SHOAL-WATER GEOLOGY AND ENVIRONMENTS, EASTERN ANDROS ISLAND, BAHAMAS

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CONTENTS

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INTRODUCTION

ANDROS,[1] largest of the Bahama Islands, lies in an area of extraordinary scientific interest. The Andros area and the bank to the west have been the scene of numerous oceanographic and geologic studies since about the middle of the nineteenth century.[2] Some of the more significant contributions in these fields are those of Alexander Agassiz (1895), Black (1930, 1933), Dall (1905), Drew (1912), Field (1931), Goldman (1926), Hess (1933), Northrop (1891), C. L. Smith (1940), Thorp (1936, 1939), and Vaughan (1912–1918).

where great areas are barely awash, to depths rarely greater and commonly less than 3 fathoms. Most of Andros is very low and marshy, and, excepting low hills along the eastern margin, the surface lies generally below about 10 feet above sea level. The island, as are almost all of the Bahamas, is composed of Pleistocene oolitic limestone, with a nearly soilless karst surface.

The Great Bahama Bank and Andros Island are bounded on the west by Florida and Santaren straits and on the east by Tongue of

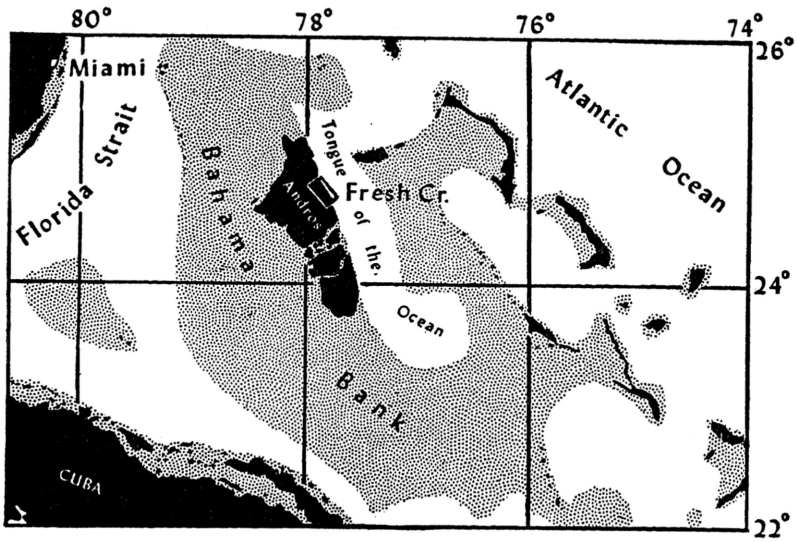

FIG. 1. Map of part of the Bahama Islands and surrounding region.

Andros Island and the Great Bahama Bank to the west occupy the summit of the Bahama plateau, an enormous plain extending over thousands of square miles. The submerged banks range in depth from sea level,

the Ocean, profound and steep-walled troughs (fig. 1).

Extensive chemical and bioclastic deposits of calcium carbonate are forming in the shallow waters and are being winnowed and gradually transported basinward where they mingle at depth with pteropods and *Globigerina* to form a fine calcareous ooze. There are few places on earth where shallow marine deposits of calcium carbonate of comparable extent are being formed. Geologists have been attracted to this area in the conviction that clues may here be found to the origin of the extraordinarily prevalent marine limestones

[1] The island is roughly 90 miles long and 40 miles across at the widest place, with an area of approximately 2000 square miles. Actually, it is an archipelago of islands separated by shallow marine channels.

[2] Louis Agassiz (1852, U. S. Coast Survey, Ann. Rept., pp. 145–160) and R. J. Nelson (1853, Quart. Jour. Geol. Soc. London, vol. 9, p. 200) were among the first to call attention to remarkable conditions of sedimentation in the region. Of course, hydrographic mapping had been undertaken much earlier.

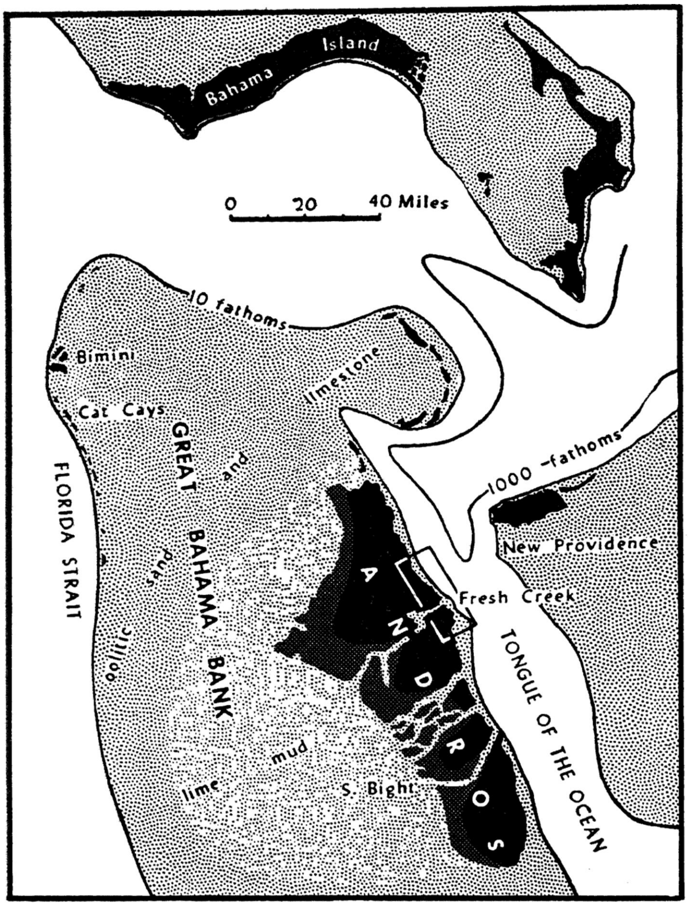

FIG. 2. Sedimentary regions of the Great Bahama Bank.

of the geologic record (Field, 1931).

In connection with investigations of Permian reefs and associated deposits in west Texas it has been necessary for us to make original studies of the complex environments of a living algal-coral reef. The barrier reef along the northeast coast of Andros Island, although not well studied, has been generally regarded as perhaps the finest coral reef in the West Indies, and was selected, therefore, as an object of our studies.

Three weeks were devoted to reef studies from a base at Fresh Creek village on the northeast coast of the island (fig. 2). A few trips were made inland on Andros, and several traverses were made over the shallow coastal waters in native sailboats for the purpose of identification and study of land and shoal-water features visible on aerial photographs. Bottom samples were dredged at many localities, but many direct observations were made by means of shallow dives, and underwater photographic records were made.

Two helmets of bell type served by hand pumps were used frequently, but we found the use of swimming masks, such as are widely used in spearfishing, to be very satisfactory at depths of less than about 2 fathoms, and some photographs were taken without use of the helmets. Approximately 1000 35-mm. Kodachrome transparencies, 500 black and white pictures, and about 1000 feet of 16-mm. Kodachrome in motion were taken as a photographic record of field operations. Approximately one-half of this record was obtained under water.

Almost all our efforts were devoted to examination of the more striking animal and plant communities and to delineation of their distributions on a map. Mapping of ecology and under-water geology in this way is new to the region.

Regular personnel of the field party included Norman D. Newell, Leader; J. Keith Rigby, Arthur J. Whiteman, John S. Bradley, and Thane Bierwert. Mr. Bierwert assumed general supervision of photography and camera maintenance and made a majority of the under-water pictures. All the members of the party took part in obtaining the abovewater photographic record.

During the stay at Fresh Creek we were visited by Morgan J. Davis, H. N. Fisk, Walter H. Bucher, Theodore Pyfrom, Sydney Pyfrom, and Eugene Pyfrom. Discussions of the field conditions during their visit and at other times have proved most helpful. We are especially grateful to the Pyfroms for their sympathetic instruction in surface diving around the reefs and the use of the swimming mask.

The particular mode of field work used here was first described to us by Dr. Preston E. Cloud, Jr., who has made similar reef studies on Pacific islands. Availability of suitable aerial photographs, of course, is a prime requisite, and we wish to express our appreciation to Dr. Harry S. Ladd and Dr. Preston E. Cloud, Jr., for the loan of a set of Navy photographs belonging to the United States Geological Survey.

We acknowledge the aid and cooperation of Mr. John C. Armstrong, of the American Museum staff, in supplying us with deepwater sediments offshore from our study area.

Finally, it is a privilege to acknowledge financial aid in the form of a grant from the Humble Oil and Refining Company to the American Museum of Natural History. Without this aid the Andros studies would not have been made.

GENERAL GEOLOGY

Introduction

Andros Island is bounded along the northeast coast by a shallow rock platform, probably wave cut, a mile or so wide, and about 2 fathoms below average low-tide level.[1] It is bounded at the outer rim by a narrow ridge of oolitic rock which rises here and there above the sea to form linear chains of low cays parallel to the Andros shore (pl. 2, fig. 4). This ridge is known locally and in some of the literature as the "barrier reef," although it clearly is mainly of inorganic origin. The shallow waters behind the barrier form the lagoon. In some places the barrier is overgrown by calcareous algae and corals for several miles along the axis. In these places the barrier expands on the seaward side to form a flourishing organic reef more than one-half of a mile across. Where the barrier has not been modified by organic accretion, it rarely exceeds 200 yards in width. An outer platform composed of country rock is marked by parallel terraces clearly visible on aerial photographs. Undoubtedly, these are submerged strand lines. The general surface of the outer platform drops from 2 fathoms to approximately 16 fathoms at the rim of Tongue of the Ocean in the Fresh Creek area. At the rim the bottom drops abruptly in nearly a sheer cliff to 90 fathoms,[2] beyond which the sea floor descends more gradually to bathyal depths.

Sediments of the shallow waters are mainly clastic remains of animal and plant skeletons, with a minor contribution from disintegration of the country rock and chemically precipitated calcium carbonate. Particles of clay and silt dimensions are swept into deep waters of Tongue of the Ocean, where they are accumulating with pteropods and planktonic Foraminifera as a very fine, light-colored, calcareous ooze. The shallow-water areas are underlain by bare rock over large areas. In other places the shifting sediment consists o a thin mantle of calcium carbonate sand. Th only stable deposits accumulating in th shallow-water areas are the algal-coral reefs

[1] The usual tidal fluctuations are about one-half of one fathom. Depths given in this report are with reference to average tide levels.

[2] Existence of this submerged scarp has long been known to fishermen of Andros. Determination of the local relief of this feature was made by Mr. John C. Armstrong in 1950.

The Country Rock

Low hills of oolitic limestone occur along the northeast or windward coast of Andros roughly paralleling the shore. In the Fresh Creek district the greatest relief, 20 to 25 feet occurs near the shore, and the topography becomes more subdued a short distance inland. There is hardly any soil cover on the island. Evidently this is the natural result of a complete lack of insoluble constituents in the limestone.

There is virtually no surface runoff. Rain water penetrates to the floating fresh-water reservoir below along closely spaced sinks and solution pipes. In places scanty accumulations of humus gather at the bottoms of plugged sink holes, providing the only arable soil of the island.

Excepting the calcareous muds of a few fresh-water lakes, to be discussed later, there is no accumulation of sediments above sea level; hence the island is being rapidly eroded, chiefly by solution.

The outcropping rock on Andros and the marginal cays consists of fine- to medium-grained oolite composed of nearly pure calcium carbonate. Borings on northern Andros made by the Superior Oil Company indicate that the oolite is there about 40 feet thick. It overlies dense, light gray limestone, a rock that does not crop out anywhere in the Bahamas. The oolite of Andros is indistinguishable from that which composes the surface of most of the Bahama Islands. A major geological problem is the origin of this deposit, undoubtedly one of the most extensive oolites in the world. Lithification of sediments now depositing in the Bahamas might not produce a rock exactly like the Bahama oolite. The general rarity of shell detritus and fossils in the rock also presents a difficult problem.

Lithologic Character of the Oolite

The oolitic limestone in the Fresh Creek area, like that at Nassau, Bimini, and elsewhere in the Bahamas, consists of fine- to medium-grained oolite of spheroidal grains cemented by crystalline calcite. According to Vaughan (1918, p. 277) this limestone is nearly pure calcium carbonate (more than 99 per cent). Both aragonite and calcite are represented (Vaughan, 1914c; 1918, p. 277). The low magnesium content is exceptional as compared with most other sediments now being deposited in the region. Vaughan considered the scarcity of magnesium-rich coralline algae in the region during formation of the country rock as a reason for the low magnesium content.

The oolite weathers in drab shades, although the rock is white, light gray, or light cream colored on fresh fracture. Commonly it is firmly cemented, but locally it is friable and can be shaped by means of wood-cutting tools.

