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FIGS. 1–19, JUNE, 1967

CARBONATE SEDIMENTATION ON HOGSTY REEF, A BAHAMIAN ATOLL[1,2]

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ABSTRACT

Hogsty Reef (21°40′N, 74°20′W) is a small (5×9 km) Bahamian atoll, with a distinct peripheral reef, a shallow (6 to 8 m) lagoon, and a pronounced leeward pass. Wind-driven currents move rapidly through the lagoon, so that the residence period of lagoon water is too short for any noticeable change in salinity or temperature.

There are three types of sediments at Hogsty Reef: sand and gravel, derived from the peripheral reef; cay sand, also derived from the surrounding reefs; and lagoonal sediment. The latter, the most abundant sediment type at Hogsty Reef, is partly composed of peripheral reef debris and some lagoonal skeletal material; but the major component is "non-skeletal" fragments, which increase westward in the lagoon, as currents become more rapid, skeletal components become fewer, and the rate of sediment accumulation (supposedly) decreases.

The non-skeletal components, which contain high (10 $^{\circ}/_{\circ\circ}$) Sr aragonite, are hypothesized to be primarily inorganically precipitated. It is suggested that in tropical waters, high current energy (combined, perhaps, with low skeletal productivity) may be the critical condition(s) necessary for inorganic precipitation of calcium carbonate, and may explain why such sediments have not been found on other atolls.

INTRODUCTION

The chief mode of carbonate sedimentation on atolls and coral reefs is the accumulation of organically derived particles, primarily algae, benthic foraminifera, coral and mollusk shells (Wiens, 1962; Ginsburg *et al.*, 1963). One exception, however, is the Bahama Banks, a large (10^5 km^2) shoal-water area, where the majority of sand-sized sediments (oolite, grapestone, cryptocrystalline lumps) are inorganically precipitated (Illing, 1954; Newell and Rigby, 1957; Newell *et al.*, 1960; Purdy, 1963). Cloud (1962) has given support to the inorganic origin of the muds leeward of Andros Island, but the Lowenstam and Epstein (1957) theory of algal formation of the muds is still favored by most carbonate workers.

Various explanations have been offered for the origin of the Bahamian inorganic sediments: warming of ocean water (Illing, 1954; Newell *et al.*, 1960); shallow depths (Newell *et al.*, 1960); the long residence period of the lagoon water (Cloud, 1962; Broecker and Takahashi, 1966); and strong tidal currents (Illing, 1954). A study of Hogsty Reef, a small atoll in the southeastern Bahamas, may help in defining the critical parameters for inorganic carbonate sedimentation. Are sediments at Hogsty Reef inorganic like those of the Bahama Banks, or organic, like those on other atolls? The distribution and genesis of the sediments on Hogsty Reef, and their relation to present-day conditions is the subject of this paper.

GENERAL FEATURES OF THE AREA

Regional Setting

The southeastern Bahamas are composed of a series of islands and shallow-water reefs, separated from one another by deep water (fig. 1). The island chain extends from Crooked Island (22°40′N, 74°20′W) southeast to Navidad Bank (20°00′N, 68°50′W). South of the southeastern Bahamas is the western extension of the Puerto Rico Trench; further south are Cuba and Hispaniola. To the north and east, steep slopes quickly plunge to oceanic depths. The Great Bahama Bank lies to the northwest.

Hogsty Reef (21°40′N, 73°50′W), a small atoll in the southeastern Bahamas, about 9 km long and 5 km wide, is nearly equidistant from Acklins Island, Great Inagua Island, and Little Inagua Island. The bottom depths surrounding Hogsty exceed 1800 m (fig. 2). A chart of Hogsty Reef, based on a British survey of 1920, is shown in figure 3. A shallow lagoon, generally less than 8 m, but more than 6 m deep, is surrounded by a prominent reef, with a gap on the western side forming a lagoon pass. Two small sand cays rise above the peripheral reef: Southeast Cay on the southwestern part of the peripheral reef, and Northwest Cay on the southwestern tip of the northern peripheral reef.

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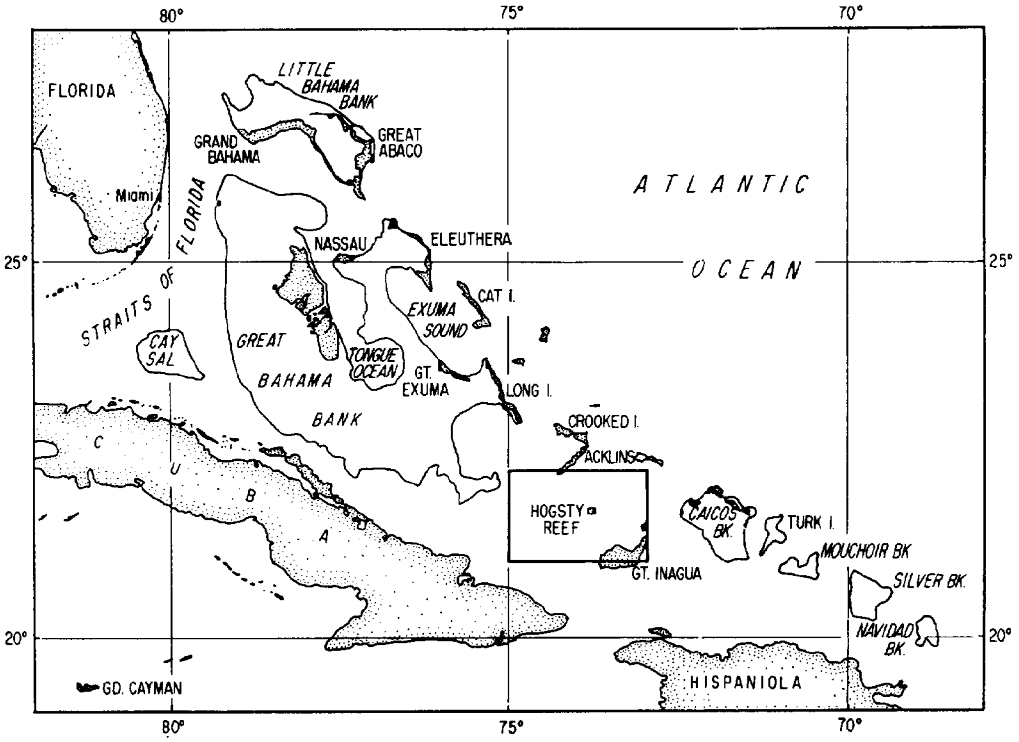

FIG. 1.—Index chart of the Bahama Islands.

Regional Geology

Doran (1955) found that the present-day morphology and geology of the southeastern Bahamas are very similar to the northern Bahamas. These islands are low-lying and composed of shallow-water reef material and lithified Pleistocene sands. The topographic highs are unlithified and lithified aeolian ridges, mainly near the shoreline. These ridges are thought to be Pleistocene features although a few dunes are presently forming.

Charles Schuchert, in his monumental work, Historical Geology of the Antillean-Caribbean Region (1935), stated that the southeastern Bahamas are a pre-existing island arc with a limestone cap. No supporting data are presented, however, and it seems probable that this conclusion was based on geomorphic analogy. The lack of local magnetic anomalies, together with local bottom topography (Milliman, in press) suggests that the southeastern Bahamas have been the site of quiet carbonate deposition for a long time. It has been concluded that while Hogsty Reef has accumulated at least 800 m of shallow-water sediments, its present atoll configuration may be related to reef growth on a Pleistocene aeolian ridge (Milliman, in press).

Climate and Oceanography

Influenced by the Atlantic high-pressure belt, which lies to the northwest, the southeastern Bahamas are less subject to annual climatic variations than the northern Bahamas (U. S. Hydrographic Office, 1958). The monthly mean annual air temperature in the latitude 20–25°N, longitude 70–75°W is 26.1°C. with a range of 4° (U. S. Hydrographic Office, 1958) (figure 3). Winds are predominantly from the east-northeast, except in June, July and August, when they are from the east-southeast (fig. 4, 5). Maximum wind velocities occur in November through January (average of 5.8 m/sec.) and minimum values in May (average, 4.4 m/sec.).

The climate at Hogsty Reef is relatively dry. At Grand Turk Island (21°29′N, 71°07′W), the closest weather station to Hogsty Reef, the annual rainfall averages 73 cm. Over 50 percent occurs from September through December (fig. 4). Hurricanes, while not a common occurrence, can cause wide-spread destruction. According to Doran (1955), from 1804 to 1937 there were 33 hurricanes in the southeastern Bahamas. One hurricane, in 1963, which destroyed a pier and several houses at Matthewtown, Great Inagua,

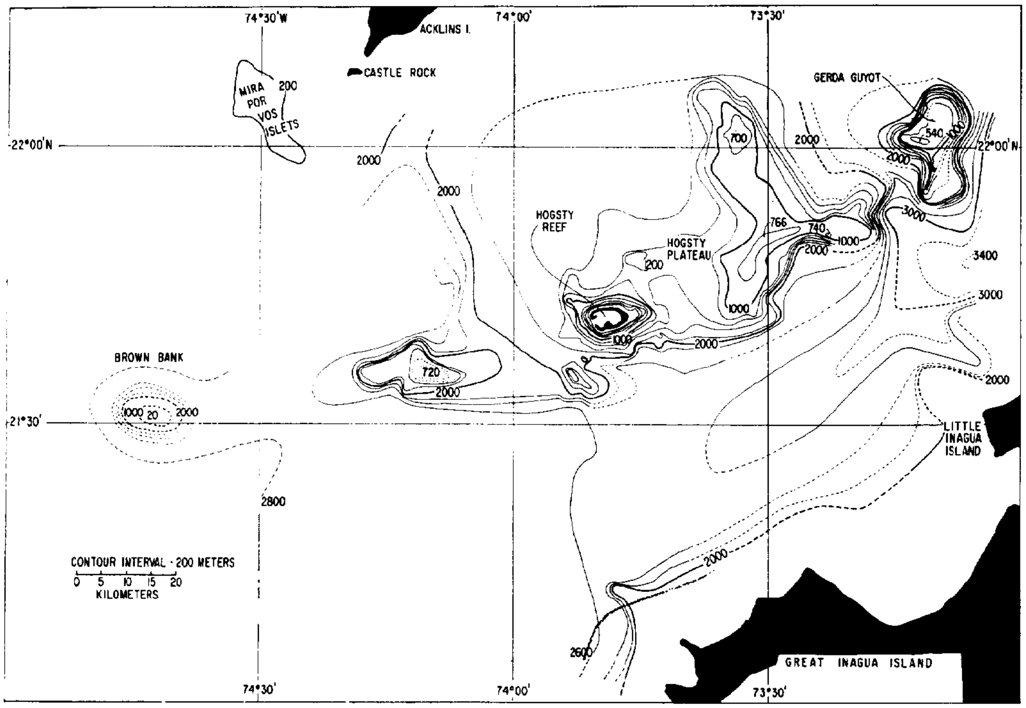

FIG. 2.—Bathymetric chart of the area surrounding Hogsty Reef.

