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Cover photo: *Diploria strigosa*, the common brain coral, preserved in growth position at the Cockburn Town fossil coral reef site (Sangamon age) on San Salvador Island. Photo by Al Curran.

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CORAL REEF TO EOLIANITE TRANSITION IN THE PLEISTOCENE ROCKS OF GREAT INAGUA ISLAND, BAHAMAS

Brian White and H. Allen Curran
Department of Geology
Smith College
Northampton, Massachusetts 01063

ABSTRACT

Great Inagua Island, the southernmost of the chain of Bahamian islands, lies approximately 100 km northeast of the eastern tip of Cuba. This paper reports the results of reconnaissance geologic field work conducted on Great Inagua Island in January, 1985, and of more detailed observations made in January, 1986, near Matthew Town, between South West Point and Devil's Point.

Excellent exposures of a fossil coral reef occur along the coast in the vicinity of Devil's Point, and scattered exposures of *in situ* fossil corals, especially *Montastrea annularis* and *Diploria strigosa*, are present farther south along the coast to just north of Matthew Town. Beds containing the fossil corals interfinger with and are overlain by medium to coarse, shelly, oolitic calcarenites of shallow subtidal origin. The subtidal facies rocks contain well-developed trough cross beds, probably formed by tidal and longshore currents, and steeply dipping, planar tabular cross beds, likely formed during storms, perhaps as washovers.

In places, trace fossils are prominent in these shallow marine, carbonate sands, including the shafts and tunnels of *Ophiomorpha* sp. and short, vertical burrows assignable to *Skolithos linearis*. The beds that contain trace fossils probably formed seaward of the swash zone where the sandy bottom was stable enough to support lined burrow systems.

The vertical sequence continues upward with better sorted, somewhat finer-grained, skeletal, oolitic calcarenites that formed as overstepping beach sands. These rocks are laminated with long, low-angle cross beds dipping towards the west along much of the coast. However, south of Matthew Town some of the beach bedding dips east and appears to represent an ancient, narrow sand spit with both east and west facing beaches. Upward there is a transition to even finer-grained and better sorted eolianites with prominent rhizomorphs. In places, these are clearly part of parabolic-like, lobate dunes with east-west axes.

The presence of fossil corals and subtidal calcarenites in modern intertidal and supratidal exposures demonstrates a former high stand of sea level, most likely of Sangamon age. The shallowing-upward sequence from subtidal marine to dunal environments resulted from sea regression. Lateral facies changes along this part of the coast of Inagua indicate progressive growth of the island during the Late Pleistocene owing to emergence, spit extension, and migration of wind-blown dunes.

INTRODUCTION

Great Inagua is the southern-most island in the Bahamas Archipelago (Index Map 1) and lies approximately 100 km northeast of the eastern end of Cuba and about the same distance north of the northwest coast of Haiti. With an area of 1,544 sq. km, Inagua is the third largest Bahamian island, exceeded in area only by Abaco and Andros. It is approximately 75 km long in an east-west direction and from 20 to 35 km from north to south. Matthew Town, located in the southwest of the island, has an average annual rainfall of approximately 60 cm with a pronounced rainy season from September to December and a lesser one in May and June. Thunderstorms forming over the island are blown westward by the prevailing easterly trade winds, making the western end of the island wetter than the eastern parts. Inagua lies on the western Atlantic hurricane track, and has an approximately 10% chance of being struck by a hurricane in any given year. Mean monthly temperatures at Matthew Town range from a low of 24°C in February to a high of 28°C in July (weather data from anon., 1985).

The major industry on Inagua is the extraction of salt from sea water by solar evaporation in salt pans, thus taking advantage of the hot, dry climate. The island is also notable for the large Bahamas National Trust wildlife sanctuary where the sole remaining nesting area in the Bahamas of the American flamingo (*Phoenocopterus ruber*) is protected.

Although Inagua has undoubtedly been visited by many geologists, the only recently published work on the geology of the island is in the form of two abstracts by Mitchell (1985a,b). In these Mitchell briefly mentions the presence of Pleistocene fossil coral reefs and evidence for shoaling upward to major dune sequences. We first visited Great Inagua in January, 1985, during an oceanographic cruise through the southern Bahamas, when we studied the Pleistocene beach and dune facies exposed along the coast from Matthew Town south to the lighthouse. We again visited the island in January, 1986, as part of a scientific expedition to Great Inagua sponsored by the CCFL Bahamian Field Station. At that time we made detailed studies of the coastal exposures southwest, west, and northwest of Matthew Town (Fig. 1) and preliminary observations of a well-exposed fossil reef that crops out for several kilometers around Devil's Point. This fossil reef was first made known to us by Steve Mitchell (personal communication) and rediscovered by Jim Carew and John Mylroie on the 1986 expedition.

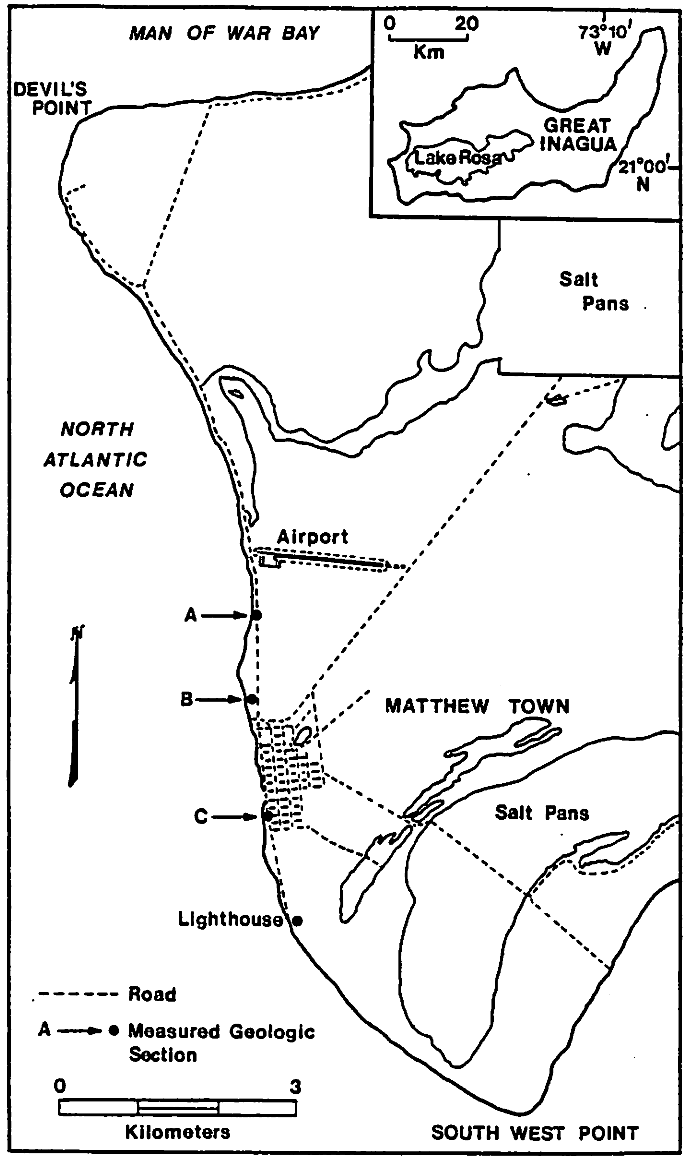


Fig. 1. Map of the southwestern coast of Great Inagua Island showing locations of measured sections and of field sites mentioned in the text.