Near Fresh Creek village and on near-by cays the country rock is stratified in uneven thin beds which commonly are inclined at low angles, rarely more than 20 degrees. Exceptionally wedge-shaped, cross-bedded, and truncated units lie beneath relatively flat strata. Generally these wedges are no more than 5 or 6 feet thick. Sporadic occurrence of marine fossils in these rocks demonstrates a marine origin for the enclosing sediments. Outside the Fresh Creek area, hills of oolitic limestone rise up to 100 feet and more above sea level. The rock of some of these hills, as, for example, the higher hills within the city of Nassau, exhibits cross-bedded wedges 30 or 40 feet thick. The structure and scale of cross-bedding suggest eolian deposition, an origin ascribed to these rocks as long ago as 1853 by Nelson and later by Northrop (1891), and Alexander Agassiz (1895). Dall (1905) was probably the first to demonstrate that the rocks on several of the islands contain marine fossils up to about 15 feet above sea level, but that rocks at higher elevations contain fresh-water and terrestrial forms. He considered the marine rocks to form extensive platforms on which younger dunes were formed during an emergent epoch. Observations on Andros by Vaughan (1912, p. 154; 1914b, p. 229) convinced him that Dall's conclusions were essentially correct. The marine fossils are not scattered throughout the oolite, but are found only in local lenses of coral sand.

Lithified Beach Ridges

A broad coastal strip about 1½ miles wide extending for several miles northwest from Love Hill village (see areal map, fig. 5) is underlain by low, parallel ridges of thin-bedded oolite. These average about 50 to 100 feet from trough to trough and can be individually traced on aerial photographs for several miles roughly parallel to the coast. Some of these are visible on the floor of the lagoon. Evidently they are being cut away by wave action as the coast is destroyed. Generally the ridges are 5 feet or less high and are separated by strips of swamp lying only slightly above high-tide level. Stratification is nearly horizontal along ridge crests, and the bedding dips gently towards the intervening troughs at 5 to 10 degrees, parallel to the present surfaces of the ridges. Evidently there has been practically no modification of the original depositional surface.

The inland border of this belt of low ridges and swales is bounded by a low scarp some 10 feet high. Apparently this scarp is an old sea cliff whose base is now out of reach of storm waves and is perhaps 3 or 4 feet above the level of high tides.

The parallel ridges are judged to be beach ridges formed, when the sea was slightly higher than now, by accretion of successive accumulations of nearly pure oolitic sand. It is remarkable that shell detritus is almost wholly absent in this rock. Evidently the adjacent sea floor was nearly barren of benthonic animals during oolite deposition, quite unlike present conditions.

Lithified Longshore Bars

The rock that composes numerous cays at the outer margin of the Andros lagoon is indistinguishable from the country rock of Andros. Stratification is somewhat irregular, with numerous wedges of beds cross-bedded on a small scale. Bedding planes tend to dip radially from the summits of the cays approximately corresponding to the external form of the cays. In view of the fact that there is little or no tendency for erosion to follow bedding planes, it is probable that the cays have been little altered in form since they were deposited. The form, distribution, internal structure, and location of the cays at the outer edge of a 2-fathom terrace suggest that they were formed as longshore bars. Presumably, they were formed during a time of greater submergence than at present. High Cay rises some 40 feet above sea level. It may be that the higher deposits of this island were piled up by eolian agencies, because there is no evidence elsewhere in the region of submergence to that depth.

Field observations, aided by aerial photographs, reveals that the cays are in reality subaerial projections along a nearly continuous under-water ridge. Between cays the ridge generally rises to within about 1 fathom, or slightly less, of the surface at low tides. In the northern and southern parts of the Fresh Creek map area, the oolite ridge passes underneath luxuriant algal-coral growth which forms a veneer over the preëxisting ridge. Corals and coralline algae are very sparse in the intervening area on the ridge.

Chains of cays and rocks occur throughout the Bahamas at the outer rims of the shallow banks, commonly rising from waters no deeper than 3 fathoms. Presumably, they were formed where storm waves impinged on the rims of the shallow banks.

Fossils

One of the puzzling features of the Bahama oolite is the rarity of recognizable organic remains. Shell detritus makes up only an infinitesimal proportion of the rock. The fact leads to an inescapable conclusion that the composing sediments were laid down under conditions inimical to organisms capable of fossilization. Those fossils that have been found generally are well preserved, and the general absence of fossils cannot be ascribed to recrystallization or destruction of shells after burial. A few small marine gastropod and pelecypod shells were found embedded in oolite on Long Cay, but in general the rocks of the cays are quite barren of fossils, as are the lithified beach deposits north of Love Hill village.

A number of fossil localities in the country rock have been discovered by several investigators (Northrop, 1891, p. 7; Field, 1931, p. 781; Vaughan, 1912, p. 154; 1914b, p. 230). Mainly, the fossils belong to marine species still living in the region. A number of small coral patch reefs have been recognized along the northeast shore of Andros Island, and all of these occur within about 10 or 11 feet of high-tide level. Where the base of a reef is shown, as at Nicholstown and Mangrove Cay, northern Andros (Field, 1931, p. 781), it can be demonstrated that underlying and overlying rocks consist of oolitic limestone.

A small elevated reef occurs at the east edge of Fresh Creek village, where it is exposed beneath bedded oolite in a low sea cliff (pl. 2, fig. 5). Most of the fossils are rather badly recrystallized fragments of a staghorn coral (*Acropora* cf. *cervicornis*). Pelecypods and gastropods in excellent state of preservation occur in association with brain corals of the *Maeandra* type. The base of the bioherm is below sea level and is not exposed, but thin layers of brecciated oolite interfinger laterally with the corals and pass over the highest part of the reef at an elevation of about 11 feet above high-tide level. Beds of oolite are arched over the reef, with dips of 5 degrees or so along the flanks. Apparently drifting oolite sand was spread over the reef, forming a submarine ridge over a coral core. Probably there has been no differential compaction, because there was little or no differential loading.

At about the same stratigraphic horizon as the above-described reef patch, a few scattered fossil corals and mollusks were found ¼ mile above the mouth of Fresh Creek within 1 to 3 feet of sea level. These isolated fossils occur in oolite matrix.

The fossil reef at Fresh Creek contains very little oolite. Probably half of the rock consists of broken fragments of staghorn corals (pl. 2, fig. 6), with a small admixture of mollusks. The cementing matrix probably is a *Lithothamnion* by analogy with present reef patches in the area. The petrology of this reef has not yet been studied.

This reef lies near the core of an oolite ridge about 1 mile long and a few hundred feet wide, paralleling the shore from Fresh Creek to Calabash Bay. The stratification of the oolite dips away from the ridge axis on both flanks throughout its extent. The reef core is visible, however, for only a few hundred feet immediately to the north of Fresh Creek along the water's edge. It can be assumed that the reef is more or less coextensive with the ridge of overlying unfossiliferous oolite. Only core drilling along the ridge axis would verify the assumption.

It is interesting to speculate on the possibility that the oolite ridge, which forms much of the Andros barrier, was deposited over a reef core. There is, however, no evidence that this is the case. The general rarity of organic detritus in the oolite strongly supports the conclusion that coexisting reefs were small and of strictly limited distribution.

Origin of the Pleistocene Oolite

The remarkably widespread occurrence of oolitic limestone in the Bahamas invites speculation as to its origin. Evidently the prevalent sediment at times of extensive Pleistocene submergence was a fine to medium sand composed almost entirely of spheroidal ooliths. Rocks composed of other types of sediments now common in the region are rare or unknown.

A great deal of attention has been given to the origin of the Bahama oolite by C. L. Smith (1940, p. 170), Thorp (1936, pp. 68–70; 1939, p. 292), and particularly by Vaughan (1914b, p. 229; 1914c, pp. 49–54; 1918, pp. 277–280). Some of the conclusions of these investigators are in rather close agreement: (1) ooliths are forming *in situ* in calcium carbonate ooze on the Great Bahama Bank just west of Andros, but these are not exactly like the Pleistocene ooliths; (2) oolitic sand is rather common at the north end of the Great Bahama Bank, but probably is derived from disintegration of Pleistocene rocks which form cays and underlie the bank.

Oolitic Sand of the Bahama Banks

First, let us consider the question whether or not the oolitic sands of the banks are derived from breakdown of the country rocks.

While studying the sediments of the lagoon near Fresh Creek, we tried to determine the relative importance of sediments derived from disintegration of the limestone oolite of the country rock. Clearly, the rock is being dissolved by the rain and is broken down by waves along shores. Solution of the rock by sea water probably is negligible, because there is no evidence that calcite or aragonite is soluble in the warm Bahamian sea water (Vaughan, 1918, p. 268). Either the ooliths are masked by a much greater proportion of bioclastic detritus, or, as we believe probable, the oolitic structure is destroyed by myriads of boring, burrowing, and rock-destroying organisms of the shore and shallow bottom. These include bacteria, boring algae, sponges, worms, mollusks, and echinoids. They weaken the rock by solution and abrasion so that it crumbles under the effects of waves and currents. Even gastropods and chitons, not often considered to be rock destroyers, have a demonstrable effect by excavating shallow pits in rock surfaces. It is a well-known fact that parrot fish crush and eat limestone.

The modifications of the country rock by organic diagenesis are especially evident in the destruction of the oolitic texture. Near Fresh Creek, rocks just beneath the water surface are riddled by organisms and are altered to a depth varying from 1 or 2 inches to 6 inches or more beneath rock surfaces. In this altered zone the oolitic texture is largely or completely destroyed. Examination of the calcareous sand of the lagoon fails to reveal ooliths or fragments of identifiable oolitic limestone. Goldman (1926, p. 40) had the same experience with lagoonal sand near Cocoanut Point, northeast Andros. Since this is the situation along the northeast coast of Andros, it is difficult to understand how oolitic rocks of the Great Bahama Bank could supply large quantities of pure oolitic sand through simple disintegration, unless, of course, organisms have a very different effect there on the submerged rock surfaces.

Extensive bars or banks of white calcareous sand are shown on hydrographic charts at many localities on the banks. On the Great Bahama Bank these are developed on a grand scale between Bimini and the northern end of Andros and along the rim of the bank west of Andros where they have been noted by Rich (1948) and compared with lenticular oil-bearing sandstones of the geologic record. Many of these bars, or "bores" as they were termed by Agassiz (1895, pp. 37–39), resemble longitudinal dunes covered by giant "ripples" as seen from the air (pl. 1, figs. 2–5). Others resemble "barchans" (pl. 1, fig. 1). They differ conspicuously from eolian features, however, in their relatively low relief. The ridges of the northern part of the Great

Bahama Bank range from ½ fathom to 1½ fathoms from trough to crest. Some of them are more than ½ mile wide and several miles long. There is an exaggeration of apparent relief produced by very sparse growth of turtle grass (*Thallassia*) and algae in the troughs where the underlying bed rock is exposed on the sea floor or only shallowly covered. Many of the ridges are barely awash at low tide. According to various investigators the bars are barren of animal and plant life, so it must be assumed that the sand is in more or less continuous motion. Agassiz (1895, p. 39, pl. 13, fig. 1) describes parallel broad ridges of sand on the edge of the bank at the southern end of Tongue of the Ocean. Some of these are ½ mile wide and 12 miles long. A few of the ridges are dry at low tide; others range down to depths of 3 fathoms on ridges and 4 to 6 fathoms in the broad intervening channels.

Unfortunately, there are virtually no records of the character of the sand itself. Vaughan (1918, p. 274) found that the Great Bank is underlain by oolitic limestone from Cat Cay to the Northwest Channel and that the rock surface is covered by a mantle of oolitic sand, some of which was "still embedded in a hard matrix." He concluded, because of this, that much of the sand was derived from disintegration of the limestone. This seems improbable to us.

John Armstrong has supplied us with two samples of oolite sand from a sand bar in the area just east of South Cat Cay (pl. 1, fig. 6). The sand consists entirely of fine and medium grains of well-formed soft ooliths. These are lustrous, with no sign of wear. Probably they are of recent origin. In view of the the fact that the Great Bahama Bank is populated by very impoverished fauna and flora (C. L. Smith, 1940) incapable of producing significant quantities of calcareous detritus, it is probable that much or all of the sand of the marginal areas of the bank is composed of oolite.

Vaughan's (1914b, p. 227; 1914c) discovery of ooliths *in situ* in the calcareous ooze immediately west of Andros suggests the possibility that ooliths are winnowed and segregated from the calcareous mud during storms. He concluded (Vaughan, 1918, p. 228), however, that should the oolitic muds be indurated, they would not be the same as the oolitic rocks now elevated above sea level. The former contain a larger percentage of $MgCO_3$ (2.72 per cent) than the latter, and the zonal structure of the ooliths is not so highly developed. If ooliths are now being systematically segregated from the muds by currents and waves, it is possible that they continue to grow by accretion while being shifted about. Thorp (1936) examined bottom muds collected by Vaughan near Boca Chica Key, Florida, in which there were many perfect oolite grains consisting of several concentric shells. He thought that these may have formed in the mud, but recognized the possibility that they were derived from older oolite.

Calcium Carbonate Mud of the Great Bahama Bank

The low, swampy surface of the west coast of Andros Island and the west entrances of bights and estuaries are covered by a blanketing deposit of fine calcium carbonate mud (pl. 2, fig. 2) which spreads seaward across the Great Bank (fig. 2) on the lee side of the island. The mud exceptionally reaches a thickness of 30 feet over the limestone country rock near the shore and thins in both directions away from the shore (Field, 1931, p. 777). Lithified equivalents of the mud are unknown; hence the deposit is either very young or it changes to limestone at a remarkably slow rate. Field (*ibid.*) used the term "drewite" for these sediments, although he had earlier introduced the name for a different type of material in the Tortugas lagoon (Thorp, 1936, p. 79).