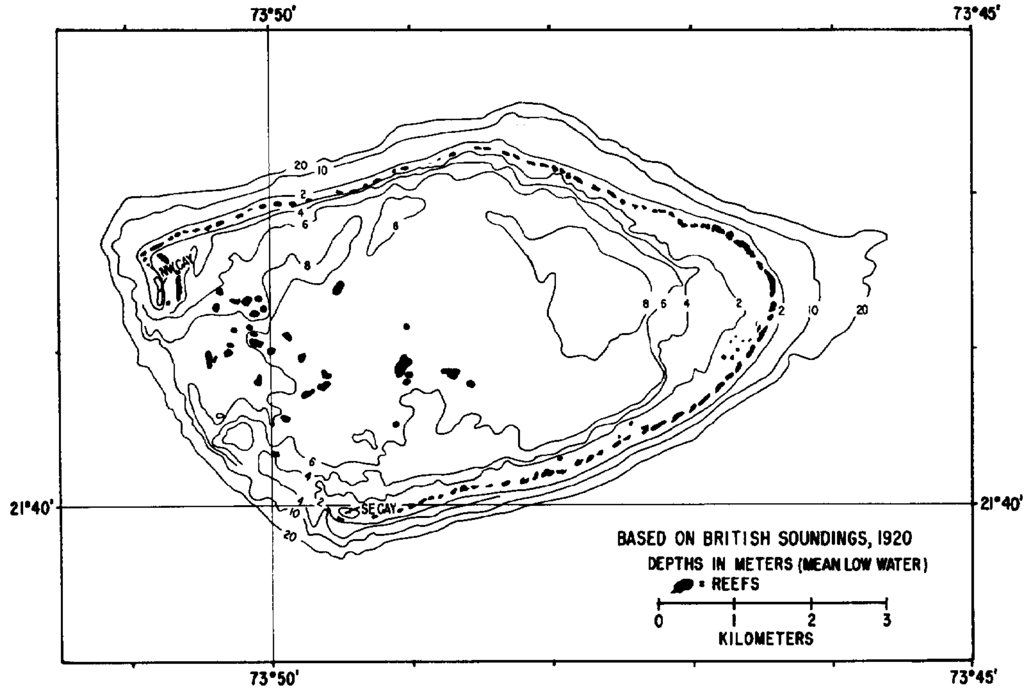

FIG. 3.—Chart of the lagoonal and shoal-water area of Hogsty Reef.

probably came near to, or passed over Hogsty Reef.

Lying in the trade wind belt, Hogsty Reef is subject to a near constant westward drift. Seasonal variations in the sea, swell, and currents correspond closely to the variations in the wind, (fig. 5). The tidal rage at Hogsty Reef has been measured to be about 0.6 m, with a slightly greater range during spring tides.

PREVIOUS WORKERS

The only geological investigation of Hogsty Reef was made by Alexander Agassiz (1894). His stay at this atoll was brief (3 days), and no sediment samples were taken. A few analyses of marine sediments from various southeastern Bahama islands were made by Doran (1955). To the writer's knowledge, no other sedimentologic study has been made in the southeastern Bahamas.

There have been, however, numerous recent studies of the sediments in the northern Bahamas. Illing (1954) reported on the environment of deposition and resulting carbonate facies on Great Bahama Bank. Similar investigations were made by Newell and co-workers (Newell *et al.*, 1951; Newell and Rigby, 1957; Newell *et al.*, 1961; Purdy, 1963) and by Lowenstam (1955; Lowenstam and Epstein, 1957) and Cloud (1962).

METHODS OF STUDY

Two cruises were made to Hogsty Reef aboard the R/V GERDA, of the Institute of Marine Science, University of Miami. On the first cruise (G6426, August 1 to 15, 1964) preliminary observations were made on the bathymetry of the area, and on the general ecology, oceanography, and geology of the atoll. During the second cruise (G6522, June 7 to 20, 1965) the 1964 measurements were refined. Some further data were obtained during a cruise on the R/V PILLSBURY (P6407).

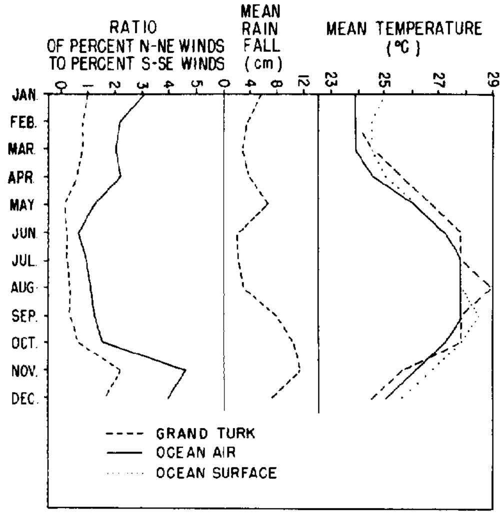

FIG. 4.—Annual climatic variations in the southeastern Bahamas (based on data from H. O. Publ. 21, 1958).

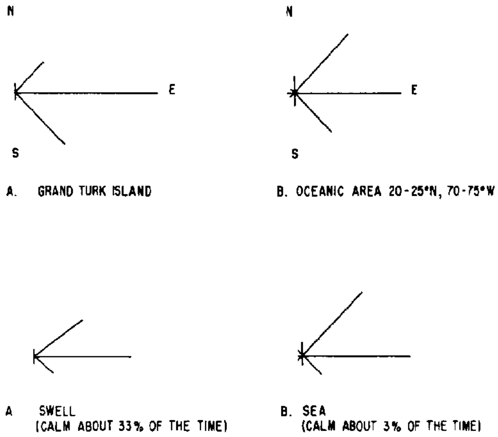

FIG. 5.—Components of mean annual wind, swell and sea (20–22°N, 73–75°W) (based on data from H. O. Publ. 21, 1958; U. S. Naval Oceanographic Office, 1963, personal communication).

Oceanography

A total of five hydrographic stations were occupied at Hogsty Reef, three in 1964 and two in 1965 (fig. 6). Each station was occupied for at least 25 hours so that changes in the aquatic environment could be related to diurnal changes and the tidal cycle, as well as to location. Current velocity and direction were measured using a current cross patterned after the design of Pritchard and Burt (1951). Hourly readings were taken at the surface, mid-depth, and one meter above the bottom. Wind speed and direction were also measured every hour.

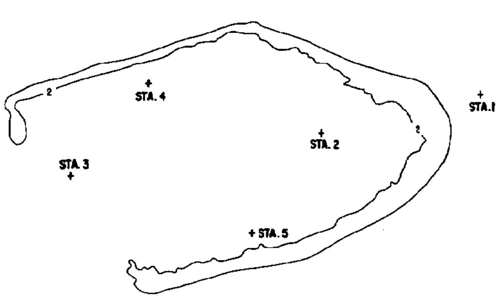

FIG. 6.—Locations of oceanographic stations.

Water samples were taken every other hour at the surface and mid-depth, using a five-liter Niskin bottle. Temperatures were recorded with reversing thermometers. Oxygen samples were drawn and preserved using standard Winkler techniques. Salinity and alkalinity samples were also drawn. Air temperature and humidity were measured with each hydrographic cast, using a psychrometer (wet-dry bulb thermometer).

The average velocities and directions of the currents and winds were calculated by vector analysis. This was done only for complete tidal cycles, so that the flood and ebb components could be accounted for. Temperature, oxygen, salinity and alkalinity were analyzed, using standard techniques (see Strickland and Parsons, 1960).

Sediments

In 1964, while the R/V GERDA was anchored at the current stations, a total of 32 surface sediment samples were taken, by skin diving, from the shoal-water environments of Hogsty Reef (fig. 7). At each sample location, the general bottom features and sediment-producing organisms were noted and recorded (table 2). In 1965 underwater photographs were taken of nearly all 1964 sample areas; it is believed that every major ecologic area of Hogsty Reef was thus studied, sampled and photographed.

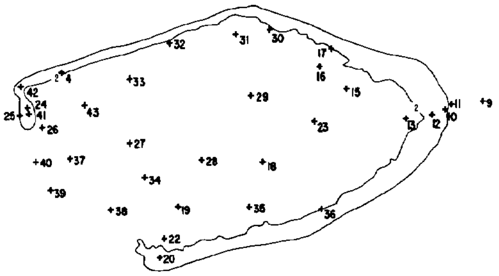

FIG. 7.—Surface sediment sample locations.