FIELD CHARACTERISTICS OF THE LIMESTONE FACIES

Background

We have studied, at least at the reconnaissance level, all of the coastal rock exposures of the southwestern part of Great Inagua from the northern limit of exposure in Man of War Bay to the lighthouse south of Matthew Town. This paper is based largely on detailed analysis of three vertical sections, located as shown in Figure 1, and strata in their immediate vicinity. Some observations and illustrations from the Devil's Point fossil coral reef and coastal exposures between the measured sections also are included. The rocks, apart from thin hematitic paleosols, are entirely limestones. Depositional facies recorded in the limestones include *in situ* coral reef, coral rubble, subtidal shelly sand bottoms both mobile and immobile, beach, and dune. Although not all facies are always present at a given locality, those that are exposed always represent a vertical shallowing-upward sequence. To avoid repetition, we will describe each facies in general and later examine the vertical relationships and differences between the measured sections.

Coral Facies

Introduction. In modern coral reefs, colonial scleractinian corals commonly form massive rocky structures. Strong waves and currents may topple, overturn, or collapse these coral structures without actually moving them any significant distance from their place of growth. Coral debris commonly accumulates in the proximity of such reefs following breakage of the in place corals and transport of the fragments a short distance away from their source. These two forms of coral occurrence can be distinguished in the fossil record of Pleistocene coral reefs, and we use the term coralstone for the former and coral rubblestone for the latter type of occurrence (Curran and White, 1985).

Coralstone facies. For approximately 7 km along the north and west-facing shores around Devil's Point, a fossil coral reef is exposed. Species of the genera *Acropora, Diploria, Montastrea*, and *Porites* are extremely well-preserved, many of them in growth position (Fig. 2a). Farther south along the coast *in situ* fossil corals, mainly *Montastrea annularis* and *Diploria strigosa*, become progressively scarcer, and none occur south of Matthew Town. Corals fossilized in growth position are exposed commonly in the present-day intertidal zone and, in places, up to at least 2 m above present sea level.

Coral Rubblestone facies. Fossilized coral debris commonly occurs overlying, underlying, and immediately adjacent to the *in situ* fossil corals. All coral species found in the fossil reef are represented in the rubblestone, but especially common are small, rounded chunks of *Montastrea annularis*, and the long, slender "branches" of *Acropora cervicornis*, the latter commonly unabraded and showing excellent preservation of structural detail (Fig. 2b). Coral rubblestone commonly is overlain by subtidal calcarenites (Fig. 2c).

Subtidal Sand Facies

Introduction. The subtidal sand facies is composed of medium to coarse, oolitic calcarenites containing a varied and well preserved shelly fauna (Fig. 3a). Some of these sands, herein called the burrowed, subtidal sand facies, were sufficiently stable to allow the formation and preservation of numerous trace fossils, whereas others were more mobile and contain many cross beds and no trace fossils. These latter beds are named the cross bedded, subtidal sand facies.

Burrowed, subtidal sand facies. This facies is characterized by the presence of trace fossils belonging to the ichnogenera *Ophiomorpha* (Fig. 3b) and *Skolithos* (Fig. 3c). In Section A, a particularly good exposure formed by recent excavation (see for example Fig. 8a), trace fossils are especially well displayed. *Skolithos linearis* specimens occur as rather short burrows, up to 4.2 cm long and averaging 2 mm in diameter. The shafts and tunnels of *Ophiomorpha* sp. are abundant and form an irregular boxwork pattern. In most instances the burrow walls have been eroded away, and it is the more lithified burrow sediment fill that has been eroded in relief on the excavation face. However, some large shafts and tunnels, up to 3 cm in diameter, with thick, micritic walls displaying a knobby exterior surface are preserved, confirming an *Ophiomorpha* sp. identification for the burrows. The trace fossils were probably formed in water deeper than 1 m and seaward of the swash zone, in a sand bottom that was stable and immobile enough to support lined burrow systems. For comparable trace fossil occurrences on San Salvador Island, Bahamas, the tracemaker organisms were identified as callianassid shrimp for *Ophiomorpha* sp. and polychaetes for *Skolithos linearis* (Curran, 1984).

Cross bedded, subtidal sand facies. Other shelly, oolitic, subtidal sands were more mobile, and these produced calcarenites that contain trough cross beds deposited by currents flowing parallel to the ancient shoreline (Figs. 4a,b), and planar tabular cross beds formed by single event flows acting perpendicular to the shoreline, probably during storms (Fig. 4c). Angular clasts of beachrock, up to 80 cm in length, occur within some of the calcarenites of this facies, showing the close proximity of deposition to a beach. Some of these clasts contain keystone vugs (Fig. 5a), which demonstrates their formation in a beach environment (Dunham, 1970).

Beach facies. The subtidal calcarenites are overlain by somewhat finer, less shelly, oolites, which contain features characteristic of the beach environment. These include long, low-angle cross beds, some with parting lineations on the lamination surfaces, that represent the swash zone. These cross beds dip westward, except for some south of Matthew Town that dip eastward. This indicates that the seaward direction for the ancient shoreline represented by these deposits was to the west for much of the study area. However, in the south there appears to have been a narrow spit that had both east- and west-facing beaches and that extended southward into the ocean. Conglomerates of well-rounded coral debris and beachrock clasts are found in some places in the lower beach facies (Fig. 5b). Rare examples of a small, slump-like structure (Fig. 5c) occur in these rocks. These may be due to minor slumping on beach erosion scarps. Such features have been noted by the authors in modern beach erosion scarps at Sandy Point, San Salvador.