The mud of the bank area consists mainly of calcium carbonate, with about 2.72 per cent $MgCO_3$ (Vaughan, 1918, p. 273). The sediment of the exposed mud flats along the Andros coast is physically like that of the bank to the west, but it differs strikingly in chemical composition. Vaughan (*op. cit.*, p. 274) discovered that the muds of the subaerial flats are strongly magnesian (13.36 per cent $MgCO_3$). He thought that this deposit had undergone a secondary concentration of magnesium, perhaps by periodic wetting by the sea during times of persistent westerly winds.

Many investigators have observed that a low, wave-cut bank in the white mud marks the shore line for long distances, but this does not necessarily mean that the area of the island is being reduced by erosion along the western margin as believed by Agassiz (1895, p. 7). The general physiography of the western shore (pl. 2, fig. 2) indicates outbuilding by deposition of calcareous mud on the general surface and in the innumerable waterways.

The calcareous mud of the bank area contains abundant small needles of aragonite (Thorp, 1936, p. 74) which make up to one-half of the deposit (Thorp, 1939, p. 290). Artificial needles of aragonite identical with those from the Great Bahama Bank were obtained by Gee, Revelle, and Fleming by passing air free of CO_2 through sea water (Thorp, 1936, p. 74). This experiment indicates that loss of CO_2 in tropical sea water (by agitation, evaporation, and increase in temperature) will result in precipitation of aragonite needles.

Several investigators have tried to determine the mode of origin of the lime mud on the bank and apparently are in agreement that the deposit is mainly a chemical precipitate. There has been disagreement, however, regarding the relative importance of inorganic and organic agencies as causes of the precipitation. The mud above sea level on Andros has not been given much attention. Drew (1912, 1914) concluded from his own studies that bacterial action on soluble calcium salts in the sea caused precipitation of the fine sediment west of Andros. His studies were continued by Kellerman and N. R. Smith (1914), and by Bavendamm (1932) who concluded that sulfate-reducing bacteria were more potent in precipitation of calcium carbonate than are Drew's denitrifying bacteria. Bavendamm found the greatest concentration of bacteria in the mangrove swamps of western Andros Island; hence he concluded that most of the sediment in question was precipitated inland and later washed out over the bank during storms. This is in harmony with the fact that shells of terrestrial mollusks are common in the mud of the bank (Field, 1931). Black (1933b) followed Bavendamm in this conclusion but noted that inorganic precipitation over the bank because of evaporation must also take place. Vaughan (1918, p. 273) had earlier concluded that the Great Bahama Bank acts as an evaporating pan and that some precipitation results from concentration of salts and loss of carbon dioxide as well as by bacterial activity.

Lipman (1924) after a thorough investigation of the subject failed to find definite evidence for bacterial precipitation of calcium carbonate from sea water. C. L. Smith (1940, p. 184) concluded that known physicochemical factors are quite adequate to explain the deposition of the calcium carbonate mud on the Great Bahama Bank even though bacteria may play a minor role in the mangrove swamps. Thorpe (1936, p. 74; 1939, p. 292) had arrived at about the same conclusion.

The consensus among later investigators is that inorganic precipitation on the bank is mainly responsible for the calcium carbonate mud. This conclusion does not, however, adequately take into account the scattered land-derived molluscan shells that are said to be more or less coextensive with the deposit itself. Currents competent to carry the shells many miles away from the shore would certainly transport seaward great quantities of the fine sediments of western Andros. Perhaps an even greater difficulty lies in the fact that the greatest thickness of the mud occurs near the shore line and the deposit on Andros compares in volume with that on the bank. It certainly seems probable to us that there is at present significant transfer of calcium carbonate in solution and limy mud from the island to the bank. It is certain that some deposition is now occurring in the swamps and bights, but it does not follow that all of the mud that covers the island area is of the same origin.

Possibly the island mud has very recently been elevated above sea level, but we know of no conclusive evidence that will shed light on this possibility.

Calcium Carbonate Mud of Fresh-water Lakes

Two groups of fresh-water lakes on eastern Andros were visited by us. These are Love Hill Pond, 1 mile west of Love Hill village, and Fresh Creek Lakes, 1½ miles southwest of Fresh Creek village. These and other fresh-water ponds fluctuate greatly in size according to the season of the year. Many of the smaller ponds become dry a few weeks after the termination of the rainy season. All are characterized by thick accumulations of bottom sediments of sticky calcium carbonate mud. At times of low water the drying mud flats are covered by polygonal crusts of algae (see Black, 1933a). Possibly the life activities of the algae play some part in the precipitation of the calcium carbonate. Very likely, however, most of the sediment is precipitated inorganically. The waters of these lakes must be thoroughly saturated with calcium bicarbonate even during times of high water. Temperatures in some of the ponds exceed those of the warm surface waters of the sea with consequent loss of CO_2. Of course, evaporation must result in continuous precipitation during dry periods. The sediment has not as yet been compared with the calcareous mud of the bank area, but the two are at least superficially alike.


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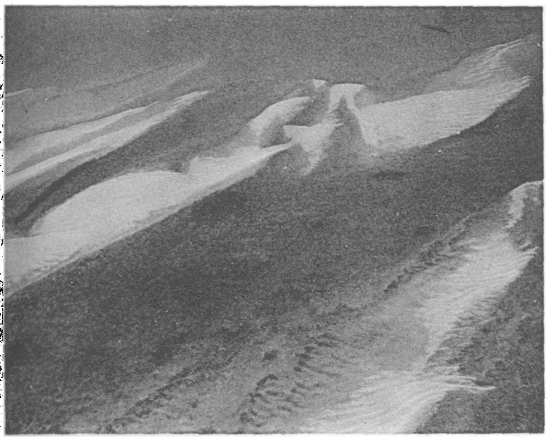
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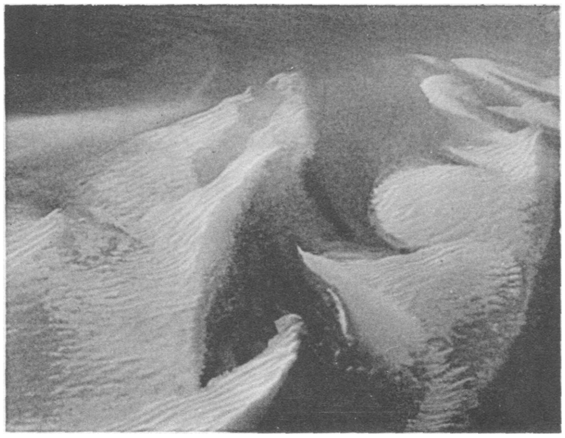
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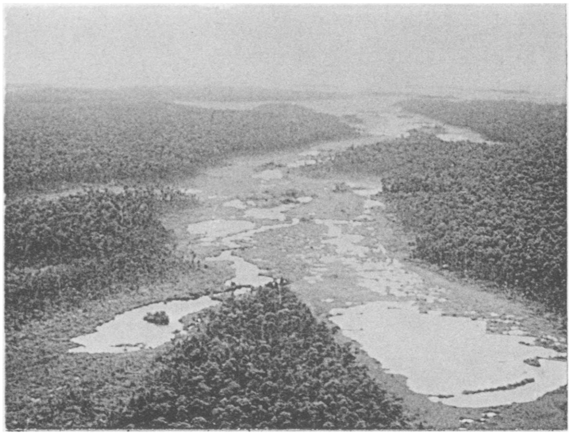
1. Under-water "barchans" just north of Nassau (Whiteman Kodachrome). 2. Longitudinal "bores" about [illegible] miles east-southeast of Gun Cay, northern Great Bahama Bank. Depth of water in troughs, 2 fathoms; airplane altitude, 1 mile (Whiteman Kodachrome). 3, 4. "Rippled" longitudinal sand bars, Great Bahama Bank, just northwest of Andros. Depth of water in troughs, about 1½ fathoms; airplane altitude, 1 mile (Newell and Whiteman Kodachromes). 5. Bars of oolite sand immediately south of South Cat Cay. Airplane altitude, 1 mile (Newell). 6. South Cat Cay and associated bars of oolitic sand; deep water of Florida Strait in background. Airplane altitude, 1 mile (Newell)



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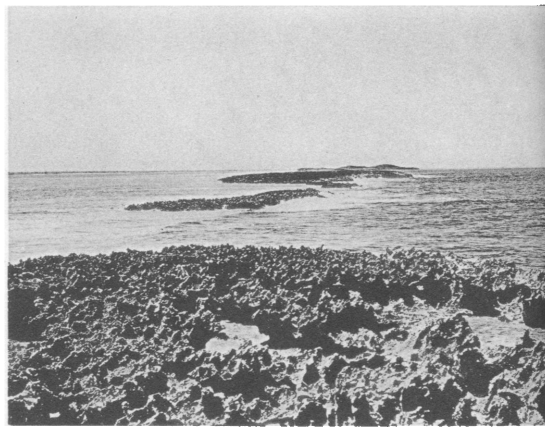

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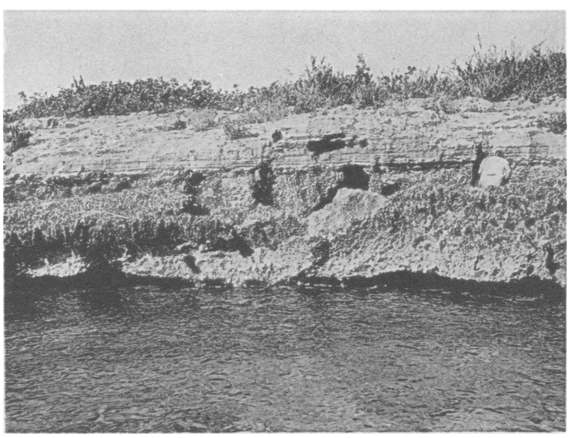

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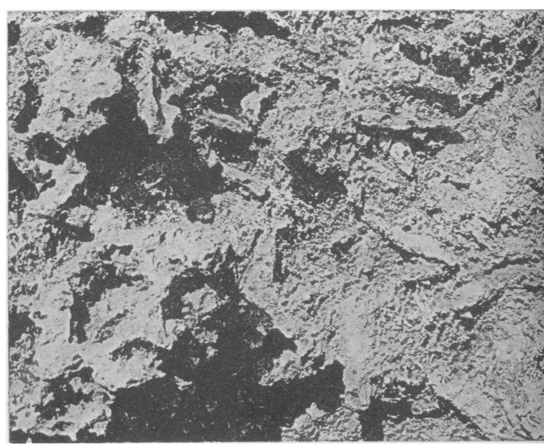

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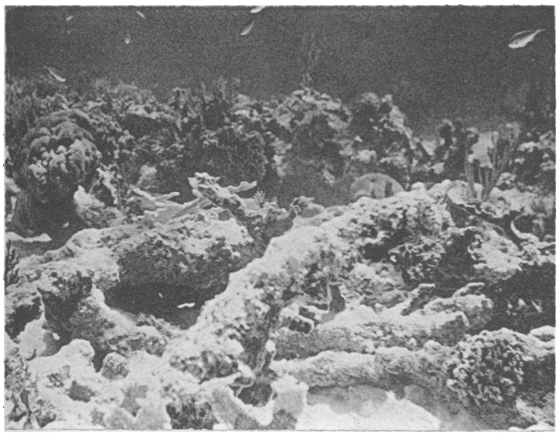
1. Old tidal channel, about 7 or 8 miles west-southwest of Fresh Creek village, left dry by relative drop in sea level (Whiteman Kodachrome). 2. West coast of Andros covered by calcium carbonate ooze, just north of South Bight entrance, Miller Creek in foreground (Newell). 3. Limestone encrustation, possibly of algal origin, over bedded country rock at Fresh Creek village (Newell). 4. Limestone oolite cays, lithified longshore bars near Fresh Creek village; looking northwestward from Long Cay (Whiteman Kodachrome). 5. Massive fossil coral reef beneath bedded oolite at Fresh Creek village (Newell). 6. Fossil corals of reef shown in 5



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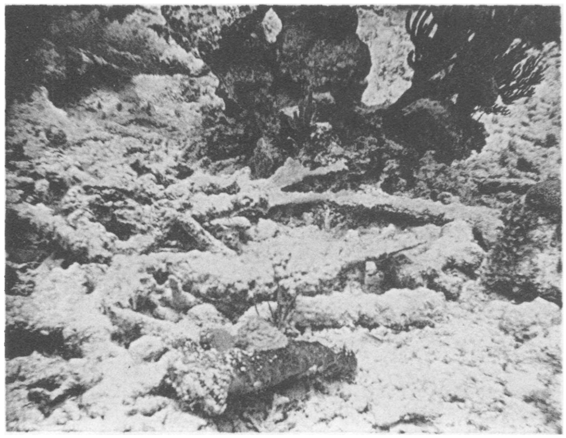