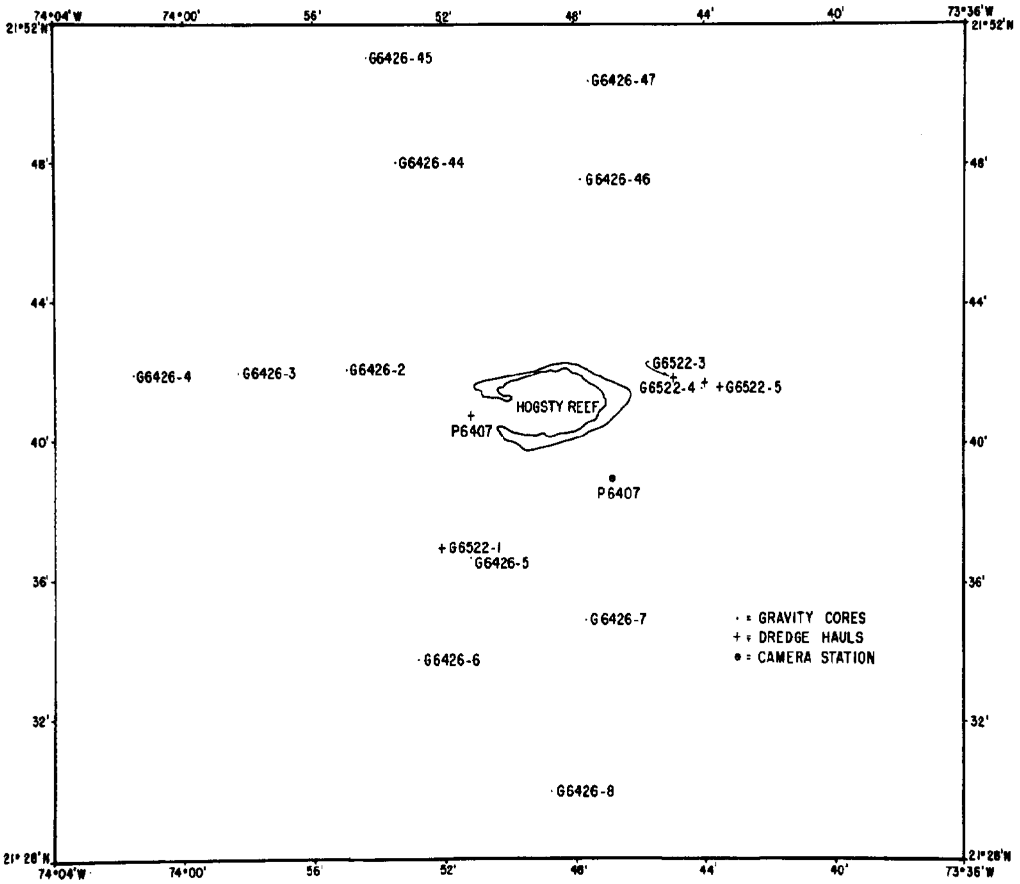

FIG. 8.—Location of gravity core and dredge stations.

In order to determine the effect of Hogsty Reef's shoalwater sediments on the surrounding deep-water sediments a series of gravity coring transects were made seaward of the break in slope, in depths between 1500 and 2500 m. Each transect consisted of one to three cores, taken at 3 to 5 km intervals normal to the reef (fig. 8); a total of ten cores were taken.

During cruise P6407 one dredge sample was obtained off the western edge of Hogsty Reef, at a depth of about 400 m. In 1965, during cruise G6522, three dredge samples were obtained from the eastern side of Hogsty Reef (fig. 8).

Size Analysis of Shoal-water Samples:—The surface sediment samples were split (quartered) until 60 to 100 grams of sample remained. This portion was placed in a bottle and washed with a dilute solution of Clorox (sodium hypochlorite), to remove the sea salts and to oxidize any organic material in the sediment. After decantation the samples were oven-dried at 80°C. and then sieved in Wentworth grades of 4, 2, 1, 0.5, 0.25, 0.125, and 0.0625 mm. The portion finer than 0.0625 mm was collected as the pan fraction.

Compositional Analysis of Sediments:—Carbonate sediments are partly detrital (e.g. eroded from a reef) and partly composed of grains formed *in situ* by various organisms or by chemical precipitation. The type of constituents contributing to a sediment varies greatly with environment (Ginsburg, 1956). Therefore the composition of carbonates tells us not only the source of the grains, but also something about the sedimentary environments.

Each sample was divided into four parts: gravel (coarser than 2 mm), coarse sand (2 to 0.50 mm), medium-fine sand (0.50 to 0.125 mm), and fine sediments (finer than 0.125 mm). The gravel-sized grains were stained with alizarine red and Feigl's solution, the aragonitic components turning purple and the calcitic components remaining colorless (see Friedman, 1959, for a description of this process). The stained grains were then identified with a binocular microscope, the mere shape of the grain many times being sufficient for identification. Sometimes, however, even with repeated acid washings and stainings, the grains were so thickly encrusted that its true origin was not revealed. In such cases the grain was identified either as encrusting (coralline) algae or as a lump (see below).

The two sand fractions were impregnated with a polyester resin (951), thin sectioned, and point-counted under a petrographic microscope. Three-hundred counts appear to be adequate to gain statistical accuracy (Ginsburg, 1956). The fraction finer than 0.125 mm was not studied, because at these small sizes carbonate grains begin to lose their identifiable characteristics (Ginsburg, 1956; Purdy, 1963).

Grains were categorized into two groups: 1) skeletal fragments, consisting of coral, mollusk, foraminifera, coralline algae and *Halimeda*, and other miscellaneous skeletal fragments, such as serpulid tubes, bryozoans and echinoderms; 2) non-skeletal fragments, including those assumed to have undergone at least one diagenetic change which altered their appearance.

Criteria for recognition of the various skeletal fragments are given by Ginsburg (1956) and Purdy (1963), but the criteria of recognition of non-skeletal fragments must be explained. The term "lump" is used to describe grains consisting of one or more smaller particles (often pelletoids) with a matrix of cryptocrystalline aragonite, estimated to form half or more of the grain (fig. 9a). The term "aggregate" describes two or more joined fragments (commonly pelletoids), with the matrix forming less than half the grain (fig. 9b). This term is preferred to "grapestone" (Illing, 1954) because the latter connotes that the constituent particles have a round shape, which is not always the case. "Pelletoids" are grains that have a spheroidal or ellipsoidal shape and the general consistency of fecal pellets (fig. 9c). It is possible, however, that a portion of these grains are rounded lumps, or thoroughly reworked oolite or cemented mud pellets. "Oolite" describes grains which "display one or more regular lamellae formed as successive coatings around a nucleus" and whose constituent crystals "show a systematic crystalline orientation with respect to the grain surface" (Newell *et al.*, 1960) (fig. 9d). "Botryoidal lumps" are grapestone (or in this paper, aggregates) having an oolitic outer coating (Illing, 1954).

Rock and sediment samples, obtained by dredging and coring were studied with a binocular microscope. In addition, each gravity core was split lengthwise and one of the lengths was impregnated with a polyester resin (951). When hard and cut, these slabs presented a relatively undisturbed surface, which could then be studied with a binocular microscope.

Geochemical Analysis of Shoal-water Sediments:—The surface sediment samples from Hogsty Reef were analyzed for aragonite, high-Mg calcite and low Mg calcite, using X-ray diffraction techniques. Samples, relatively free of organic carbon, were ground to a fine powder, and analyzed in a General Electric XRD-5 diffractometer using Cu-Kα radiation from a two-theta of 25° to 31°, at a scanning speed of 0.2 degrees per minute. The relative peaks were recorded on a General Electric type HF pulse height analyzer. Since there are essentially only two minerals present in Hogsty Reef sediments, calcite and aragonite, the analysis could be

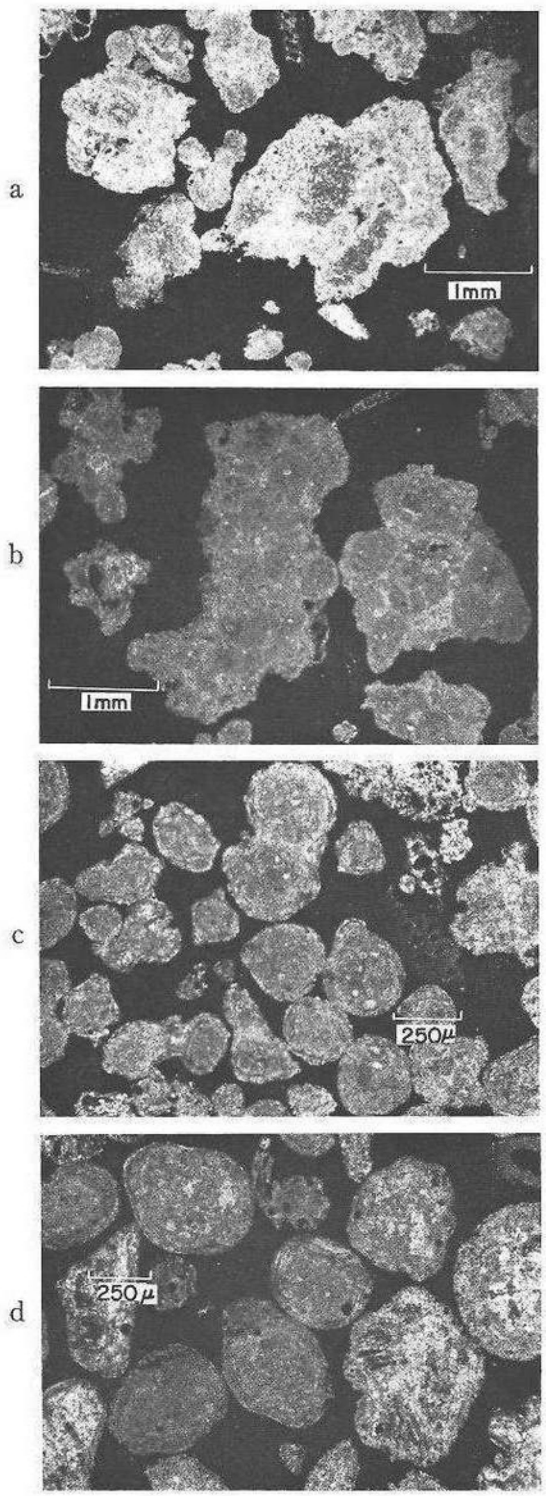

FIG. 9.—Photomicrographs of non-skeletal particles, taken under cross nicols. a. Several lumps composed of smaller grains; the matrix, a crytocrystalline aragonite, constitutes about 50 percent of the grain. b. Several aggregates, the matrix of each being less than 50 percent of the grain. c. Several pelletoids. Above them is an aggregate, composed of an ooid and a pelletoid. d. Two oolite grains are shown in the center of the picture. To the right is a partially altered coral fragment.