An unusual, but widespread, layer, 10 to 20 cm thick, separates the upper beach sediments from the overlying dunal deposits (Fig. 6a). This calcarenite bed has a porous, sponge-like texture, consisting of crowded, rather irregular, rhizomorph-like features (Fig. 6b). It is believed to represent the buried accumulation of marine grasses, mainly *Thalassia testudinum* (turtle grass) and *Syringodium filiforme* (manatee grass), and of the floating brown alga *Sargassum* that commonly collects at the landward periphery of the beach. Such plant debris commonly is mixed with sand and covered over by incipient dune sands on modern beaches (Fig. 6c).

Eolianite facies. Overlying the fossilized sea grass accumulation bed, there are fine-grained oolites with wedge planar and tabular planar cross beds, climbing wind ripple laminations, and lee-side sand lens and grain-fall layers. Such structures characterize Holocene dune deposits on San Salvador Island (White and Curran, 1985, 1987), and this facies was deposited as parabolic-like, lobate dunes with generally east-west long axes (Fig. 7a).

Effects of Emergence into the Terrestrial Environment

All the facies described above have been exposed to soil development and plant colonization in the terrestrial environment as a result of emergence above sea level. This exposure has produced a variety of features that are clearly visible in the field. These include: draped, laminar caliche (Fig. 7b); vadose pisolites (Fig. 7b); soil breccias (Fig. 7b); rhizomorphs (Fig. 7c); caliche dikes (Figs. 8a,b); and hematitic paleosols.

COMPARISON OF MEASURED SECTIONS

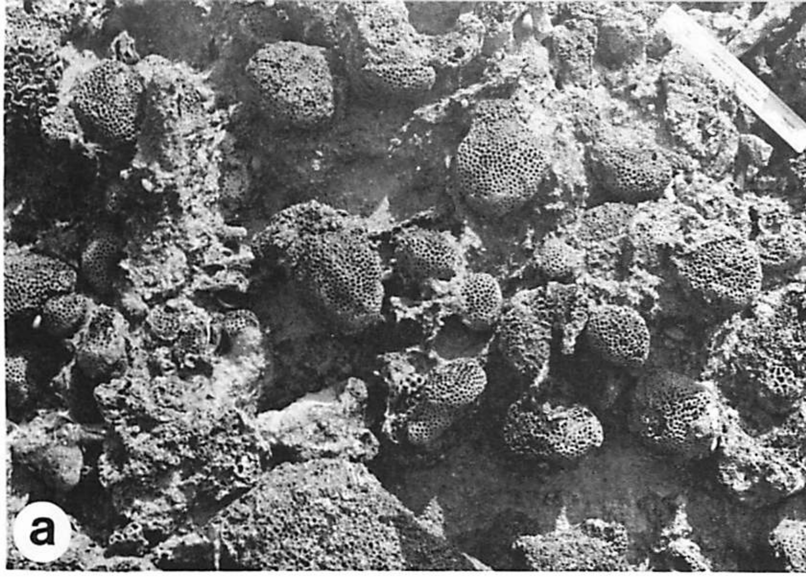
Three well-exposed vertical sections were chosen to represent the northern (Section A), central (Section B), and southern (Section C) parts of the study area, and these were measured and examined in detail (Figs. 8c, 9, 10, 11). Each section represents sedimentation during the progressive shallowing of sea water and eventual emergence into a non-marine environment. A more complete sequence is exposed at and above present sea level in the northern part of the study area, but farther south the coral facies and subtidal sand facies disappear, and the strata consist of beach and overlying dune deposits. Figure 12 demonstrates the geometric relationships between the three measured sections, using the present-day low tide level as an approximate datum.

X-RAY DIFFRACTION ANALYSIS

Samples of *Diploria strigosa* and *Montastrea annularis* from the fossil reef at Devil's Point and from *in situ* fossil corals in the vicinity of Section A were analyzed by X-ray powder diffraction. Small core samples were taken of each fossil coral in the laboratory, and these were manually ground in a mortar and pestle to prevent the conversion of calcite to aragonite that may ccur with mechanical grinding (Burns and Bredig, 1956 in Carver, 1971). The powder was passed through a 320 mesh sieve before being loaded in a powder mount. The samples were analyzed on a Phillips Norelco X-ray powder diffractometer and all were found to contain more than 95% aragonite. Those coral samples that are essentially pure aragonite are now being dated by the uranium-thorium series method.

INTERPRETATION AND GEOLOGIC HISTORY

The most prominent aspect of the stratigraphic sequence exposed along the southwest coast of Great Inagua is the presence, above present sea level, of rocks representing a transition from subtidal



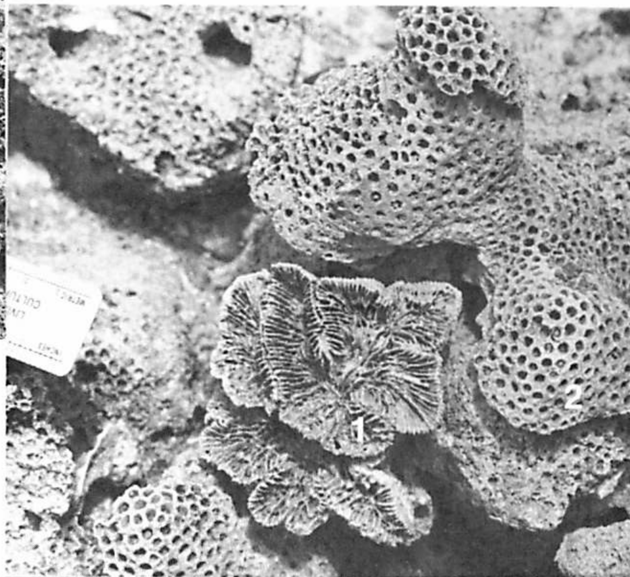


Fig. 2a. Left. View of the side of a large head of *Montastrea annularis* in growth position; Devil's Point fossil coral reef. Scale = 15 cm. Right. Rose coral, *Manicina aveolata* (1), in growth position on a *Montastrea annularis* head (2); Devil's Point fossil coral reef.