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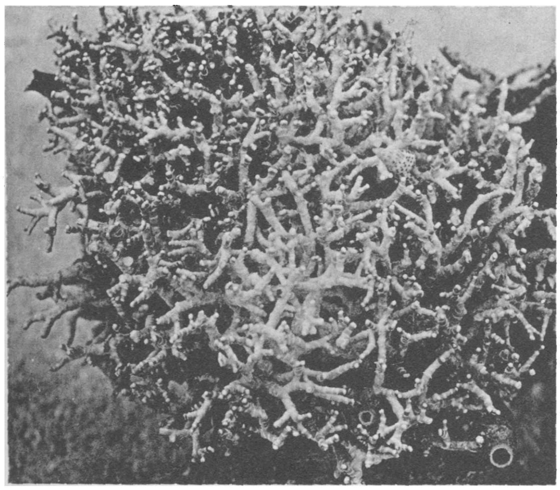

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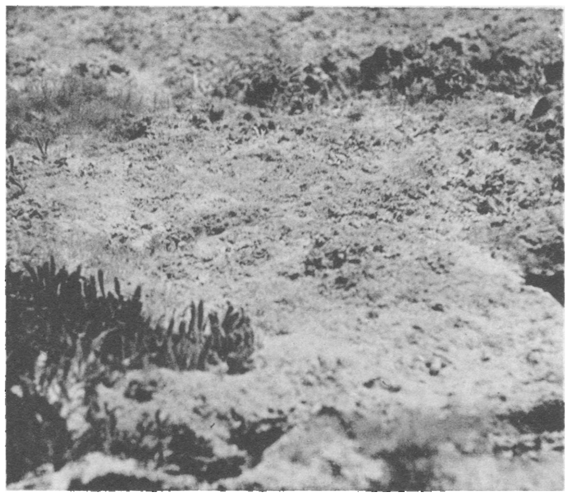

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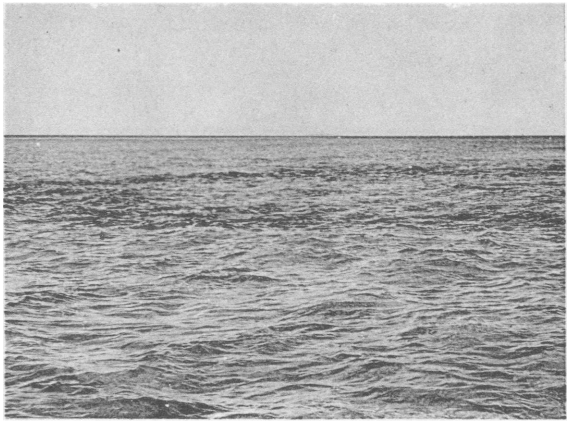
1. Prone trunks of coral (*Acropora palmata*) encrusted by *Lithothamnion*, near Love Hill channel at 3 fathoms. 2. Dead corals bound together by encrusting *Lithothamnion*, below Long Rock at 2 fathoms. 3. Bioclastic calcareous lagoonal sand composed mainly of algae, corals, and Foraminifera inhabited by a lonely heart urchin (*Clypeaster*?); 1½ fathoms, near Long Rock. 4. Beach gravel of mollusks and corals. 5. *Goniolithon strictum*, a coralline alga characteristic of quiet shallow waters, × ½. 6. Calcareous sand formed by disintegration of *Goniolithon strictum; Dasycladus* sp., a green alga, in the foreground; about ½ mile above Fresh Creek village in Fresh Creek. All photographs by Bierwert



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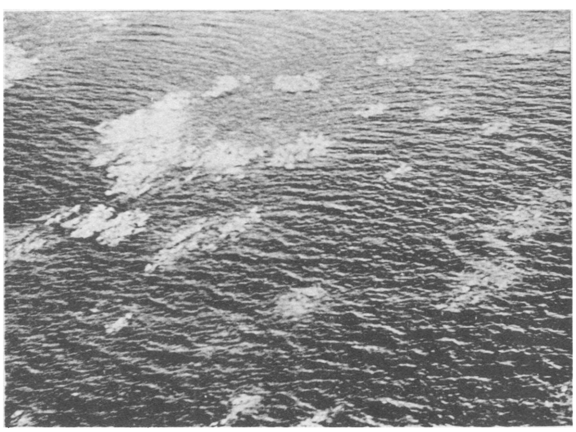

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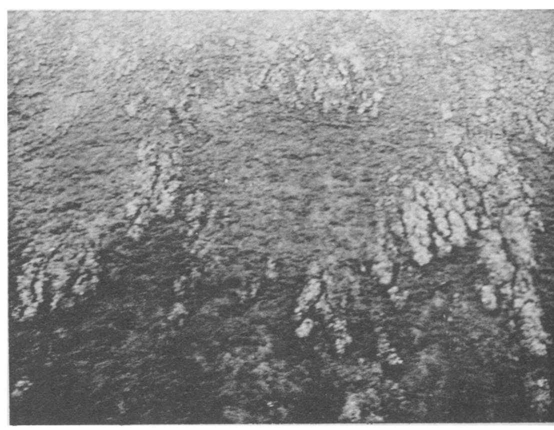

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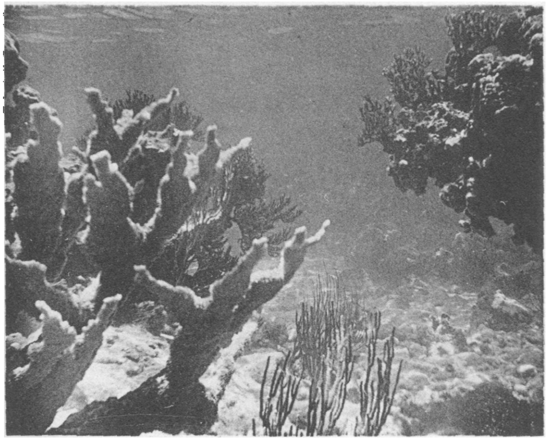
1. Gorgonian microatoll at about 1½ fathoms, 2 miles southeast of Fresh Creek village (Whiteman Kodachrome). 2. Coral reef and microatolls behind; traces of submerged terraces visible in foreground. Airplane altitude, about 1500 feet (Newell). 3. Reef, microatolls, and lagoon, just north of North Bight. Airplane altitude, about 1500 feet (Newell). 4. Reef front (same locality as in 3), showing under-water channels between coral "heads." Airplane altitude, about 2000 feet (Newell). 5, 6. Coral "heads" and channel pattern from front of reef near Staniard Creek village. Airplane altitude, about 800 feet (Bierwert and Whiteman Kodachromes)



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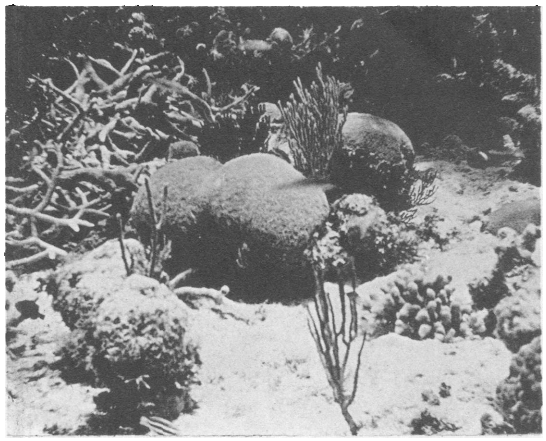

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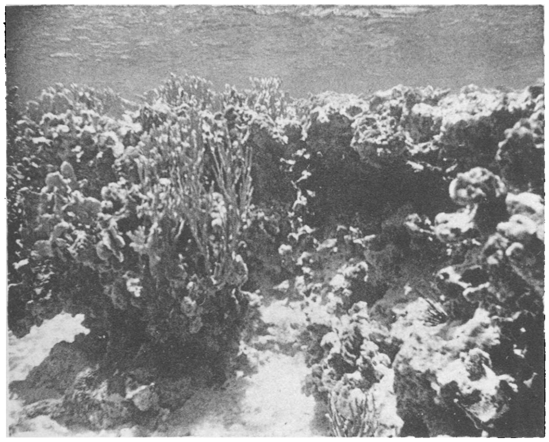

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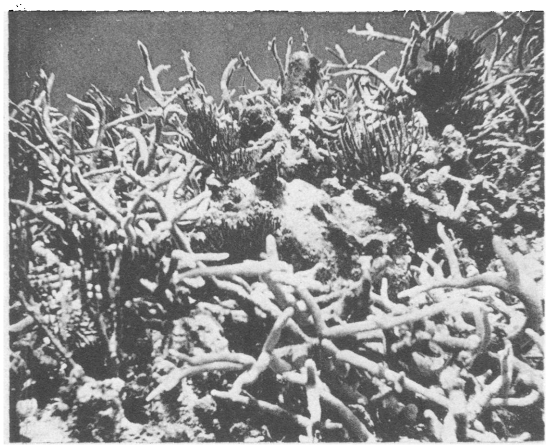

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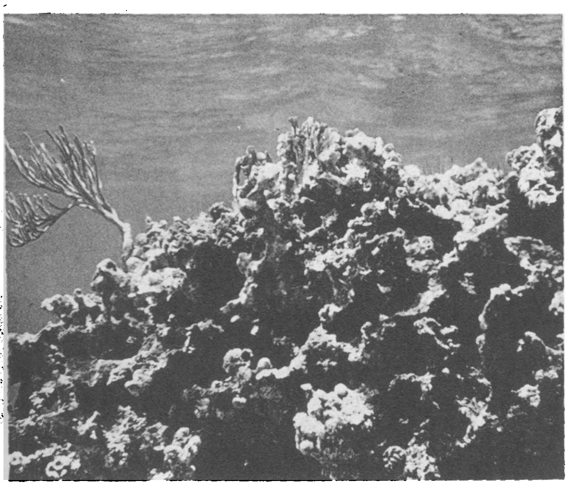

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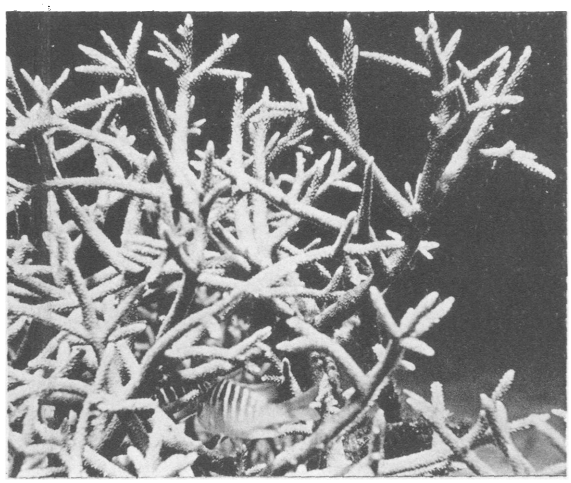

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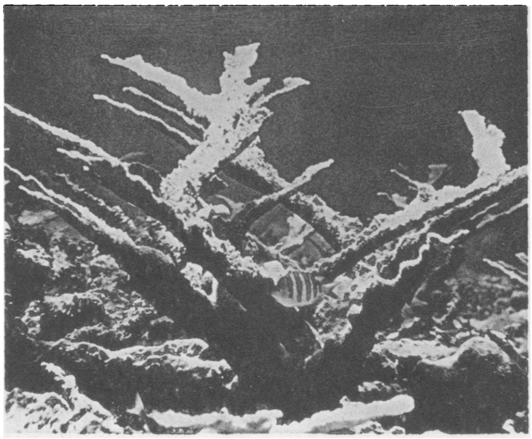
1, 3, 5. *Lithothamnion-Millepora* reef crest, photographed from shallow surge channels about 1½ fathoms deep at low tide above Goat Cay near Love Hill channel (1 and 3, Newell; 5, Bierwert Kodachrome). 2. Association of staghorn (*Acropora cervicornis*) and massive corals at the outer edge of the *palmata* zone, below Long Rock at 2 fathoms (Bierwert Kodachrome). 4. Thicket of contorted *Acropora cervicornis* at outer edge of *palmata* zone, below Long Rock at 2 fathoms (Bierwert Kodachrome). 6. Erect form of *Acropora cervicornis*, depth 1½ fathoms, in relatively quiet waters of a microatoll 2¾ miles southeast of Fresh Creek village (Bierwert Kodachrome)



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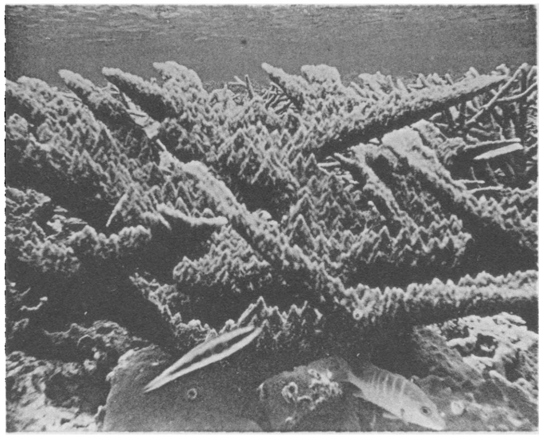