←

quantified quite simply, using a method similar to that of Friedman (1964), the assumed accuracy being ±10 percent.

The Sr and Mg concentrations in each sediment sample plus several selected standards were determined, using the Perkin-Elmer 303 Atomic Absorbtion spectrophotometer. A 250 mg portion of each sediment sample was dissolved in HCl, evaporated, diluted to 50 ml, and filtered. These samples were then analyzed, together with a set of standards of known Sr concentration. Duplicate analyses were run on most samples. The accuracy of this method is ±5 percent (O. Joensuu, 1966 personal communication). The ages of several selected samples were dated by the Carbon-14 method by Dr. H. Göte Östlund.

RESULTS

Oceanography

Current and hydrographic data collected at Hogsty during the 1964 and 1965 cruises can be found in another paper (Milliman, 1966; Appendix I, II). Resultant wind and current vectors (the average of the three depths measured) are shown in figure 10. Currents generally flowed westward, except at station 1, where sharp tidal reversals resulted in a net flow east. At station 2 there were only brief tidal reversals, the average current being about 14 cm/sec. At station 3, near the western lagoon pass, the current was

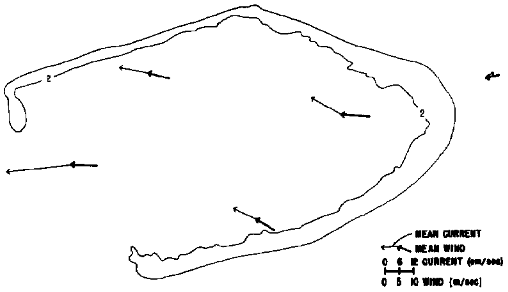

FIG. 10.—Current and wind vectors measured at Hogsty Reef in 1964 and 1965.

TABLE 1.—*Daily average of oceanographic values measured at Hogsty Reef during August 1964 and June 1965*

	Station No.	Air Temp. (°C)	Water Temp. (°C)	Salinity $(^\circ/_{ooo})$	Oxygen (ml/1)	Oxygen (per cent saturation)
8/64	1	29.1	29.07	36.249	4.45	103.5
	2	29.0	28.90	36.241	4.61	107.2
	3	28.9	28.85	36.257	4.65	107.8
6/65	4	26.6	26.47	36.636	4.79	107.5
	5	26.6	26.52	36.651	4.77	107.0

about 27 cm/sec. With lighter winds in 1965, the current velocities at stations 4 and 5 were relatively low, about 12 and 10 cm/sec. respectively.

The salinity values remained more or less constant across Hogsty Reef (table 1). The daily average water temperatures fluctuated with the air temperature. The average oxygen concentrations, showed a marked increase within the influence of the reef (compare station 1 with stations 2 and 3).

Distribution of Sediment-producing Organisms and Bottom Types

Figure 11 shows the different morphologic zones at Hogsty Reef. The distribution of the prominent sediment-producing organisms and the sediment types is given in table 2 and figures 12 and 13.

No evidence of spurs and grooves was found on the seaward reef margin. These features, oriented normal to the reef front (and therefore to incoming waves) are common on many other Caribbean reefs (Newell *et al.*, 1951; Goreau, 1959; Shinn, 1963; Storr, 1964), as well as on many Indo-Pacific atolls (Wiens, 1962). A few ridges and valleys, corresponding to spurs and grooves, were seen, but these were oriented neither with respect to the shoreline, nor to each other. Because of the roughness of the water, the outer reef was not fully investigated, but aerial photography shows no indication of such features. Therefore, while there may be some spur and groove features at Hogsty Reef, they apparently are few.

The Cays of Hogsty Reef

There are two islands on Hogsty Reef. The smaller one, Southeast Cay, located on the southern peripheral reef, is about 150 m long, 50 m wide and has a maximum elevation of about 2 m (fig. 3). Southeast Cay is surrounded by several bands of beach rock lying *en echelon*, which gently dip away from the cay towards the water. There is no other rock outcropping on the cay. Several rather poorly defined storm berms lie above high tide level.

It would not be misleading to term Southeast Cay as a sand spit, with only scattered plant cover. The plants on this cay represent a preliminary strand-plant community. There are several clumps of *Tournefortia gnaphalodes*, standing up to about one-half m high, and a few patches of the creeper, *Euphorbia mesembrianthemifolia*. Two other creepers, *Portulaca oleracea* and *Ipomea* cf. *tuba*, are also present, but not as common.

Northwest Cay, situated on the southwestern tip of the peripheral reef flat, is 270 m long and 65 m wide. Like Southeast Cay, it is surrounded

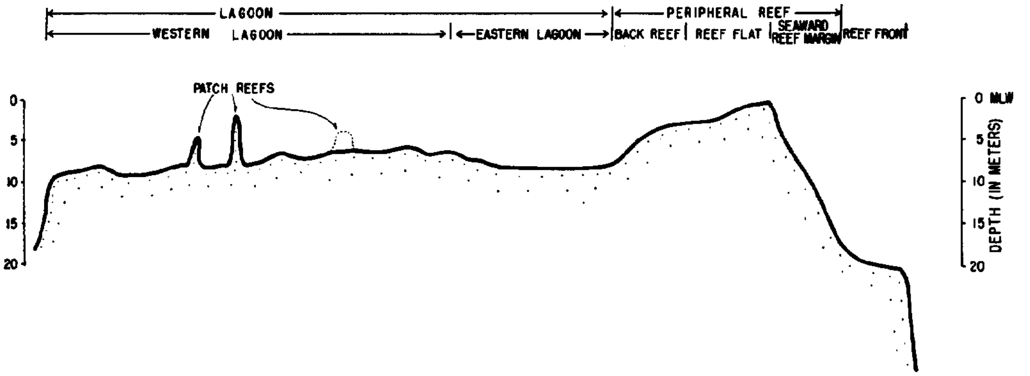

FIG. 11.—Ecologic profile of Hogsty Reef.

TABLE 2.—*Distribution of bottom types and prominent sediment-producing organisms at Hogsty Reef*

Location	Depth Range (m)	Bottom Description	Principal Sediment-contributing Organisms	Sediment	Figures
Reef front	15–20	Gently sloping bottom	Scattered heads and encrustations of *Acropora cervicornis*, *A. palmata*, *Porites*, *Siderastrea*, *Montastrea*, *Copophylia*. Abundant encrusting red algae and noncalcareous brown algae.	Little sediment cover except gravel and sand in local depressions.	
Seaward Reef margin	0–15	The bottom quickly shoals towards reef flat	Almost a complete cover of strongly oriented growths of *A. palmata*, with a few *Diploria*, *Montastrea*, *Porites*, *Millepora alcincornis*. On leeward seaward margins, the bottom is mainly populated with alcyonarians and *Diploria*, *Siderastrea*, *A. palmata*, *P. astroides*, *M. alcicornis*.	Little sediment cover, except gravel and sand in local depressions.	
Reef flat	0–2	Reefs distributed randomly over reef flat, decreasing in abundance lagoonward	Reef flat delinated by *M. alcicornis*, often exposed at low water. No algal ridge. Many coral patches behind M. Malcicornis zone, mainly *A. palmata*, *M. annularis*, *Diploria*, *Siderastrea*, *Porites*, *Agaricia*. Encrusting red algae covers much of the bottom; some green algae, abundant brown algae. Inner reef flat has more *Halimeda*, less red algae. Corals are *P. porites*, *Manicina areolata*, *M. annularis*, *S. siderea*, *Diploria*, *Dichocoenia*.	On the outer reef the sediment is mainly gravel. Sediment cover increases towards inner reef flat, with an increasing amount of sand.	12 a–c
Back reef	2–4	Generally flat with a few coral colonies. Behind windward reef flat, back reef is wide, perhaps 1 km. Behind leeward peripheral reef, back reef is narrow, only a few 10 m.	A few coral colonies, the same species as on the inner reef flat. Gastropod *Strombus gigas* is common. Patches of *Halimeda*, *Pennicilus*, *Udotea*, along with grasses *Thalassia testudinum* and *Syringodium filiforme*.	Increasing sediment cover towards lagoon; increasingly fine, with some *Strombus* rubble.	12 d
Eastern lagoon	6–8	Flat, with some grass beds near back reefs.	Bottom is generally thinly covered with *T. testudinum* and *S. filiforme* sprouts, along with some *Halimeda* and *Pennicilus*. *S. gigas*, the starfish *Oreaster* and various pelcypods are common. Judging from the number of mounds, burrowing animals must be the predominant lagoon organisms.	Medium to fine sand with some silt.	13 a
Western lagoon	6–8	Flat, with rippled sand, occasional patch reefs.	Few grasses or green algae. Benthic fauna is less common than in eastern lagoon.	Well-sorted sand, with little silt.	13 b
Patch reefs	2–8	About 35 in western lagoon. Some are low-lying coral mounds, others are 2 to 5 m in height.	Some consists mainly of one species of coral, such as *M. annularis*, *Agaricia*, *Diploria*. Others have additional genera, *Dendrogyra*, *Favia*, *Acropora*. Alcyonarians, sponges and encrusting red algae are prominent.	A coarse sediment which decreases in size away from the patch reef.	13 c

by beach rock, which is particularly abundant on the northern and western shores. The beach rock, covered with various kinds of algae and barnacles, does not lie in bands, but the outcrops are wider (especially on the northern part of Northwest Cay) than at Southeast Cay. Long fissures in the beach rock, similar to those seen in the Marshall Islands (Emery *et al.*, 1954, plate 38), are common.