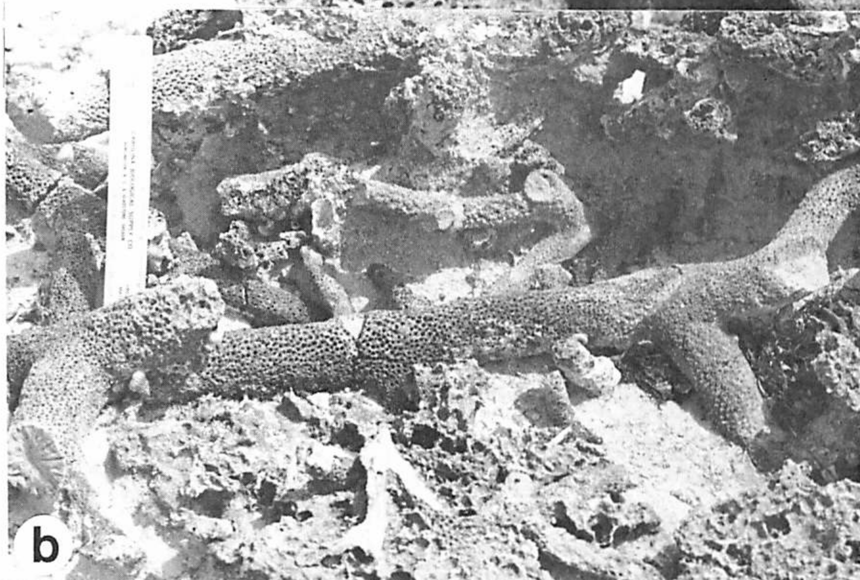


Fig. 2b. Coral rubblestone composed principally of pieces of *Acropora cervicornis*; Devil's Point fossil coral reef. Scale = 15 cm.

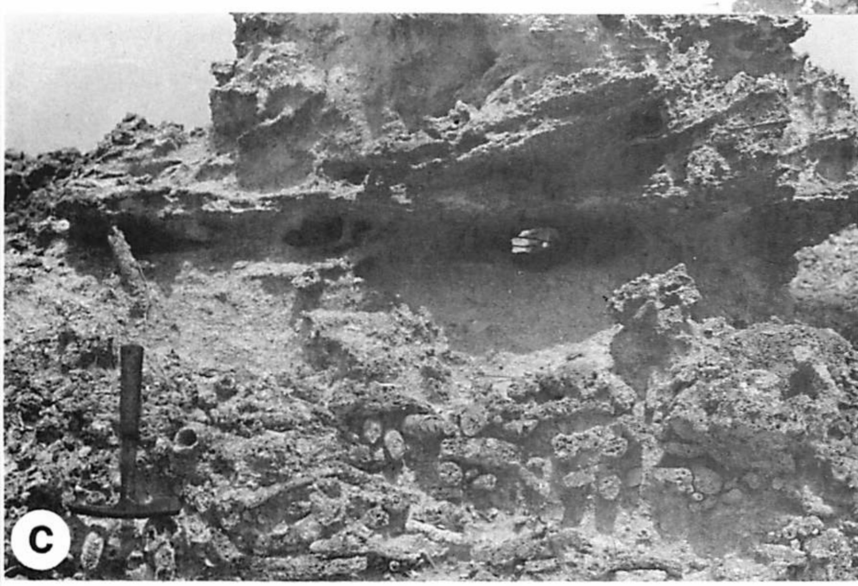


Fig. 2c. Coral rubblestone overlain by subtidal calcarenites, which contain planar tabular cross beds; Devil's Point fossil coral reef.

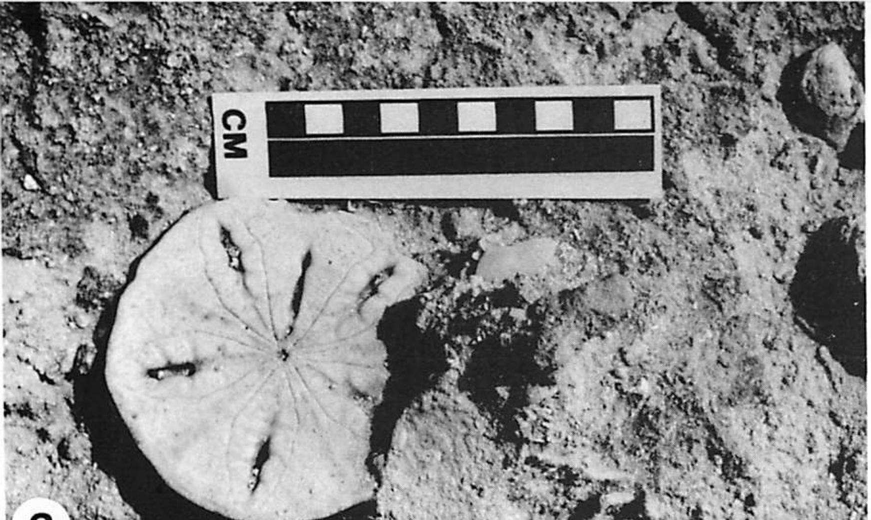


Fig. 3a. Fossil sand dollar, *Leodia sexiesperforata*, in shelly subtidal calcarenites.

Fig. 3b. Specimens of *Ophiomorpha sp.* in the burrowed, subtidal sand facies, Section A.