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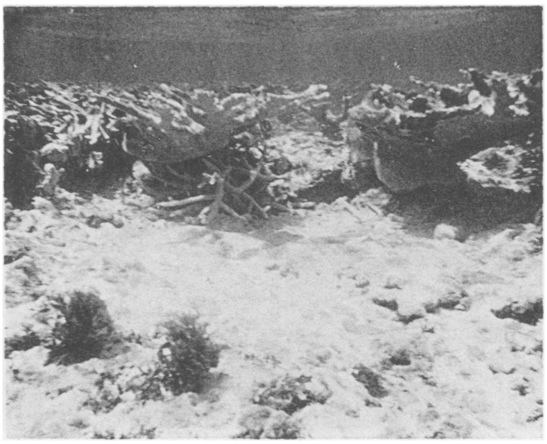

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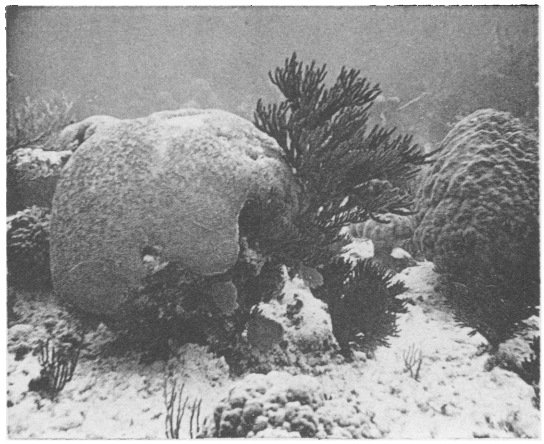

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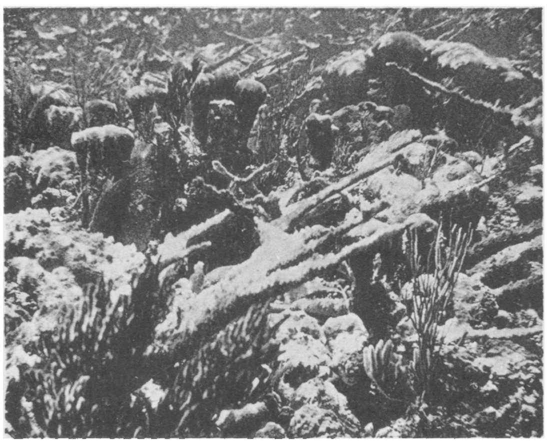

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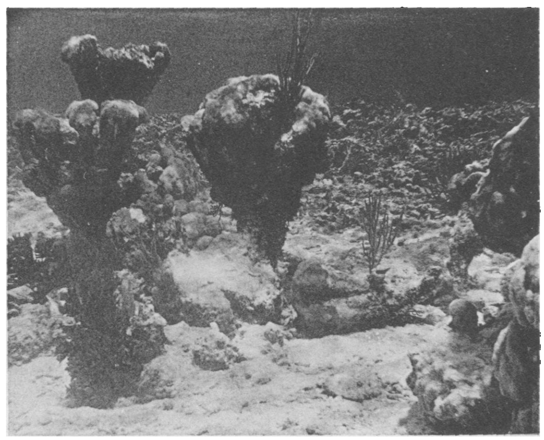

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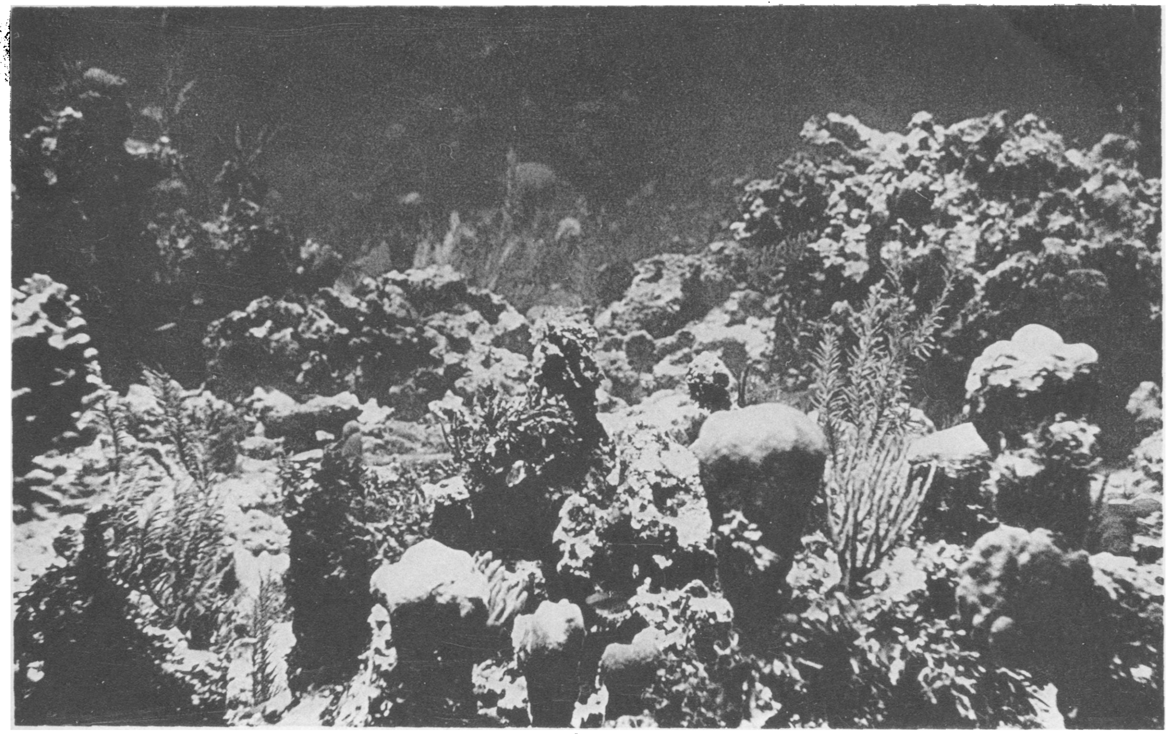
1. *Acropora palmata*, erect growth form characteristic of deeper waters beyond *palmata* zone, near Love Hill channel at about 3 fathoms (Bierwert Kodachrome). 2. Accordant crests and stocky form characteristic of *Acropora palmata* at shallower depths in *palmata* zone; below Long Rock at about 1½ fathoms (Bierwert). 3. Stocky growth form of *Acropora palmata* near reef crest, surge channel in foreground; above Goat Cay, near Love Hill channel at about 5 feet (Newell). 4. Massive coral in surge channel near reef crest; below Long Rock at 2 fathoms (Bierwert). 5. Diverse coral fauna below *palmata* zone; below Long Rock at 3 fathoms (Bierwert). 6. Pedunculate corals behind reef crest, near Love Hill channel at 1½ fathoms (Newell)



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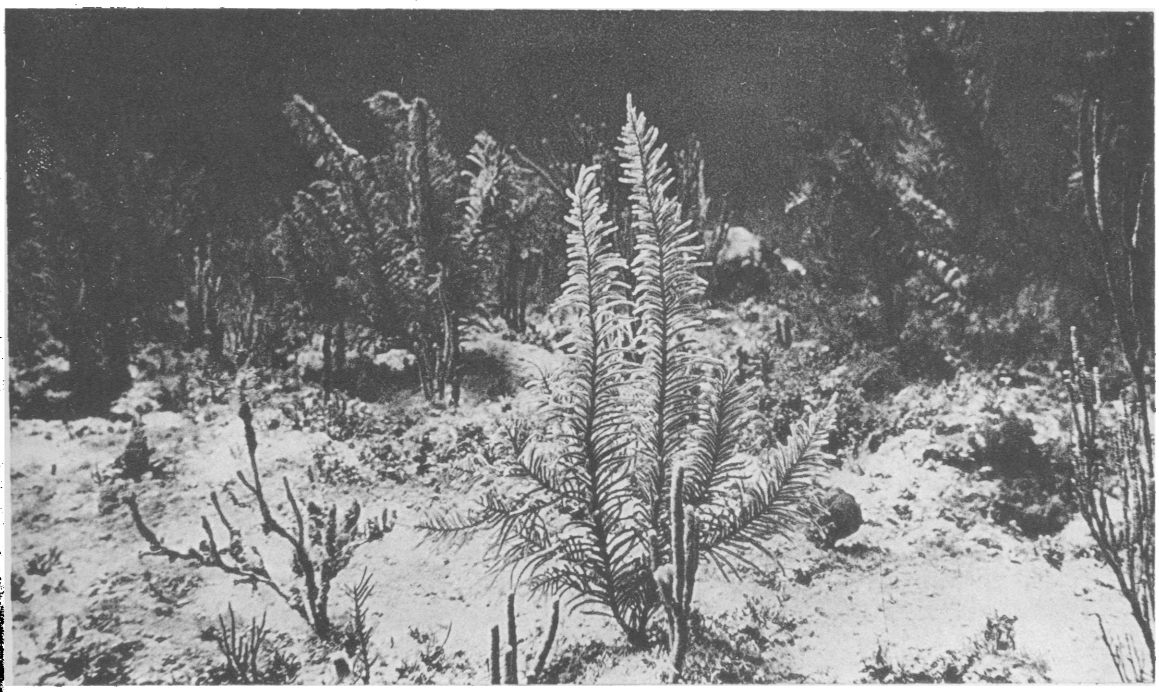

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1. Sparse reef development at a surge channel on the lagoon side of the reef crest. Pedunculate corals in foreground and irregular mass of *Lithothamnion* in right background; near Love Hill channel at 2 fathoms (Bierwert Kodachrome). 2. Gorgonian community characteristic of lagoon rocky floor; about 2 miles southeast of Fresh Creek village at 2 fathoms (Bierwert Kodachrome)

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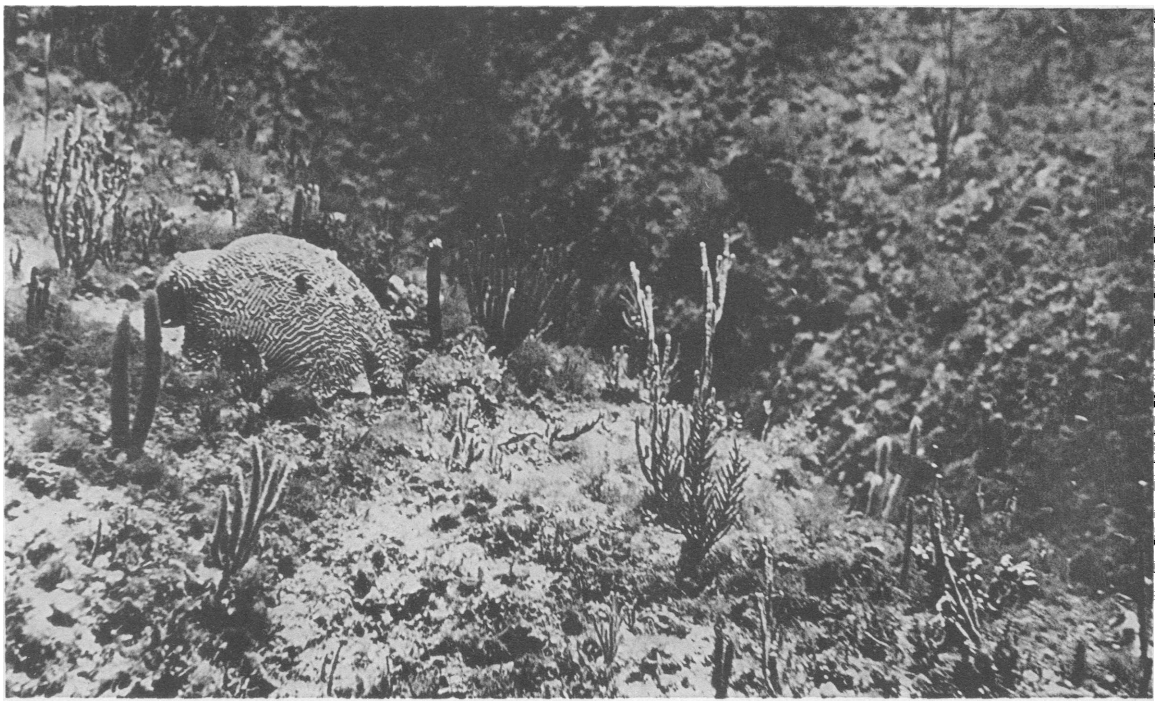

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1. Rock floor community, at about 3 fathoms, west side of South Bimini. The green alga *Udotea* sp., a few stunted coral heads and sea fans survive in spite of the fine calcium carbonate from the bank which sifts over the rocky bottom (Bierwert Kodachrome). 2. Under-water channel or groove, east side of mid-point of Long Cay, near Fresh Creek, at 4 fathoms (Bierwert Kodachrome)

PRINCIPAL HABITATS AND SEDIMENTARY ENVIRONMENTS

Introduction

SHOAL-WATER marine environments in the Fresh Creek area are dominated by the peculiar conditions of sedimentation that prevail there. Terrigenous sediments are wholly lacking, and there is hardly any organic accumulation in the region. The rocks and sediments are dominantly calcium carbonate, with minor amounts of magnesium carbonate. Other sedimentary constituents are infinitesimal. There is so little vegetation on Andros and so little surface drainage that humus is not concentrated. Except for the muds of the mangrove swamps, which commonly are gray and emit a mild odor of H_2S, the sediments are relatively free from organic matter and, therefore, contain little of nutritive value. Mud-dwelling detritus feeders are mainly limited to the swamps and waterways of the island, and the sand-dwelling communities consist, for the most part, of a few vagrant echinoderms adapted for life in the comparatively sterile wastes of shifting sands.