There is a change in the beach slope at the rubble zone; further inland the slope is more gradual. The slope again increases where the land plants begin growing, the cay reaching a maximum elevation of about 4 m. This height is nearly constant over the entire vegetated portion of the cay (fig. 13d). The top of the cay is covered with the creepers *E. mesembrianthemifolia* and *Ambrosia hispida*. Low-lying shrubs, *T. gnaphalodes*, are situated around the periphery of the top. In lesser amounts are the creepers *I.* cf. *tuba* and *P. oleracea*, the shrubs *Scaevola plumieri*, *Batis maritima* and *Suriana maritima*, and the sand burr *Cenchrus pauciflorus*. There were several small coconut palms, *Cocos nucifera*, and one Australian pine, *Casuarina equisetifolia* in 1965.

Sediments of Hogsty Reef

Textural Properties:—The textural properties of carbonate sediments are determined not only by sorting and transport, but also by the formation of *in situ* sediments. Therefore great caution must be used when defining carbonate sediments by their size parameters. The following generalizations, however, can be made: mean grain size (Inman, 1952) increases greatly in the vicinity of the windward peripheral reef (fig. 14); leeward of the back reef, in the eastern lagoon, is fine sand and silt; in the western lagoon the sediment increases in size; patch reefs may also cause a local increase in particle size.

Compositional Properties:—The average composition of each sediment sample was computed by considering the percent abundance of each size grade, plus the weight percent of the "fine-sized" sediments (finer than 0.125 mm). Thus for each sediment sample, the relative abundance of skeletal fragments, non-skeletal fragments, unknowns and fine sediment was tabulated. The 32 surface sediment samples have been grouped into 6 categories, each having distinctive compositional properties and representing different environments: the peripheral reef, the back reef, the eastern lagoon, the western lagoon, the patch reefs, and the cays. For each category the average composition was calculated, together with the range of values (table 3).

The distribution of constituent particles across Hogsty Reef is shown in figure 15. Leeward of the peripheral reef, skeletal fragments (especially coral and coralline algae) decrease, and non-skeletal components increase. *Halimeda* content is low throughout both the reef flat and lagoon sediments. There is considerable fine-sized sediment ($<125\mu$) in the eastern lagoon, but only small amount in the western lagoon. Non-skeletal grains increase in abundance in the western lagoon; skeletal fragments (mainly mollusk and foraminifera) are few, except for the local influence of patch reefs. Oolite, while increasing in the western lagoon, never constitutes more than 6 percent of the sediment. A N–S cross section (fig. 15) shows a similar distribution of sediments. Figure 16 shows the areal distribution of these sedimentary facies.

Geochemistry of Surface Sediment Samples:—At least 60 percent of every sediment sample collected at Hogsty Reef is aragonite, the remainder being predominantly high Mg calcite (table 4). A plot of the aragonite/high Mg calcite ratio across Hogsty Reef (fig. 17) indicates a relative increase in aragonite and decrease in high Mg calcite lagoonward of the peripheral reef.

The results of the Sr and Mg analyses are given in table 4; the Sr content increases with

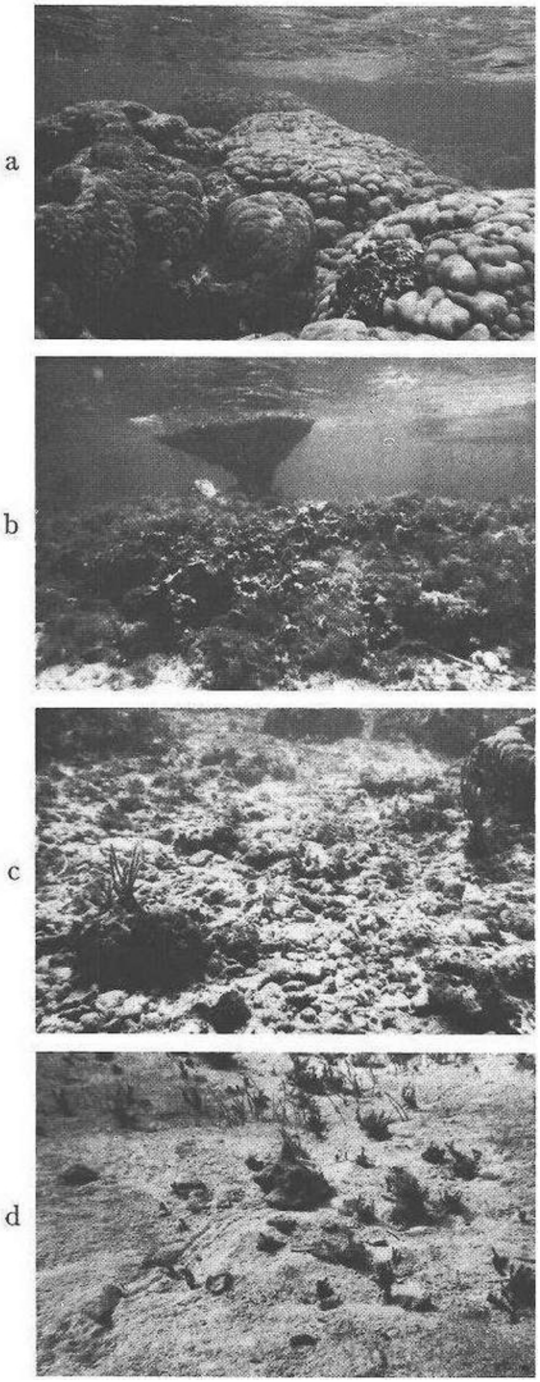

FIG. 12.—Photographs of the reef and back reef environments at Hogsty Reef. a. In places on the reef flat there are flourishing living reefs, such as this reef of *Montastrea annularis*, with nearly breaks the surface at low tide. b. Much of the reef flat is quite barren, with only occasional heads of coral. Note the dead coral, *Acropora palmata* and the abundant algal cover. c. The outer parts of the reef flat are covered with coarse coral rubble. d. In the back reef the sediment is mostly sand-sized. Larger rubble is contributed by conchs, *Strombus gigas*, which, while living, browse the bottom (note trail trending up from the lower left hand corner). Also seen are sprouts of grass (*Syringodium*) and algae (*Halimeda*).

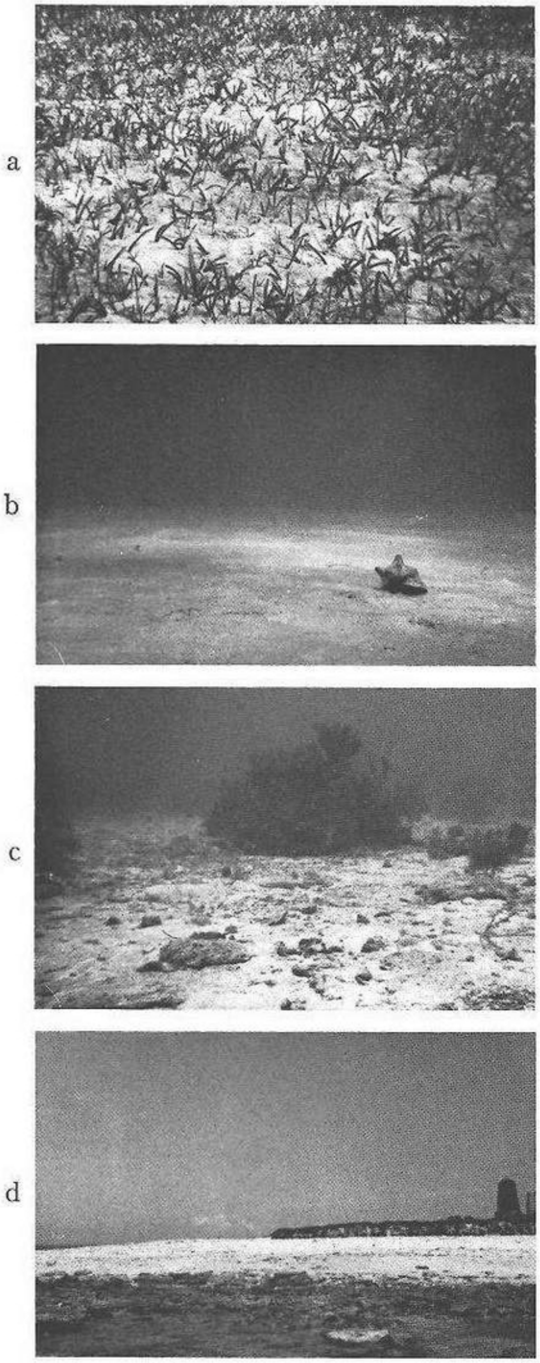

FIG. 13.—Photographs of the lagoon and a cay of Hogsty Reef. a. In the eastern lagoon there are large patches covered by *Thallssia testudinum* sprouts. The sediment is fine sand. b. Most of the western lagoon is barren of grass and algae. Occasional conchs and starfish are usually the only signs of life. c. Patch reefs locally contribute sediment in the western lagoon; note the abundance of coral rubble on the bottom. This low-lying reef, is in a depth of about 8 m near the lagoon pass. d. The middle of Northwest Cay, ocvered with vegetation, is about 4 m high. The shore (foreground) is lined with beach rock.

increasing distance leeward from the windward reef (fig. 17). Results of the samples dated by Dr. H. Göte Östlund, show that sediments leeward of the peripheral reef (sample 13) and by a lagoonal patch reef (sample 28) are each about 1800 years old; the three lagoon samples are 2500 to 2800 years old (fig. 17).

Sediment Seaward of Hogsty Reef

A dredge haul from a depth of 600 m on the western slope of Hogsty Reef (P6407-D15) recovered many shallow-water sediments, including non-skeletal particles which bear a strong resemblance to the sediments in the western lagoon. On the eastern flanks of Hogsty Reef the remains of many shoal-water organisms were recovered at depths between 400 and 600 m (G6522-D3). This included many species of shallow-water coral, *Agaricia* being the most abundant, and great quantity of *Halimeda* plates. In the deeper samples (G6522-D4, 5; 700 to 1300m) there was no trace of shallow-water sediments, only Mn slabs and Mn-encrusted deep-water corals.