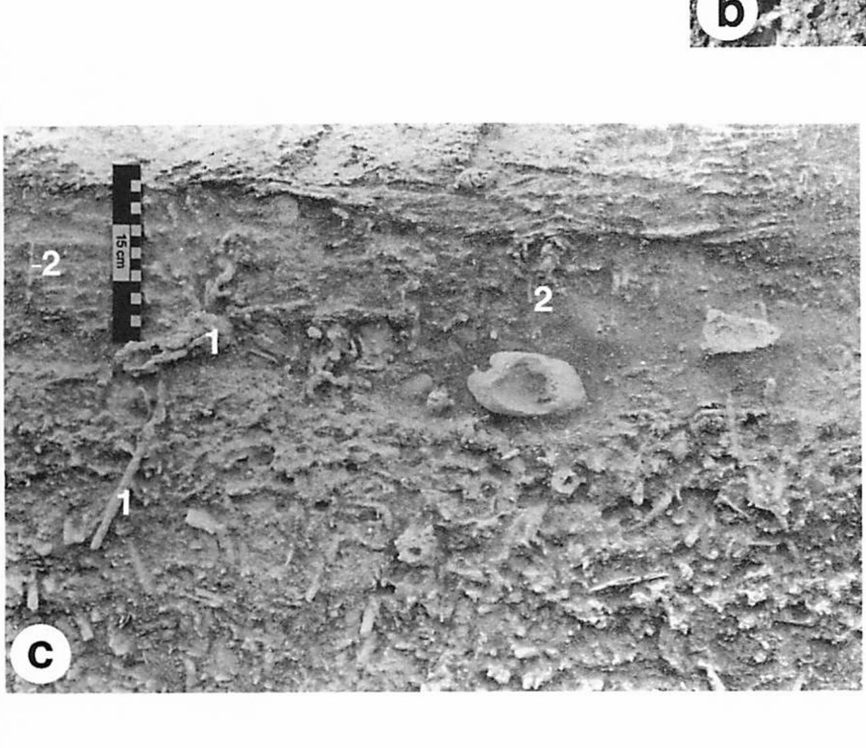
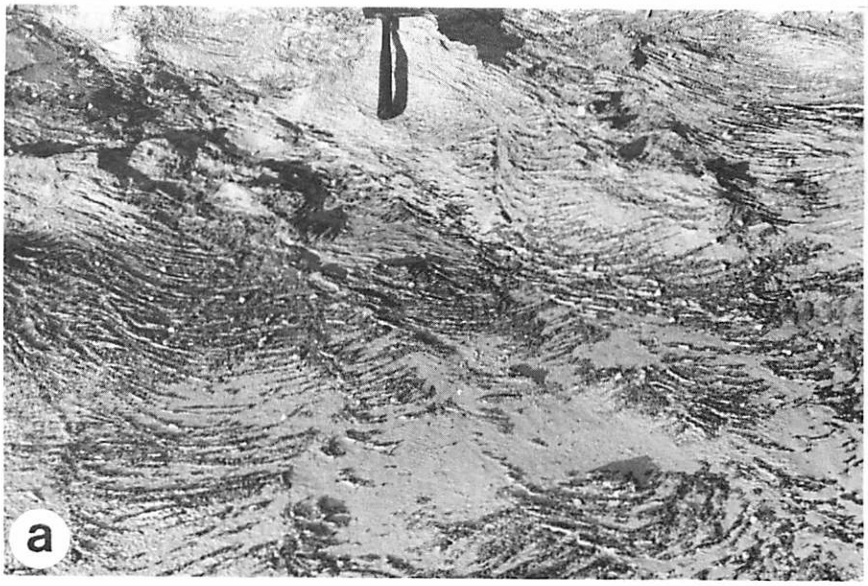


Fig. 3c. The trace fossils *Ophiomorpha sp.* (both burrow walls and lithified burrow fillings) (1) and *Skolithos linearis* (2) and small beachrock clasts in the burrowed, subtidal sand facies, Section A.

Fig. 4a. Bedding surface view of trough cross beds in the cross bedded, subtidal sand facies, near Section B.



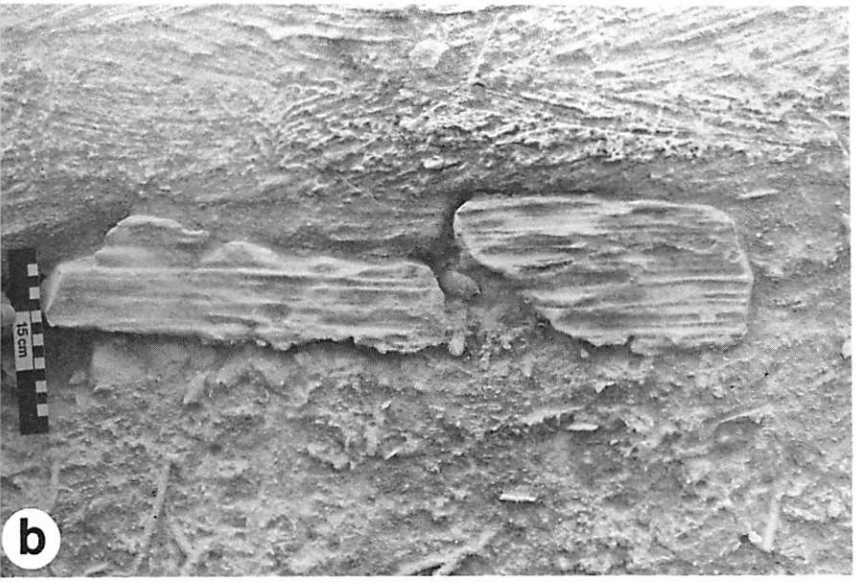


Fig. 4b. Lithified *Ophiomorpha sp.* burrow fillings and beachrock clasts of the burrowed, subtidal sand facies overlain by trough cross beds of the cross bedded, subtidal sand facies, Section A.

Fig. 4c. Planar, tabular cross beds of the cross bedded, subtidal sand facies, Section B.

Fig. 5a. Clast of beach calcarenite with keystone vugs in the cross bedded, subtidal sand facies, Section A.

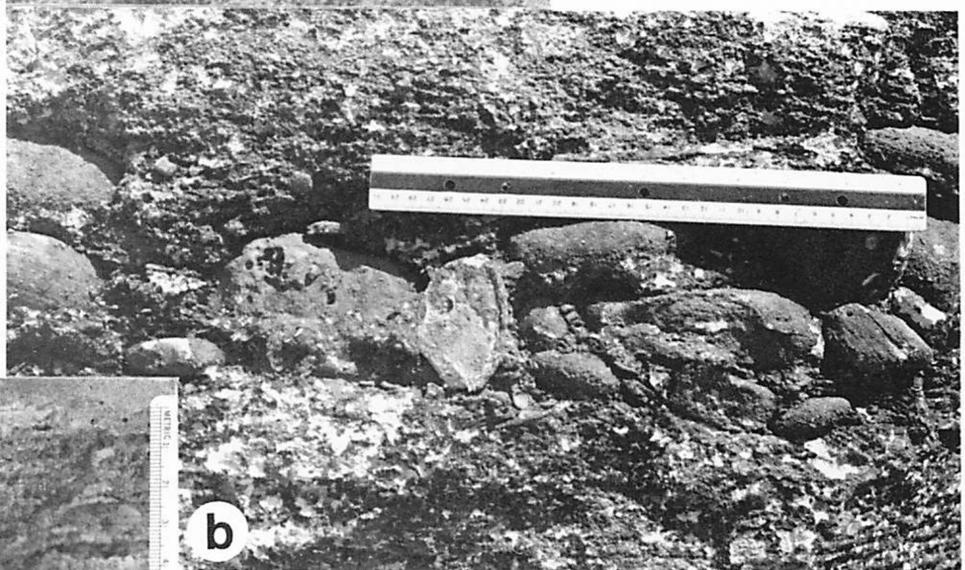


Fig. 5b. Conglomerate of beach calcarenite and coral clasts in the lower beach facies, near Section B. Scale = 30 cm.