The tidal range is nearly that of the open ocean, approximately 3 feet for normal tides, and the near shore areas generally are sufficiently deep to remain covered at low tides. Consequently, the littoral zone is narrow, and successive ecologic zones of the shore tend to merge and overlap. The limestone rocks of the shore are poorly suited for the attachment of brown algae, so that these forms are an inconspicuous part of the shore life.

The majority of shallow-water benthos are forms that live upon or within rocks. This is partly because rock surfaces are relatively extensive, but also it is because these waters are characterized by vigorous currents in which only solid rocks afford substantial footing.

Coralline algae and stony corals are very sparse opposite the entrance to Fresh Creek, and there is no reef for several miles along the barrier near the latitude of Fresh Creek. Fresh Creek is a tidal inlet, narrow at the entrance, and widening into great shallow lakes in the interior. The water of Fresh Creek was not noticeably fresher than that of the ocean at the height of the dry season (June) when we visited the area, but there must be significant dilution of the waters of this tidal channel during the rainy season. Presumably, reef development opposite Fresh Creek entrance has been inhibited by occasional outflow of brackish waters from Fresh Creek.

Shore Habitats

Benthonic organisms of the shores of Andros and outlying cays in the Fresh Creek area are distributed in a number of well-defined ecologic zones. Many of the forms exhibit marked selectivity with respect to topography and constitution of the substratum.

Both sand and rock bottom occur low (zone A) in the intertidal belt. Along the shore on both sides of Fresh Creek entrance there is a broad, wave-cut bench of country rock that is just awash during normal low tides. The rock is deeply altered, friable, and pitted by innumerable holes and undercut ledges. Depressions form small tidal pools. Echinoids are conspicuous here; they are represented by *Echinometra subangularis* and *Toxopneustes variegatus*. The former remains low enough to be constantly wet, even though exposed to the air between waves, and lives in both protected and exposed places. It commonly occupies holes beneath ledges where it must be subjected to strong pounding by surf. Some individuals were observed to be entrapped in cavities, the openings of which were smaller than the echinoid.

The much larger, short-spined, gray echinoid *Toxopneustes variegatus* commonly is found in relatively open tide pools and unprotected flat rocky areas. Rarely was it observed in cavities. Instead it utilizes shells and plants attached to the aboral surface for concealment. The bits of extraneous material are held over the back by means of long tube feet. In the majority of individuals observed, mangrove leaves were used for the purpose. The use of camouflage and the natural light color of these echinoids enable them to blend well with the prevailing colors of the substratum on which they are characteristically found.

Green algae of the genera *Dasycladus* and

Padina are abundant in the deeper pools, but these forms are most characteristic of the sublittoral bottoms.

In a few protected places, as within Fresh Creek estuary, there are low-level beaches composed of calcium carbonate sand and pebbles and a very minor admixture of decomposing organic matter. These commonly are only 5 or 6 feet wide, but south of Fresh Creek entrance there are beaches up to 50 feet across. The biota of this habitat is very sparse. The only conspicuous form is *Dasycladus*, which adheres to pebbles in small tufts.

The most extensive ecological zone (B) lies between normal tides along the rocks and low seacliffs of the Andros shore and outlying cays. The rocks of this zone are deeply weathered and are conspicuously modified by organisms. The original oolitic texture of the rock has been destroyed near the surface. Commonly the rocks are stained yellowish brown by microscopic plants.

A small acorn barnacle (*Chthamalus fragilis* ?) is scattered over surfaces in the higher part of the zone, and a robust chiton is abundant in the lower part. Gastropods, however, dominate the rock surfaces, and they swarm in countless numbers throughout the intertidal zone.

At the extreme lower limit of the normal low tides are found the robust *Livona pica* and small limpets, followed just above by *Nerita peleronta*. The latter ranges perhaps a foot or so above normal low-tide level, overlapping the lower part of the range of *Tectarius muricatus* which swarms over the higher part of the intertidal zone and above.

Landward from the intertidal zone lies the fascinating splash zone (C) which covers most of the area of the cays as the result of their exposure to the full violence of storm waves. The northeast coast of Andros is protected by a shallow lagoon and barrier. Consequently, the splash zone is inconspicuous on Andros.

The rocks of this zone are stained dark gray in the lower part, probably by microscopic plants. In the upper part of the zone the rocks assume natural, unmodified rock colors, light gray to white-buff. They are etched and furrowed in a very characteristic manner, especially on the cays (pl. 2, fig. 4). Evidently the particular erosion form of the splash zone results from shore processes in which solution by rain water is hardly significant. Organisms probably play an important part in erosion by softening the rock. The latter, consequently, is rendered vulnerable to abrasion and hydraulic action of storm waves. Liberation of CO_2 by lichens and algae possibly is of some significance in the decay of these rock surfaces, and possibly production of acids by bacteria (Paine, Linggook, Schimmer, and Thrupp, 1933) is also a potent factor.

The extreme dissection of the splash zone is not found elsewhere in the region, so that solution by rain water is not primarily responsible. Evidently continued wetting by salt spray under subaerial conditions favors the factors responsible for this type of erosion.

Gastropods of the species *Tectarius muricatus*, *Echinella* cf. *nodulosa*, and *Cerithium* cf. *literatum* are the abundant forms of the splash zone. Representatives of *Tectarius muricatus*, in harmony with the rock surfaces of the splash zone, tend to be dark gray near the high-tide level and light gray above. The shell of *Echinella* cf. *nodulosa* is dark gray, which fits it well for life in the stained rock pools low in the zone. It can endure for long periods the high temperatures and concentrated salts of these tiny pools. The adaptive coloration of the gastropods of the intertidal and splash zones is really quite striking. Virtually all of them harmonize well with the various color tones of the rocks on which they live. This can be readily tested by transferring a *Livona pica* a few inches above its normal range or by placing a *Cerithium* near the low-water mark where these forms, in consequence of the increased color contrast, become relatively conspicuous and would be quickly destroyed by predatory birds.

Above the splash zone along the Andros coast there is an obscure, wave-cut bench and nick replaced here and there by a high-level beach. Since these features are well above the normal high-water level, they are presumed to be formed by storm waves, but they may represent an elevated strand corresponding to that recognized by Dixon (Field, 1931, p. 780). The rock surfaces and beaches of the storm line are covered by debris from both sea and land. Normally, they are occupied by small terrestrial and amphibious arthropods and sand worms. Hosts of small hermit crabs of many species are most evident.

A special feature of the rock bench, especially well shown with the estuary at Fresh Creek dock, is a thick deposit of banded limestone which is forming as a thick encrustation over the oolitic bedrock (pl. 2, fig. 3). The secondary deposit forms a botryoidal encrustation in and around tide pools. In some cases it forms slightly elevated rims around some of the pools. Internally the deposit is banded or laminated in alternating thin layers of dark and thicker layers of cream-colored hard limestone. This is probably the same material as that referred to by Dixon (Field, 1931, p. 780) as a stalagmite-like deposit over an elevated terrace of northeastern Andros, the Berry Islands, and elsewhere. The origin of this deposit is uncertain. At Fresh Creek it occurs low enough in places to be covered at high tides, and probably it is in process of formation at these low levels. Some of this material occurs 8 or 10 feet higher, however, completely beyond the influence of the sea. Apparently it is being destroyed by solution at higher levels. Below high-tide level small rock pools in the encrusting deposit contain living algae. Possibly the algae are partly responsible for precipitation of the calcium carbonate which forms the deposit. However, it is equally possible that the calcium carbonate is precipitated by evaporation of the trapped sea water. Accumulations of salt occur in most of the pools. There is no lime mud in the depressions, therefore no indication that the hard rock is formed by lithification of soft sediment.

Estuary and Lagoon

The barrier formed by cays, submerged shoals, and algal-coral reefs lies about 1 to 3 miles from the Andros shore. The water in the intervening area is uniformly quite shallow, ranging from a little less than 1 to about 2½ fathoms at low tide. Thus, it is comparable in depth with the marginal areas of the Great Bahama Bank, and like the Bank the Andros lagoon is floored by oolitic limestone over which there is a thin shifting blanket of recent sediments. The lagoon floor may be a wave-cut terrace. If so, it was cut before the barrier was formed.

Storms and the regular tidal fluctuations produce vigorous currents which flow through gaps in the barrier, across the lagoon, and through the estuaries such as Stafford and Fresh creeks. Sediments finer than fine sand are negligible in the lagoon. Fine sediment occurs in mud banks a half mile or so above the mouth of Fresh Creek, but the channel of that stream cuts across bedrock for many miles inland. Fresh Creek entrance is narrow, not more than about 50 yards across, where it cuts through low coastal hills.

Inland the stream widens until it merges with a complex of anastamosing broad waterways and extensive lakes which are only slightly less salty than the sea during the dry season. In the rainy season they may become brackish. Locally, large numbers of the gastropod *Neritina* cf. *virginea* and two or three small pelecypods occur in these waters.

Although a great deal of water flows in and out of Fresh Creek at high velocities with the tides, it is probable that not much of the fine sediment of the inland waters escapes to the sea, or, if it does, that it escapes slowly. Outflowing water at the mouth of Fresh Creek is relatively clear.

The green alga *Dascycladus* extends far up Fresh Creek, as does the marine grass *Thallasia*. Within a mile or so of the entrance species of *Sargassum*, *Udotea*, *Padina*, and *Penicillus*[1] are common, but these are characteristic marine forms of the region. A small patch of *Goniolithon strictum*, a lithothamnion, occurs one-half mile above the mouth of Fresh Creek (pl. 3, figs. 5, 6). A small, purple finger sponge, a *Cerithium*, and a large sea slug (*Tethys?*) are characteristic associates of *Goniolithon strictum*. The *Cerithium* was observed feeding on the surface slime of the alga. Another lagoonal

[1] *Penicillus* is illustrated on plate 8, figure 1, where it is inadvertently termed *Udotea*.

form, the coral *Siderastrea radians*, occurs a short distance up the creek. This species is particularly hardy and can withstand rather great fluctuations in salinity and water temperature. Significantly, gorgonians scarcely enter the estuary, although they occur quite near the shore on both sides of Fresh Creek entrance. A pelecypod, *Pedalion alata*, clings to rocks and mangrove roots between tide levels in the estuary for several miles inland from the mouth.

Much of the floor of the lagoon is formed of bare rock swept free of sediment by currents and waves. Elsewhere, the lagoon is floored by scattered thin patches of fine sand and by extensive areas of sand of greater thickness. The communities of bare rock and sparse sand bottoms are varied and show few significant differences. The true sand bottoms are inhabited chiefly by echinoderms.

The rock bottom is perforated by openings ranging from microscopic borings and solution pits 2 feet across to great sink holes locally designated "blue holes" or "ocean holes." These large depressions are well known to the local citizens and attracted the attention of Northrop (1891, p. 12) and Agassiz (1895, pp. 7, 39). Many of these are visible on aerial photographs of the lagoon and Andros. For the most part they are completely submerged below sea level. Vaughan (1912, p. 154; 1914b, p. 230) cites a blue hole three-fourths of a mile northwest of Booth Bay, in North Bight, which has a depth of about 32 fathoms. He concludes that this was formed by subaerial agencies when the area stood 192 feet higher than it does now. Some of the smaller cavities contain rounded cobbles of country rock and coral. Possibly agitation of the entrapped rocks during storms produces appreciable excavation. Many of the smaller holes are occupied by the large black urchin *Centrechinus antillarum*. It is probable that these and other echinoids are in a limited way responsible for enlarging preëxisting pits by means of their tube feet. Some individuals of *Centrechinus antillarum* show asymmetrical development of their spines, closely reflecting irregularities of the cavities which they inhabit. It is evident that these forms must regularly return to a particular refuge.

Like the rocks of the intertidal shore zone, the rocks of the lagoon are profoundly altered by burrowing and rock-crushing organisms (gephyrids, *Eunice*, *Cliona*), and rock samples from the lagoon floor are thoroughly infested to depths extending inches into the rock.

The rock bottom sustains a rich and varied biota of attached and vagrant forms. Many seaweeds (*Sargassum*, *Padina*, *Dasycladus*, *Udotea*, *Penicillus*, *Acetabularia*, *Halimeda*, *Caulerpa*, *Laurencia*, *Blodgettia*, *Liguria*, and others) provide a scanty carpet hardly concealing the rock floor anywhere. The delicate shrub-like *Goniolithon strictum* (pl. 3, figs. 5, 6) was observed to cover small areas in less than 1 fathom of water on both sides of the lagoon. The skeletons of this plant are quite brittle and fragile. Wherever there is a concentration of the species, the associated sediment is largely composed of detritus produced by destruction of the brittle calcareous fronds. *Halimeda*, on the other hand, is very sparsely represented, and probably is a very unimportant sediment former.