In every transect the length of the gravity cores increased with distance from Hogsty Reef, although the variation in percent of coarse particles (coarser than 62 μ) showed no trend with location. In the impregnated cores there was no visual evidence of turbidite layers, such as are found in the sediments seaward of the northern Bahamas (Ericson *et al.*, 1952; Rusnak and Nesteroff, 1964). The main constituents of the coarse fraction from the top 2 cm of each core are planktonic foraminifera and planktonic gastropods. Heavier fragments, looking unlike the planktonic components, were seen in nearly every sample.

DISCUSSION: THE PRESENT-DAY ENVIRONMENT OF HOGSTY REEF

Sedimentary Environment

Distribution and Origin of Hogsty Reef Sediments:—The composition of a carbonate sediment is dependent upon three factors: the population and productivity of any sediment-producing organism relative to the other components; the tendency for physical, chemical and biological alteration and destruction of any sediment component relative of other components; and the rate of sediment accumulation (Milliman, 1966). By relating these factors to the results obtained from surface sediment analyses,

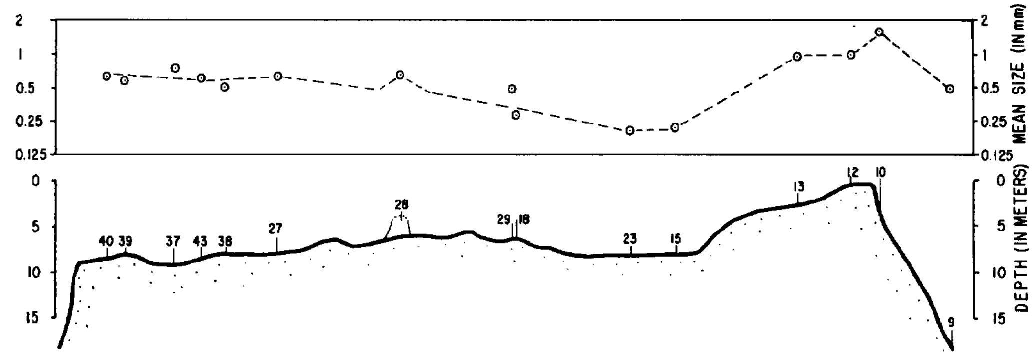

FIG. 14.—Variation of sediment mean grain size across Hogsty Reef.

an understanding of the present-day sedimentation on Hogsty Reef can be achieved.

The coarse peripheral reef sediment is the result of the nearby production of corals, mollusks and coralline algae, together with the high wave energy, which effectively removes fine sediment. The cay sediments, with similar constituents (see above), are derived from the peripheral reefs. The soils (the substratum of plant growth; Fosberg and Carroll, 1965) on the cays are texturally and compositionally almost identical to their parent material, the beach sands. The nearly complete lack of alteration of these soils is explained by the relative sparseness of vegetation and the semi-arid climate. Winds can transport cay sediments westward; the size and composition of sample 25, taken leeward of Northwest Cay, in about 2 m of water, shows that it was derived from the cay.

Some of the lagoon sediment at Hogsty Reef is debris washed in from the peripheral reefs and some is lagoonal skeleta, but most of the sediment is non-skeletal. Since the sediments on other atolls are primarily skeletal, composed of foraminifera, *Halimeda* and mollusk (Wiens, 1962; Hoskin, 1963), Hogsty Reef is unique. It is interesting, however, to note the close petrographic resemblance between the lagoonal sedimentary facies at Hogsty Reef and the grapestone facies on the Great Bahama Bank (Purdy, 1963). The sediment in the western lagoon at Hogsty Reef has 15 percent skeletal fragments, 83 percent non-skeletal fragments, and 2 percent fine debris (table 3) compared to 12.7 percent skeletal grains, 82.7 percent non-skeletal, and 4.5 percent fine debris in the Great Bahama Bank grapestone facies (Purdy, 1963). Moreover, the assemblage of cryptocrystalline grains, grapestone and fecal pellets in the grapestone facies can be equivocated with the lump, aggregate and pelletoid assemblage of Hogsty Reef.

Origin of the Non-skeletal Particles: It is impossible, with petrographic analysis alone, to determine the origin of the non-skeletal grains at Hogsty Reef. Geochemical data, however, give a clue to their origin.

The lagoon sediments have a marked increase

TABLE 3.—*Average composition of sediments from different areas at Hogsty Reef*

		Reef Flat (5 samples)		Back Reef (6 samples)		Cay sediments (4 samples)		Eastern Lagoon (4 samples)		Western Lagoon (6 samples)		Patch Reef (7 samples)	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
skeletal fragments	Coral	31	25–32	22	18–25	31	28–38	4	tr.–10	1	tr.–4	15	8–28
	Mollusk	20	12–24	23	18–31	20	19–24	9	5–15	9	5–13	16	12–19
	Foram.	4	2–6	5	3–9	1	1–2	6	4–11	3	1–7	4	2–6
	Coralline Algae	19	6–28	18	12–27	16	13–19	2	0–7	tr.	tr.–2	5	2–13
	Halimeda	1	tr.–2	3	tr.–9	1	1–2	2	1–3	1	tr.–2	3	1–8
	Miscell.	1	tr.–2	1	1–2	1	0–1	1	1–2	1	tr.–1	1	tr.–2
	Total	76	73–82	72	68–83	70	66–79	24	12–42	15	8–47	44	29–64
non-skeletals	Lump	16	9–23	22	10–29	18	15–21	36	32–39	49	39–58	32	21–42
	Pelletoid	1	tr.–3	1	tr.–5	5	tr.–7	14	4–26	16	10–18	1	5–16
	Oolite	tr.	0–tr.	tr.	0–1	tr.	0–1	tr.	0–tr.	1	tr.–3	2	tr.–6
	Aggregate	tr.	0–1	tr.	0–1	1	tr.–2	3	1–7	16	11–23	7	1–15
	Botryoidal Lump	tr.	0–tr.	tr.	0–tr.	tr.	0–tr.	tr.	0–1	1	tr.–2	tr.	0–1
	Total	17	9–22	23	10–32	24	16–26	53	37–72	83	48–90	42	
	Unknown	5	4–5	5	3–7	5	4–6	2	1–5	1	tr.–3	3	2–5
	Weight Percentage less than 125 μ	1	0–5	1	tr.–3	0	0–tr.	20	15–21	2	1–6	1	tr.–3

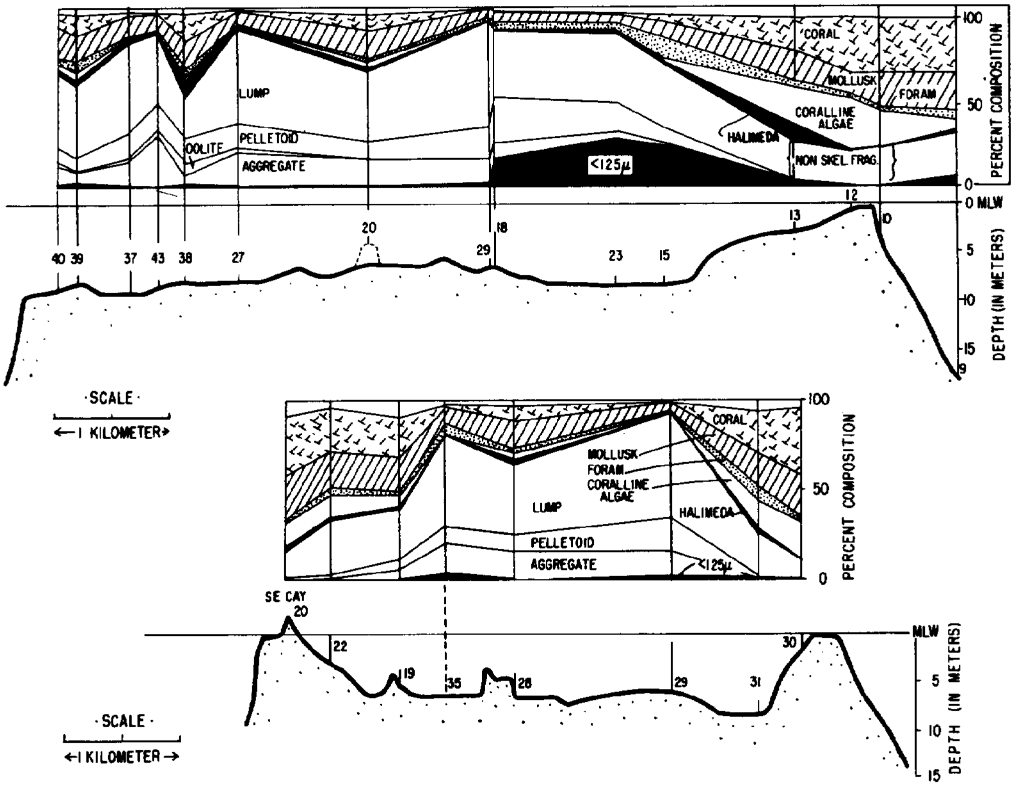

FIG. 15.—Distribution of constituent particles across Hogsty Reef.

