance
Acropora cervicornis	317
Porites porites	136
Porites astreoides	24
Mycetophyllia lamarckiana	17
Dead	247
Total	741

Transect 2

Species	Distance
Acropora cervicornis	263
Agaricia agaricites	183
Porites porites	50
Montastrea annularis	29
Porites divaricata	32
Montastrea cavernosa	6
Dead	358
Total	931

Transect 3

Species	Distance
Montastrea annularis	179
Acropora cervicornis	157
Agaricia agaricites	132
Porites porites	21
Millepora alcicornis	10
Porites astreoides	8
Mycetophyllia lamarckiana	7
Siderastrea radians	6
Eusmilia fastigiata	3
Dead	346
Total	869

Transect 4

Species	Distance
Montastrea annularis	346
Acropora cervicornis	292
Agaricia agaricites	86
Porites astreoides	18
Porites porites	5
Dead	240
Total	987

Transect 5

Species	Distance
Acropora cervicornis	119
Agaricia agaricites	42
Montastrea annularis	38
Diploria labyrinthiformis	35
Montastrea cavernosa	28
Porites porites	5
Siderastrea radians	2
Millepora alcicornis	1
Dead	164
Total	434

Transect 6

Species	Distance
Montastrea annularis	115
Acropora cervicornis	97
Diploria labyrinthiformis	61
Agaricia agaricites	55
Montastrea cavernosa	28
Porites astreoides	14
Eusmilia fastigiata	9
Siderastrea radians	8
Porites porites	3
Dead	474
Total	864

Transect 7

Species	Distance
Acropora cervicornis	112
Agaricia agaricites	50
Montastrea cavernosa	35
Montastrea annularis	32
Eusmilia fastigiata	16
Porites divaricata	14
Porites porites	7
Agaricia fragilis	4
Siderastrea siderea	4
Dead	100
Total	374