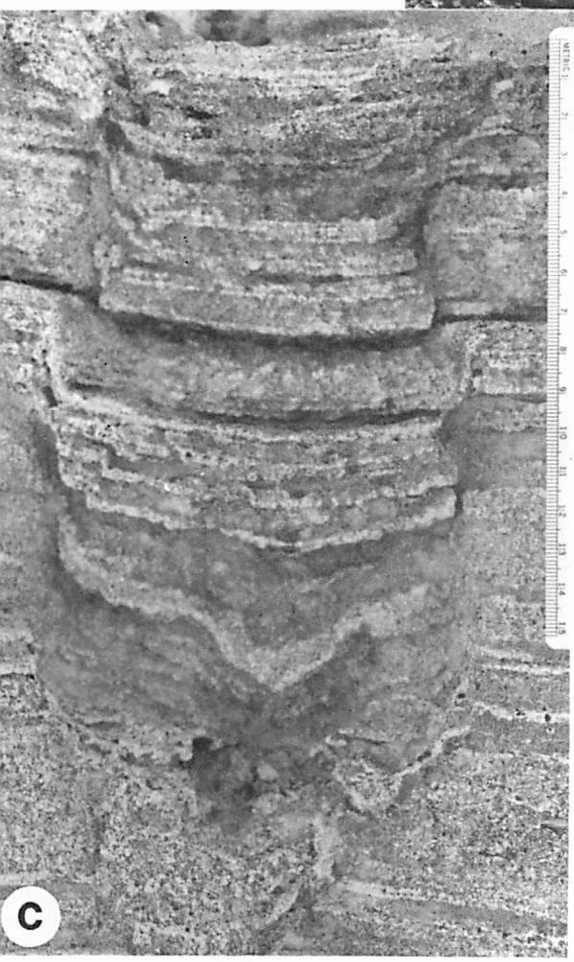


Fig. 5c. Slump structure believed to have formed on a beach erosion scarp; beach facies, near Section B.

Fig. 6c. Erosion scarp in beach, Grahams Harbour, San Salvador Island revealing a layer of accumulated marine plant debris (arrow) at the contact between upper beach and dune sands. Scarp is about 60 cm high.

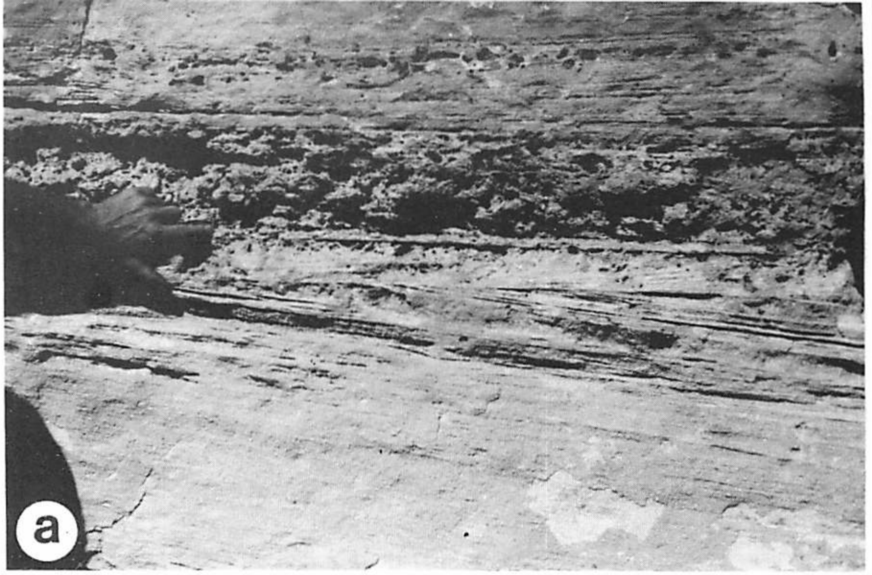


Fig. 6b. Close-up of plant accumulation layer of Figure 6a showing porous texture and rhizomorph-like structures, Section C.

Fig. 6a. Bed (indicated by pointing finger) thought to represent a fossilized marine plant accumulation near the contact between upper beach and dune calcarenites, Section C.

Fig. 7a. View along the east-west axis of a parabolic-like, lobate dune, near Section B.

Fig. 7b. Left. Laminar caliche (1) and vadose pisolites (2) in the beach facies, near Section C. Right. Paleosol breccias (3) and vadose pisolites (2) in the beach facies, near Section C.

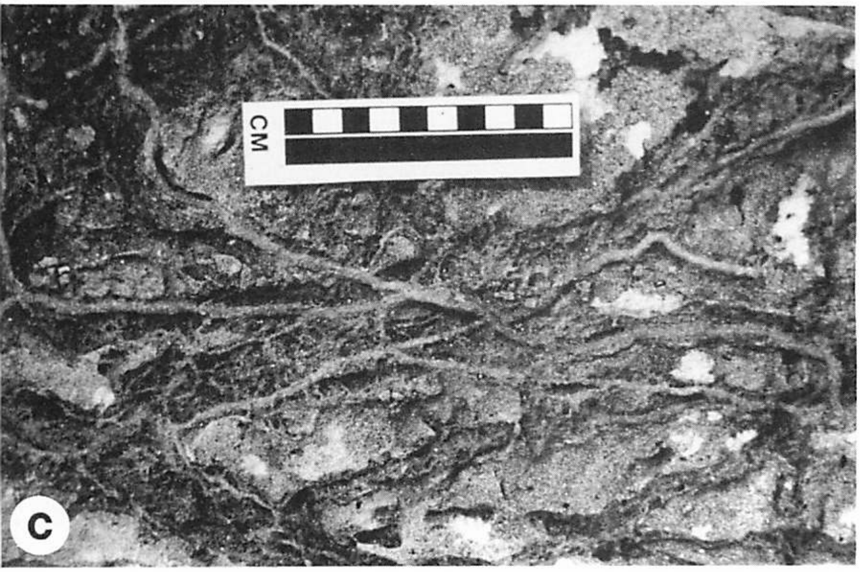
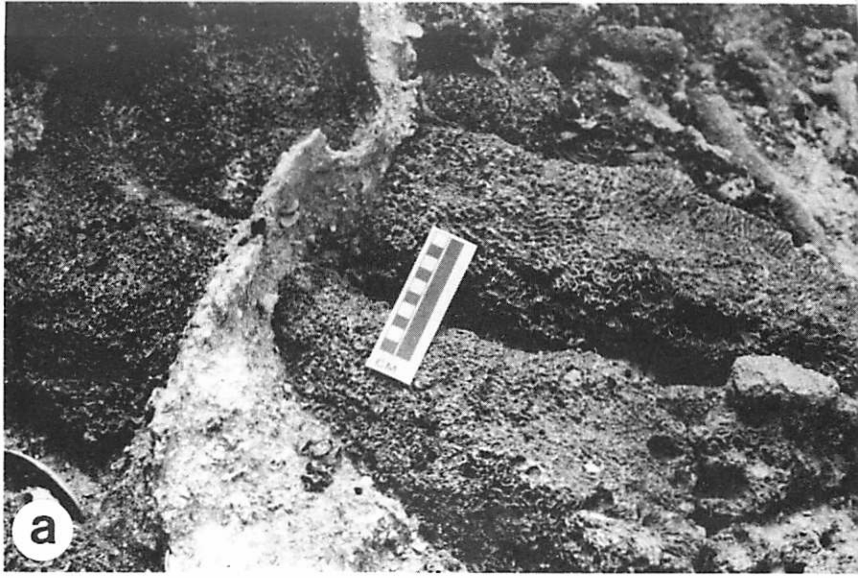


Fig. 7c. Rhizomorphs on bedding surface in the beach facies, near Section C.