Gorgonians of many kinds are common where the rock floor is not too deeply buried by sand. In fact, these are easily the most characteristic and conspicuous benthonic animals in the lagoon.

A small, brown, spheroidal stony coral (*Siderastrea radians*) forms isolated heads up to several inches in diameter. There are two or three less common ahermatypic corals that are widely distributed in the lagoon. Immediately behind the barrier are numerous small patch reefs containing a number of ahermatypic corals. These are considered below with the discussion of the coral reefs.

A number of byssate and cemented pelecypods occupy this ecological zone. *Pinctada radiata*, *Mytilus exustus*, *Volsella tulipa*, several arcids, a *Pteria*, a *Codakia*, *Glycimeris americanus*, several cardiids, *Asaphis deflorata*, and *Chama sarda* occur here. The last-named form lives cemented to rock surfaces. The others live in grassy areas or attached to gorgonians. *Atrina rigida* lives shallowly buried in sand. The great conchs *Strombus gigas* and *Cassis tuberosa* frequent grassy areas in search of pelecypods. Dead shells of the following gastropods were found along the Andros shore of the lagoon: *Tonna perdix pennata*, *Astraea longispina*, *Diodora listeri*, *Cerithidea turrita?*, and *Lepeta caeca*. Remains of the cephalopods *Spirula spirula* and *Sepia* sp. were likewise found on the beach.

Extensive sand areas are bare of bottom vegetation. The sand is apparently deeper here and is unstable. Systems of current ripples are common, ranging in wave length from 2 or 3 inches to at least 4 feet. In certain areas of very vigorous currents the sand forms slender parallel ridges shaped something like longitudinal dunes except that the under-water features have relatively low relief. Commonly intervening troughs are occupied by a sparse cover of marine grass or algae which clearly outlines even very subdued features of topography.

The only conspicuous benthonic animals of the sand wastes are echinoderms. Possibly these are as abundant in the grassy sand bottoms, but there they are somewhat masked. The noteworthy fact about their distribution is that they venture into areas nearly devoid of vegetation. The giant starfish *Oreaster recticulata* is remarkably abundant in some sand areas. During one traverse we estimated an average of one individual for each acre of bottom. It would be interesting to know something of the food habits of this animal. A large, black holothurian (*Holothuria floridana*) is fairly common, as is a large heart urchin (*Echinocardium* ? sp.). *Clypeaster rosaceus* is quite rare. Numerically most abundant of the echinoids is *Mellita testudinata*, a keyhole sand dollar.

Probably the most abundant animals in the lagoon are Foraminifera which make up an appreciable fraction of the calcareous sand. Families most abundantly represented in four samples are:

Peneroplidae	42.6%
Miliolidae	15.3
Rotaliidae	15.0
Nonionidae	14.3

An exhaustive analysis of lagoonal sand from Andros was made by Goldman (1926). His samples were collected from just behind the barrier reef at Cocoanut Point, near Nicholstown, about 25 miles northwest of Fresh Creek. The general setting is very like that of the Fresh Creek area. According to Goldman's conclusions, the sand is more than half coralline algae and stony corals (scleractinians), and more than one-tenth of the samples was composed of Foraminifera.

The percentage by weight of gravel and sand from the lagoon (from Goldman, 1926, p. 54) is:

Pure calcium carbonate	
Stony corals	24.4%
Halimeda	17.0
Mollusks	6.1
"Limestone"	1.7
	49.2%
Calcium magnesium carbonate	
Coralline algae	32.6%
Foraminifera	11.6
Alcyonaria	1.2
Bryozoa	1.5
Crustacea	1.7
Worm tubes	1.1
Echinoderms	1.0
Calcareous sponges	0.1
	50.8%

The adjusted composition of the sample of gravel and sand from the Andros lagoon (from Goldman, 1926, p. 53) is:

$CaCO_3$	94.59%
$MgCO_3$	5.24
SiO_2	.09
$(AlFe)_2O_3$	.08
	100.00%

According to Goldman (1926, p. 65) the sand composition differs from equivalent proportions of fresh control material. The results indicate a relative decrease in the amount of magnesium carbonate, calcium sulphate, and calcium phosphate after deposition of the sand.

The Barrier

As explained on an earlier page, the barrier is formed by (1) a narrow ridge of oolite which rises to the surface here and there to form small cays, and (2) algal-coral reefs, much broader than the oolite ridge and built on the front and over the oolite ridge. Although these reefs form a barrier in the nautical, ecological, and geomorphic sense, they are not a direct result of subsidence, and they do not lie at the margin of the Andros platform. They are really a special form of the fringing reef. Since these reefs lie on a platform and are separated from the shore by a shallow lagoon, they have been designated by the special term "bank reefs" (F. G. Walton Smith, 1948, p. 36).

The oolite barrier in the Fresh Creek area commonly rises to half a fathom between the cays. A number of deeper channels extending down to 2 fathoms interrupt the continuity of the ridge and provide passage for strong tidal currents. The biota of the ridge is not greatly different from that of lagoonal rock bottom except that gorgonians of the barrier are less abundant and smaller. A small yellow sea fan is especially characteristic of depths less than about 1 fathom. Scattered colonies of *Millepora alcicornis* first appear here, but they become commoner in the vicinity of the reefs. Patches of pink pavement lithothamnion (*Lithothamnion aemulans?*) are common along the crest of the ridge and the outer margin of the cays just below low-tide level and were not recognized below about 2 or 3 fathoms. Stony corals are poorly developed along the ridge except near the reefs. Outlying individuals are found mainly on the seaward face of the barrier, where they are somewhat shielded from the unfavorable waters of Fresh Creek.

Luxuriant extensive communities of stony corals, *Millepora* and *Lithothamnion*, are building long reefs along the seaward face of the barrier of the northeast coast of Andros Island. The discontinuity in reef growth caused by the waters of Fresh Creek is a local condition and does not invalidate the prevalent belief that these are the most extensive reefs in the Western Hemisphere. Yet it must be borne in mind that the organic accumulation over the core of country rock is apparently thin and probably entirely post-Pleistocene in age. Alexander Agassiz (1895, p. 138) correctly assessed the very minor role of corals as sediment formers in the Bahamas, and Vaughan (1918, p. 279) concluded that the Andros reef does not contain sufficient coral material to make a continuous ridge along the island 100 feet wide and 12 feet thick.

Where reef development is well advanced, as, for example, in the sector between High Cay and North Bight or between Goat Cay and Staniard Creek, the crest lies near the lagoonal margin of the reef. Flat mesas of cellular lithothamnion rock with scattered erect stolons of blade-like or finger-like *Millepora alcicornis* form the highest part of the reef. The reef crest is dissected by closely spaced, steep-walled, tidal channels (pl. 5, figs. 1, 3, 5) which are kept open by strong currents. A few scattered hemispherical corals and gorgonians live in the channels, but generally this is an unfavorable environment in which the water is murky from suspended sediment. The innumerable holes and pits in the lithothamnion rock provide admirable shelter for *Centrechinus antillarum* which in spite of its very long and fragile spines is very much at home in turbulent waters of the reef crest. Sabelliform worms and *Chama sarda* and a great variety of ascidians are in evidence here.

Prominence of coralline algae along the lee margin of the reef suggests that the lagoon may receive a disproportionate quantity of algal detritus as compared with that from stony corals. The effectiveness of *Goniolithon strictum* in the production of sand in the lagoon (pl. 3, figs. 5, 6) has already been noted. It may be that the proportion of coralline algae (32.6 per cent) found by Goldman (1926, p. 54) in the lagoonal sand at Cocoanut Point is much higher than that of reef sand on the seaward side of the reef. Considering the general topography of the sea floor, it is highly probable that most of the clastic detritus from the reef as a whole is swept seaward and does not enter the lagoon. Nevertheless, the coralline algae probably are quantitatively more important than the corals in production of sediments, as shown by the studies of Thorp (1936, p. 52) who found that calcareous algae form 18 per cent and corals 6 per cent, on the average, of 24 samples from various localities in the Bahamas.

The *Lithothamnion-Millepora* ridge generally is less than about 75 yards across and is not exposed at normal low tides, although it may reach within a few inches of the surface. On the seaward side it is gradually replaced by a belt dominated by *Acropora* *palmata*, the elkhorn coral. The zone of *Acropora palmata* ranges from depths of about ½ fathom to 2 fathoms, beyond which the species mingles with a rich fauna of reef-forming corals. At normal low tides about 6 inches of the extremities of the *palmata* fronds are exposed in this zone. Colonies of the species in deeper waters commonly do not reach the surface, although great tree-like forms 20 feet high are not uncommon. Characteristically, the growth form varies from massive and squat in shallow waters to slender and erect in deeper waters (pl. 6, figs. 1, 2, 3).

The higher branches are inclined away from the sea front in a way that exerts minimum resistence to surf. There is an alignment of closely spaced, anastamosing surge channels normal to the reef front. Colonies of *Acropora palmata* are crowded between the channels in a way that clearly reflects the channel pattern (pl. 4, figs. 4, 5, 6). *Lithothamnion* probably grows among the trunks of *Acropora palmata*, but it is conspicuous only where it encrusts dead and prone coral branches and in many places doubles the original diameter of the coral (pl. 3, figs. 1, 2). In such places the algal crust binds coral fragments to form a loose-textured rock mass. The surge channels are floored by rippled, loose sand derived from the lagoon and from disintegration within the reef. Loose, fine sediment does not accumulate here.

In the deeper part of the *palmata* zone the much more fragile *Acropora cervicornis* makes its appearance. At about 3 fathoms to 6 or 7 fathoms large hemispherical and massive corals of *Montastrea annularis*, *Diploria strigosa*, *D. labyrinthiformis*, *Siderastrea siderea*, and *Dendrogyra cylindrus* form the strong framework of the reef. The smaller and more fragile *Agaricia agaricites*, *Porites porites*, and *Acropora cervicornis* grow between them.

Vaughan (1916b) notes that the more massive corals in the Florida-Bahama region grow most vigorously at 18 meters but extend down to 31 meters. But in the Fresh Creek district most vigorous reef formation is at about half this depth, from 4 to about 7 fathoms. Reef development was not recorded at greater depths, and corals become sparse seaward from the reef front.

Immediately behind the barrier at several localities are irregular oval, or ring-like, patches of gorgonians and corals surrounded by nearly uninhabited sand floor. These patches range in diameter from about 30 to 100 meters (pl. 4, figs. 1, 2, 3), and growth is most vigorous at the periphery where food and oxygen are most available. They resemble the microatolls of Bikini (Ladd, Tracey, Wells, and Emery, 1950, p. 415). Characteristically, the microatolls immediately behind the barrier are fringed by a peripheral ring of blue sea fans and pens with scattered corals of *Acropora cervicornis*, *Manicina areolata*, *Porites porites*, *Porites furcata*, *Diploria labyrinthiformis*, and *Siderastrea radians*. The central area is occupied by sand and dead corals. The general form and relations suggest initiation of growth at a point followed by radial expansion. Explanation of the dead and unpopulated area the central area is not certain. Perhaps the relatively poor circulation of the lagoon waters does not provide sufficient oxygen and food behind the favored periphery.

A few hundred feet behind the barrier microatolls are relatively small and imperfect. They consist almost entirely of gorgonians. A few circular patches of *Thallasia* grass superficially resemble microatolls, but they are not ring-like in structure.

Restriction of reef growth to the Andros barrier poses questions that cannot now be answered. The rim of the outer platform at about 16 fathoms would at first consideration seem to be a particularly favorable place for reef development, but there are no reefs located there. Drew (1912) records a temperature of 22° C. at 100 fathoms off the coast opposite the east end of South Bight. This record was taken May 8, 1911, when the surface temperature was 26.90° C. According to Vaughan (1916a) continuous temperatures below 21° C. will kill reef corals. Probably minimum temperatures at the rim of Tongue of the Ocean are above this figure, but records are not adequate. The Andros reef, as are others in the Bahamas, is situated near the windward margin of a submerged platform where nutrients, plankton, and conditions of oxygenation are suitable. It was pointed out by

Vaughan (1916a) long ago that most of the reefs of the western Atlantic, the Gulf of Mexico, and the Caribbean have grown upon antecedent platforms and terraced surfaces, but none of these reefs rise from considerable depths. Apparently reef formation on Andros has occurred only at times when the sea was as high as or higher than it is at present. Low-water stages, such as those responsible for the terraces of the outer platform, were evidently accompanied by environment unsuitable for reef growth.

Outer Platform

On the seaward side of the barrier the bottom consists of rock, presumably like that of Andros, covered by a very sparse growth of green algae, gorgonians, and a few hemispherical corals (pl. 8, fig. 2). The surface slopes from 2 fathoms just outside the cays to approximately 16 fathoms at the rim of Tongue of the Ocean, and it is interrupted by several low terraces that are visible here and there on aerial photographs. By means of a hand line we attempted to determine depths of some of the terraces. Tentatively we concluded that breaks in the general slope occur at 2, 4, and 16 fathoms. At least seven bands are shown by the photographs, and these are interpreted as representing at least four separate terraces (fig. 4B).