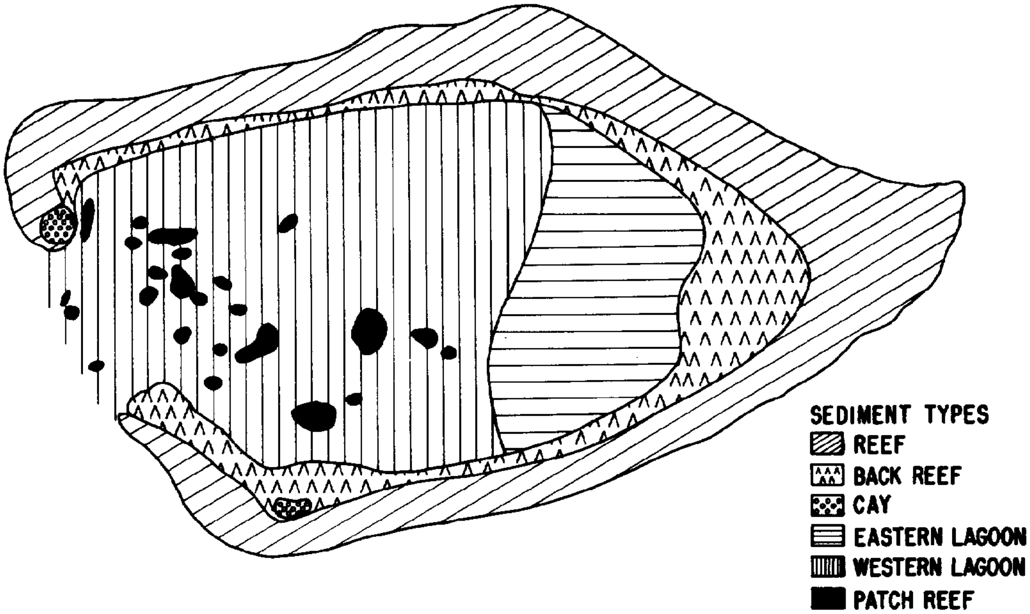

FIG. 16.—Sediment facies at Hogsty Reef.

TABLE 4.—*Geochemical data of surface sediments from Hogsty Reef and other selected samples*

Sample No.	% High-Mg calcite	% Low-Mg calcite	% Aragonite	$^{\circ}/_{\circ\circ}$ Mg	$^{\circ}/_{\circ\circ}$ Sr
9	14.6	—	85.3	12.3	5.10
10	25.5	—	74.4	20.8	4.10
13	34.0	—	65.9	24.8	3.40
15	13.3	—	86.6	10.9	6.35
15 ($<125\mu$)	16.9	—	83.0	13.6	7.30
16	13.5	—	86.4	13.0	5.95
16 ($<125\mu$)	13.7	—	86.2	14.0	5.80
17	20.8	0.7	78.4	16.8	4.75
18	5.4	0.6	93.9	5.5	8.55
18 ($<125\mu$)	9.5	0.7	89.7	8.6	7.50
19	10.2	—	89.7	9.0	7.05
20	12.3	—	87.6	11.2	6.40
22	10.6	0.5	88.8	9.4	6.55
23	7.7	0.6	91.6	7.3	7.25
23 ($<125\mu$)	12.2	—	87.7	10.0	6.95
24	9.8	0.4	89.7	9.8	7.75
25	11.5	—	88.7	10.7	8.10
26	11.1	0.9	87.9	10.3	6.65
27	4.6	1.3	94.0	4.0	9.00
28	5.4	0.9	93.6	5.1	9.05
29	3.9	1.4	94.6	4.3	8.65
30	18.6	—	81.3	16.7	5.50
31	17.7	—	82.2	15.6	4.85
32	21.1	—	78.8	17.4	5.15
33	9.4	—	90.5	5.7	7.75
33 ($<125\mu$)	14.2	—	85.7	11.3	7.00
34	7.8	0.4	91.7	7.0	7.25
35	5.6	0.7	93.6	5.6	7.85
36	29.3	—	70.6	25.0	4.40
37	4.2	0.6	95.1	4.0	7.80
38	6.1	1.0	92.8	6.8	7.50
39	6.3	0.3	93.3	5.5	7.75
40	4.5	0.9	94.0	3.9	7.30
41	9.5	0.7	89.7	9.0	7.50
42	17.8	0.3	81.8	14.5	5.00
43	4.0	1.0	94.8	3.7	8.00
oolite (Brown's Cay)	tr	—	99.	1.1	10.00
oolite (S. Cat Cay)	tr	—	99.	1.1	10.10
Acropora palmata	—	—	99.	0.9	8.50
Halimeda opuntia	—	—	99.	2.3	8.20
grapestone (Great Bahama Bank)	4.2	—	95.8	3.4	9.20
29 (non-skeletal grains)	4.7	—	95.3	4.4	9.30

of Sr-rich (over 9 $^{\circ}/_{\circ\circ}$ aragonite (fig. 17)). Part of this increase results from the relative decrease of low-Sr, high-Mg calcite (in response to the decreasing sedimentary influence of coralline algae in the lagoon) and the corresponding increase of aragonite. This factor can be corrected by calculating the Sr content of the aragonite portion of each sample:

$$(1) \qquad aX + bY = Z$$

where:

a = the percent aragonite in the sample
b = the percent calcite in the sample
X = the Sr content in the aragonite
Y = the Sr content in the calcite
Z = the Sr content in the total sample

Knowing a, b, and Z (table 4), and assuming that $Y = 2^{\circ}/_{\circ\circ}$ (Odum, 1957; Matthews, 1966), X is calculated. The Sr differences between the reef and lagoon samples, while decreasing with this calculation (column b, table 6), do not change nearly enough to explain the Sr increase in the lagoon sediments. Therefore this increase must represent an introduction of Sr-rich aragonite. Strontium values of grapestone sediments from the Great Bank Bahama are similarly high (table 4).

Of the aragonite-forming organisms, the Sr values for green algae and corals are between 7 and 8.5 $^{\circ}/_{\circ\circ}$ (table 5); mollusks and other organisms contain significantly less (2 to 3$^{\circ}/_{\circ\circ}$). As reef debris in the lagoon is diluted with mollusks and foraminifera (see above), its Sr concentration should decrease. Therefore the lagoonal Sr increase does not appear to be organically derived.

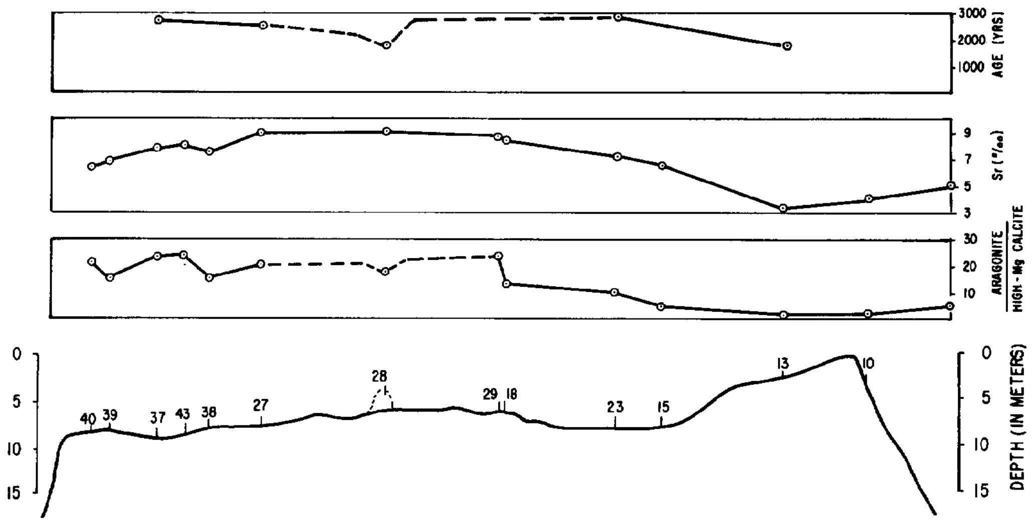

FIG. 17.—Geochemical variations across Hogsty Reef.

The possible exception may be bacteria, which precipitate aragonite (Greenfield, 1963) and may also, by degradation of organic material, alter the micro-environment to a level conducive for the precipitation of calcium carbonate (Purdy, 1963). At Hogsty Reef the currents are strong and the bottom sediment is rippled, thus making it an unlikely place for the accumulation of the products of bacterial decomposition.

Only inorganically precipitated aragonite has Sr values sufficiently high (greater than 9.5°/oo) to form the high-Sr lagoonal sands (table 5). It

TABLE 5.—*Sr content of high-Sr carbonates*

Material	Location	No. analyses	Carbonate mineralogy	Sr anal. method	Sr (°/oo)	Sr/Ca (atoms 10^{-3})	Worker(s)
Algae							
Halimeda sp.	Long Key, Fla.	1	Arag.	FP	9.3	10.8	O
Halimeda opuntia	S. Brit. Hond.	1	Arag.	AA	8.5	9.85	M
Halimeda opuntia	Key Largo, Fla.	1	Arag.	AA	8.2	9.5	this paper
Penicillus dumetosus	S. Brit. Hond.	1	Arag.	AA	7.9	9.15	M
Rhepocephalus sp.	S. Brit. Hond.	1	Arag.	AA	8.0	9.30	M
Scleractinia							
Porites porites	Dry Tortugas, Fla.	1	Arag.	FP	8.7	10.00	O
Isophyllia fragilis	Bermuda	1	Arag.	FP	9.2	10.60	O
various specimens	Indo-Pacific	12	Arag.	FP	8.5–9.8	9.90–11.40	O
Hexacorallia	Pacific		Arag.	FP	8.5	9.86	T & C
Acropora cervicornis	S. Brit. Hond.	6	Arag.	AA	6.3–7.8	7.3–9.05	M
Acropora palmata	S. Brit. Hond.	3	Arag.	AA	7.5–7.8	8.7–9.05	M
Acropora palmata	Key Largo, Fla.	1	Arag.	AA	8.5	9.85	this paper
Montastrea annularis	S. Brit. Hond.	1	Arag.	AA	7.3	8.5	M
"Inorganic" Precipitates							
oolite	Cat Cay, Bahamas	1	Arag.	ES	10.08	11.7	K
pseudo-oolite	Bahamas	1	Arag.	ES	10.6	12.5	Z & W
oolite	Bahamas	2	Arag.	AA	10.0–10.1	11.5–11.8	this paper
artificially precipitated		5	Arag.	FP	9.7*	11.30	O
drewite	Bahamas	1	Arag.	FP	9.0	10.5	O
grapestone	Bahamas	1	Arag.	AA	9.5**	11.10	this paper
Sea Water							
ocean water						8.9	T & C
ocean water				FP		9.23	O
ocean water				FP		9.27	T

* Average (cf. Graf, 1960).
** Recalculated for 100% aragonite.
FP—flame photometry.
AA—atomic absorption.
ES—emission spectrophotometry.
O—Odum, 1957.
M—Matthews, 1966.
T & C—Thompson and Chow, 1955.
K—Kahle, 1965.
Z & W—Zeller and Wray, 1956.
T—Turekian, 1964.