Fig. 8a. Narrow caliche dike cutting coral bblestone; Devil's Point fossil coral reef.



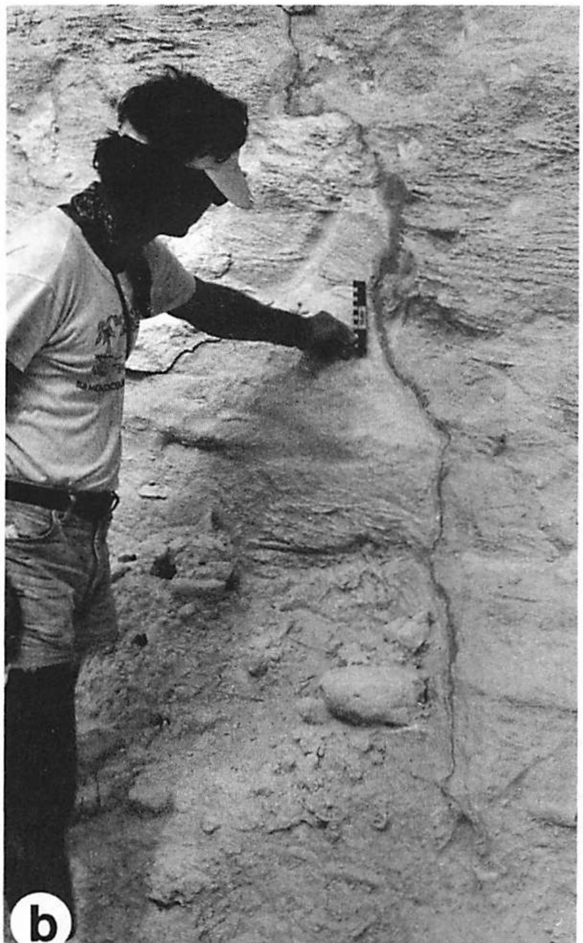


Fig. 8b. Caliche dike cutting subtidal calcarenites, Section A.

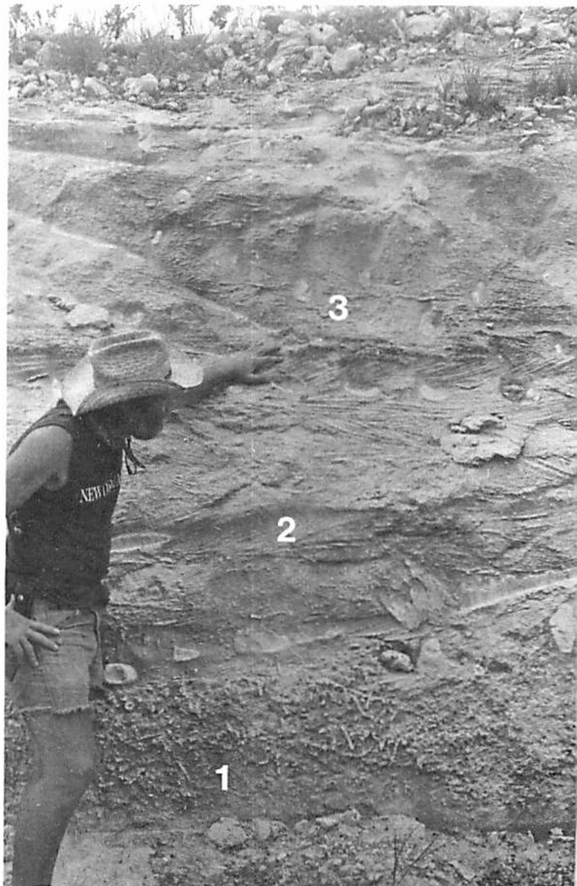


Fig. 8c. Facies of Section A exposed in a recent excavation. 1 = burrowed, subtidal sand facies; 2 = cross bedded, subtidal sand facies; 3 = beach facies.

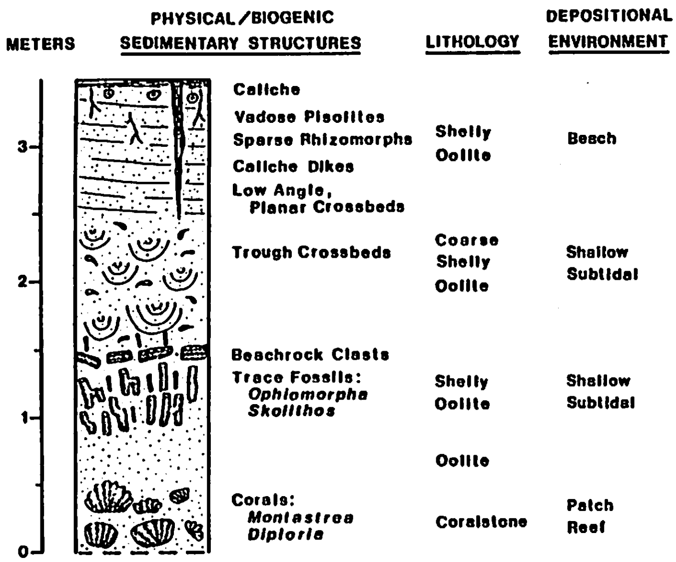


Fig. 9. Section A stratigraphy.

marine environments to terrestrial, dunal conditions. A wide variety of corals, including *Acropora palmata* and *A. cervicornis, Montastrea annularis, Porites porites*, and several species of *Diploria*, formed a fossil coral reef that is continuously exposed around Devil's Point. Farther south, the corals become restricted to *in situ* heads of *Montastrea annularis* and *Diploria strigosa*, and these have a non-continuous, patchy distribution. A tentative explanation for this is that the Devil's Point reef represents a bank/barrier reef in its northern area, similar to the Cockburn Town fossil coral reef exposed on San Salvador Island, Bahamas (Curran and White, 1985), and that the corals farther south represent small patch reefs, that, perhaps, grew in a lagoon on the landward side of the bank/barrier reef. The coral rubblestones consist of the debris of coral species found in the associated fossil reefs and clearly were derived from them, as is commonly the case with modern reefs.