Immediately outside the barrier, extending seaward for several hundred meters, there is a spectacular development of closely spaced, parallel, straight furrows in the rock floor of the outer platform. They tend to be arranged normal to the front of the barrier They are best developed and most easily examined offshore from the limestone cays and clearly are unrelated to growth of corals or algae.

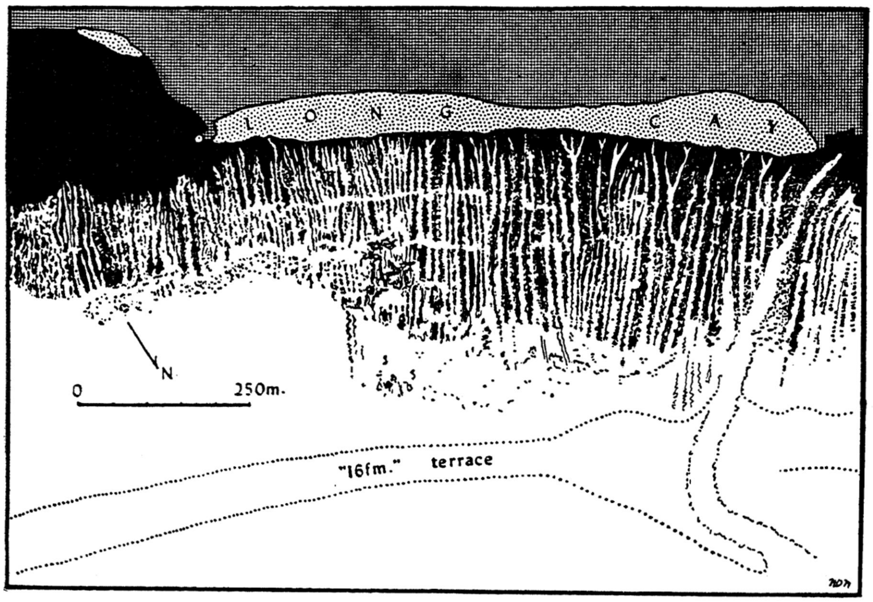

Fig. 3. Submarine grooves off Long Cay, about 1 mile northeast of Fresh Creek village.

A number of these grooves were examined in front of Long Cay, about 1 mile northeast of Fresh Creek village (fig. 3; pl. 8, fig. 2). Since they are incised in oolitic country rock they evidently are erosional features. The furrows or grooves are about 15 feet wide and 10 feet deep near shore (general surface at 2 fathoms) where they were examined by means of diving helmets. These grooves may be somewhat above the average dimensions. Some are separated by as much as 50 meters of undissected surface. In other places the grooves are so closely spaced that the divides are no broader than the width of the grooves. They have nearly vertical walls, which may be slightly undercut on one or the other side, but there is no indication of modification of profile by algal accretions. The heads of the grooves contain very little sand for 100 meters or so, but in deeper water each groove is floored by white sand producing a form remarkably like arroyos of subarid regions. The grooves do not correspond to indenta-

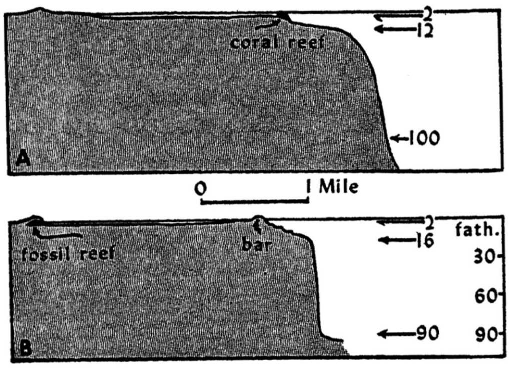

FIG. 4. Profiles across submerged platform, Andros Island. A. Profile through Mangrove Cay, northeastern Andros (after Vaughan, 1918). B. Profile through Fresh Creek village.

tions of the shore nor to surface topography of the barrier, but originate as spoon-shaped incisions near the shore line. There are many potholes in the floors of the grooves, and these are commonly filled with rounded boulders and pebbles of coral. The potholes certainly are now being excavated.

At the time of our studies the sea was quite calm. We were interested to note that there was no indication of bottom currents in these grooves. Unquestionably, mechanical abrasion of the rock floors is negligible in quiet waters. The only explanation that appears reasonable at present is that the grooves are erosional features produced during storms. The general orientation of the grooves is radial with respect to bathymetric levels; hence gravity must be a controlling factor. The most obvious explanation, to which we are at present inclined, is that the grooves are cut by currents that return spent water seaward in response to gravity. Inrushing translation waves interfere, no doubt, with the outflowing water. This in some manner has developed channels in which undertow currents can flow seaward with a minimum of turbulence. The Andros grooves resemble rather closely similar features described by Ladd, Tracey, Wells, and Emery (1950, p. 412), Fairbridge (1950, p. 338), and others with the exception that some of the Andros grooves occur over large areas in which corals and coralline algae are inconsequential. Where corals grow around the surge channels they certainly modify the form of the channels, but the evidence indicates that similar channels may be formed by erosional processes. It was thought by Kuenen (1933), Hanzawa (*fide* Ladd, Tracey, Wells, and Emery, *tom. cit.*, p. 413), and Ladd, Tracey, Wells, and Emery (*loc. cit.*) that similar grooves of organic reefs are mainly constructional and serve to dissipate the destructive energy of the sea.

Tongue of the Ocean

Fishermen of Andros are familiar with the fact that a precipitous under-water escarpment forms the southwest rim of Tongue of the Ocean. Vaughan (1912, p. 154; 1914b, p. 230; 1918, p. 279) was impressed by the abrupt steepening of bottom slope at the margin of the Andros outer platform. According to his observations the platform rim ranges between about 12 fathoms in northern Andros (fig. 4A) to 20 fathoms east of South Bight. Our own soundings indicate an approximate depth of 16 fathoms off Fresh Creek (fig. 4B). The rim of the platform which is shown on the accompanying map (fig. 5) is in most places readily visible on aerial photographs. Mr. John C. Armstrong (personal communication) has determined by soundings that the escarpment is here nearly vertical and reaches to about 90 fathoms. Schalk (1946, p. 1228) has reported a similar cliff on Eleuthera Island between 30 and 100 fathoms. Possibly this submerged escarpment is an old sea cliff, and probably it was exposed to the waves at low eustatic levels of the sea during the Pleistocene.

A short distance beyond the escarpment, the bottom (*fide* Armstrong) is covered by increasingly fine materials which form a fine white calcium carbonate ooze filled with pteropods and *Globigerina*. Vaughan (1918, p. 276) has described similar deep-water samples from Tongue of the Ocean.

Foraminifera from the depths of Tongue of the Ocean, studied by Norton (1930), included a number of shallow-water forms. This is not surprising in view of the evidence that strong currents are continually bearing sediments from the lagoon towards the ocean along surge channels and grooves.

The light color of the bottom sediments of Tongue of the Ocean indicates that little organic matter is trapped in the deposit. Possibly there is very little organic matter available as compared with the volume of the sediment. Or it may be that organic fractions of the sediment are almost completely consumed by bottom scavengers of Tongue of the Ocean. Presumably there is effective bottom circulation.

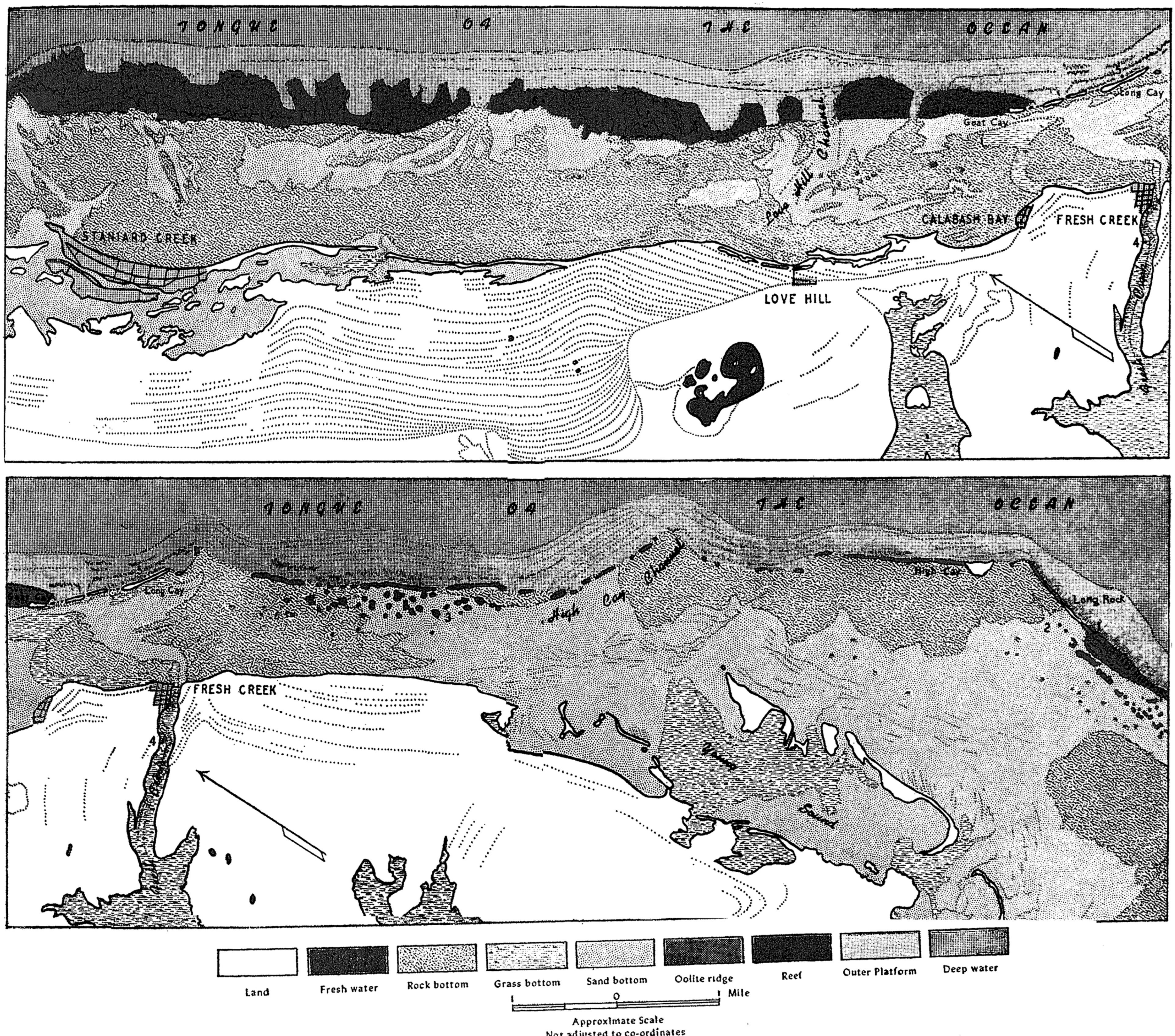

FIG. 5. Areal geology and shoal-water habitats in the Fresh Creek area, Andros Island. Top, northwest area; bottom, southeast area.

GEOLOGIC HISTORY

Available observational data are wholly inadequate for a summary of the history of the Andros region. Those clues that are fairly well established point to great fluctuations in sea level within comparatively recent time, presumably during the Pleistocene.

The exposed rocks of Andros were formed when the area was submerged and the sea was at least 2 fathoms higher than it is at present. Bank conditions of sedimentation extended continuously from the Florida and Santaren straits to Tongue of the Ocean. Chemical precipitation of calcium carbonate mud and oolites in supersaline waters at elevated temperatures were inimical to benthonic animals except over small areas (such as the fossil reef at Fresh Creek). These were so limited in distribution that shell detritus formed an insignificant part of the sediments.

Probably it was at this time that the Great Bahama Bank and the Andros lagoon assumed essentially the present form as the result of both wave erosion and deposition of sediments. Outlying cays formed of oolite sand were built in equilibrium with respect to the wind conditions then prevailing. A relative drop in sea level by a few fathoms led to the formation of beach ridges, exposed the Andros lagoon, and resulted in the formation of a shore at the outer margin of the cays. There was limited dune formation during this and later stages of emergence. Sink-hole formation commenced over exposed areas, and lithification of the oolitic sand resulted by deposition of calcium carbonate from percolating meteoric waters. Some of the water-ways across the island were left dry (pl. 2, fig. 1).

Successive pauses in relative emergence of the coast resulted in the formation of a succession of strand lines cut in relatively soft materials on the outer platform. The final low level found the waves beating against a high escarpment which possibly was already in existence before the Pleistocene.

A return to the present sea level may have been too rapid to permit reef formation until the final stages of inundation. Or it may be that the minimum temperatures of waters near the Tongue of the Ocean were too low to permit reef formation until recently. In any case, the modern reefs are confined to comparatively shallow waters.

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