TABLE 6.—*Computed amounts of Sr in aragonite, percent inorganically precipitated aragonite and total percent precipitated for each surface sediment sample from Hogsty Reef*

Sample No.	a $^{\circ}/_{oo}$ Sr in sample	b $^{\circ}/_{oo}$ Sr in aragonite	c % aragonite precipitated	d % sample precipitated
9	5.10	5.65		
10	4.10	4.82		
13	3.40	4.12		
15	6.35	7.01	37	32
15 ($<125\mu$)	7.30	8.38		
16	5.95	6.57	22	19
16 ($<125\mu$)	5.80	6.41		
17	4.75	5.48		
18	8.55	8.96	74	69
18 ($<125\mu$)	7.50	8.14		
19	7.05	7.64		
20	6.40	7.02		
22	6.55	7.12		
23	7.25	7.72	48	44
23 ($<125\mu$)	6.95	7.65		
24	7.75	8.41		
25	8.10	8.90		
26	6.65	7.29		
27	9.00	9.43	87	82
28	9.05	9.52	77	73
29	8.65	9.01		
30	5.50	6.30		
31	4.85	5.46		
32	5.15	6.00		
33	7.75	8.36	62	56
33 ($<125\mu$)	7.00	7.80		
34	7.25	7.74		
35	7.85	8.25	60	56
36	4.40	5.39		
37	7.80	8.09	57	54
38	7.50	7.94		
39	7.75	8.17		
40	7.30	7.59		
41	7.50	8.11		
42	5.00	5.66		
43	8.00	8.32	62	59

is significant to note that there is a direct relation between the amount of Sr and the percentage of non-skeletal fragments in the lagoon sediment samples (fig. 18), with oolite values being the highest. Thus it seems probable that a large amount of the lagoonal sand was inorganically precipitated. Illing (1954) has attributed a physiochemical origin to the grapestone and oolite grains on the Great Bahama Bank.

The amount of inorganically precipitated aragonite in each sediment sample can be calculated if the following assumptions are made: 1) all sediment in the lagoon is either derived from the peripheral reefs, or is inorganically precipitated; 2) there is no inorganically precipitated aragonite in the reef sediment; and 3) there is no selective destruction of the various reef skeleta as they are transported into the lagoon. Thus, by assuming a Sr content of the reef aragonite ($5.6^{\circ}/_{oo}$, the average of the 10 reef and back reef samples) the amount of inorganic aragonite can be calculated.

Let

c = the percent of inorganic aragonite in the sample

W_1 = the Sr content of inorganic aragonite $(10.0^{\circ}/_{oo})$

$100-c$ = the percent of reef-derived aragonite in the sample

W_2 = the Sr content of the reef aragonite $(5.6\ ^{\circ}/_{oo})$

X = the Sr content in the aragonite portion of the sample

Therefore:

$$cW_1 + W_2(100 - c) = X(100) \tag{2}$$

The results are given in column *c*, table 6. Knowing the amount of aragonite in the sample, the percent of inorganic precipitate for the total sample can be calculated (column *d*, table 6).

The conditions assumed in making these estimates are obviously in error. Reef sediments are diluted with low Sr lagoonal sediment, and reef

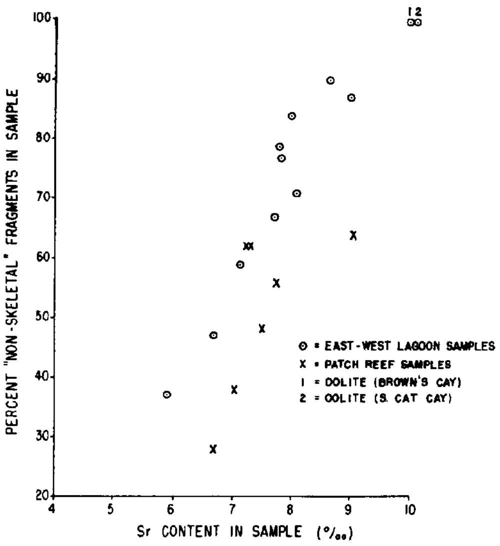

FIG. 18.—The relation of Sr content to the percent of non-skeletal particles in the sediment at Hogsty Reef.

coral and *Halimeda*, being relatively porous, are probably preferentially altered and destroyed. Thus the skeletal components in the lagoon sediments should have a Sr content somewhat lower than assumed, with the result that the calculation of inorganic aragonite is a minimum estimate. Patch reef samples, on the other hand, being enriched with coral and *Halimeda*, which tend to increase the Sr content, have disproportionately lower non-skeletal concentrations than the lagoon samples (fig. 18).

It can be concluded that most of the non-skeletal fragments in the lagoon of Hogsty Reef are inorganically precipitated (fig. 19). Some of the fine sediment in the eastern lagoon may be inorganically precipitated, but as its Sr values are generally the same or less than those of the the sand fractions (table 4), most is probably the debris of sand-sized particles. Some of this mud may be reincorporated into pelletoids and the matrix of other non-skeletal fragments; Illing (1954) noted a large amount of silt-sized particles in the Great Bahama Bank grapestone.

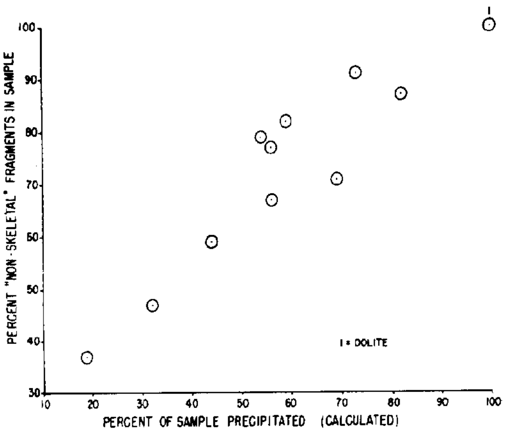

FIG. 19.—The relation of the calculated inorganically precipitated sediment with amount of non-skeletal fragments in lagoon sediment at Hogsty Reef.

Environmental Conditions for Precipitation of Aragonite

The oceanographic measurements taken at Hogsty Reef can be assumed to be a rough approximation of the average environment, although there is no doubt that seasonal variations do occur (see above). As in the northern Marshall Islands (Von Arx, 1954), the lagoonal currents at Hogsty Reef appear to be mainly wind-derived, both by the crashing waves on the peripheral reefs and by wind stress on the lagoonal waters. The increase in current velocity in the western parts of the lagoon is most probably caused by the transport of water over the northern and southern peripheral reefs; aerial photographs show a refraction of waves along the entire eastern front of the atoll. Tidal fluctuations are considered to be of only minor influence.

It can be concluded that the residence time of the lagoon water at Hogsty Reef is very brief, probably between 12 and 24 hours, depending on the wind velocity. The fact that neither the temperature nor salinity were seen to change with location in the lagoon (table 1) also indicates a short residence time.

Therefore high current and wave energy, not long-term lagoon water residence, may be the critical parameters for inorganic precipitation of calcium carbonate at Hogsty Reef. Strong currents 1) remove fine-sized sediments, thus lowering the rate of sediment accumulation; 2) expose the grains (potential nuclei for inorganic precipitation) to a greater amount of calcium carbonate-rich water (Revelle and Fairbridge, 1957) per unit of time; and 3) cause turbulence which lessens physiochemical gradients with depth (Newell *et al.*, 1960).

Low biologic (skeletal) productivity may also aid in the inorganic precipitation of aragonite. The few reefs on the peripheral reef flat and the sparse lagoon organisms may contribute relatively little sediment to the lagoon, thus accentuating the low rate of sediment accumulation at Hogsty Reef. Unfortunately no method of comparing skeletal productivity on various reefs has been devised.

While the amount of inorganically precipitated sediment increase westward in the lagoon, oolite is not present in the high concentrations found in the northern Bahamas. The reason for this lack of oolite may be because of the lagoon's depth (optimal conditions are at 1 m; Newell *et al.*, 1960), or because there is little or no tidal reversal of currents. The high oolite concentrations in the northern Bahamas are in areas of strong tidal oscillations, so that sediment particles tend to oscillate *in situ* and therefore remain in the lagoon a longer time. Without tidal influence and since there is no lagoon pass sill, sediment at Hogsty Reef is swept out the lagoon into deeper water by the westward currents.

CONCLUSIONS

The origin of the lagoonal sediments at Hogsty Reef can be briefly summarized. Reef material (coral, coralline algae and mollusk) is washed into the lagoon by waves and currents. As this sediment is transported westward, its composition changes markedly, both by dilution with lagoonal skeleta (foraminifera and mollusk) and by alteration and reduction. Most of the sand-sized lagoonal sediment, comprised mainly of non-skeletal fragments (lumps, aggregates, peletoids, oolite), is inorganically precipitated. Some of the fine debris found in the eastern lagoon may be reincorporated into these non-skeletal particles. As current velocities increase in the western lagoon, the fine-sized fraction is winnowed away, thus lowering the rate of sediment accumulation. The western lagoon sediment, therefore becomes more non-skeletal in character, through longer exposure to reworking and precipitation.

The predominantly non-skeletal lagoon sediment at Hogsty Reef is unique among atolls; it does, however closely resemble (both petrographically and chemically) the grapestone sediments of the Great Bahama Bank. High current and wave energy, together with low biologic (skeletal) productivity, may be the critical parameters for the inorganic precipitation of calcium carbonate in a tropical environment. It will be interesting to compare the sediments of other high energy atolls with those found at Hogsty Reef.

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