Shelly, subtidal sands accumulated adjacent to, and eventually, over the corals and coral rubble. At times, sand formed a stable substrate where callianassid shrimps, polychaetes, and possibly other animals burrowed extensively, leaving a record now seen as the trace fossils Ophiomorpha *sp.* and *Skolithos linearis*. In order for these burrows to have formed and been preserved, these sands must have been away from the surf zone and protected from significant wave and current activity. Other subtidal sands clearly were more mobile as they contain planar tabular cross beds and abundant trough cross beds. Preliminary, and somewhat limited, data show that the planar tabular cross beds dip offshore, while the trough cross beds indicate transportation along the coast. This situation is remarkably similar to the Cockburn Town fossil coral reef on San Salvador, where the planar tabular cross beds were interpreted as storm deposits and the trough cross beds as due to longshore currents (Curran and White, 1985). Angular blocks of beachrock, up to 80 cm across, found in some of the subtidal sand beds show the proximity of these sands to a beach.

Shoaling allowed the westward advance of beach sands over the subtidal sands in much of the area. However, in the south a narrow sandspit appears to have extended in a southerly direction. In addition to the beach bedding, two unusual features are preserved in the beach sediments. The slump structures interpreted as having formed on an erosion scarp could be expected to be rare, as their preservation potential ought to be very low, and, indeed, only two examples were found. On the other hand, the accumulation of plant debris along the landward edge of the backshore at or near the base of incipient dunes, is a common feature of many Bahamian sand beaches and could be expected to leave a record in rocks of the appropriate facies. On Inagua, a porous, laterally extensive bed that we think

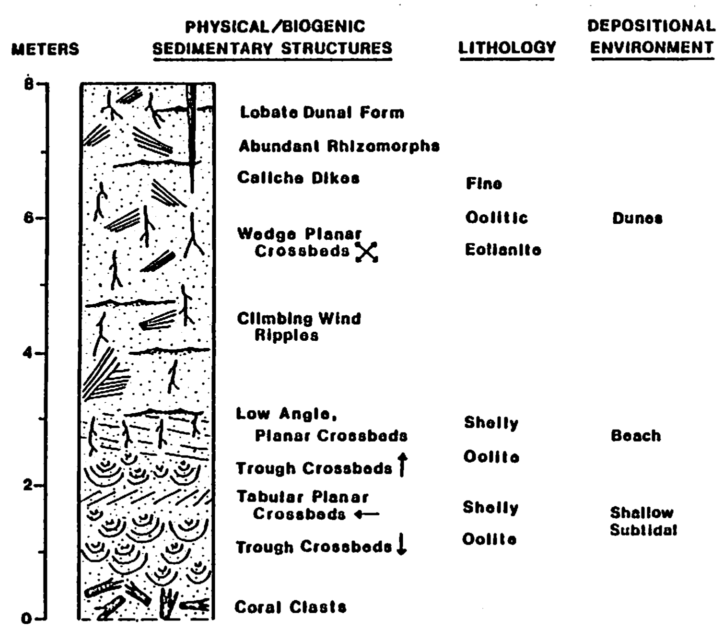


Fig. 10. Section B stratigraphy.

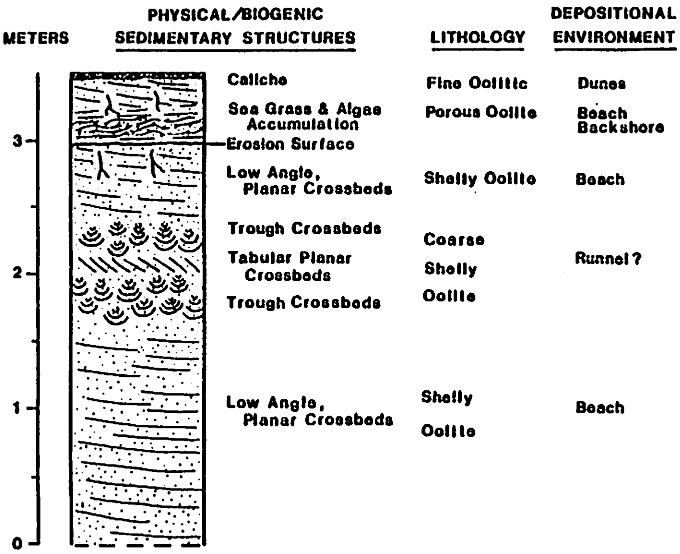


Fig. 11. Section C stratigraphy.

represents a sand-covered accumulation of sea grasses and algae commonly occurs at the contact between beach sediments and eolianites. Abundant plant debris commonly is washed ashore and accumulates on the backshore of modern beaches, and we interpret this bed as the fossil analog of such deposits.

Emergence above high tide level permitted the accumulation of carbonate sand dunes, presumably composed of sands derived from the beaches by wind action. The dunes were small and lobate in form, with the long axes of the dunes lying approximately east-to-west and roughly parallel to the direction of the prevailing easterly trade winds. Similar parabolic-like, lobate, eolianite dunes have been described from San Salvador Island by White and Curran (1985, 1987), and from Bermuda by Mackenzie (1964a, b).

As a result of sea level fall, all facies from *in situ* corals through the shallowing-upward sequence became part of an island where they were exposed to terrestrial processes. This island was, at least in part, vegetated, as shown by the numerous root traces preserved by the precipitation around individual roots of enclosing, dense micrite. The term rhizomorph was used by Northrop (1890) for root traces preserved in this fashion in Bahamian carbonate rocks. On Inagua, rhizomorphs are particularly abundant in the eolianites, but they occur in all facies, including the coralstone facies, thus providing dramatic evidence of the change from marine to non-marine conditions. The evidence of a vegetated land surface implies the availability of soil, and the presence of laminar caliche, caliche dikes, vadose pisolites, and soil breccias shows that processes involved with soil formation were active. Many of the paleosols are reddened by hematite, for which there is no obvious local source. This hematite may have been derived from elsewhere, possibly Africa, by long distance eolian transportation. Thin, laminated caliche occurs draped over many of the beds and forms a hard, resistant layer. Laminated caliche also fills vertical to sub-vertical fractures and fissures which cut across all facies of the sequence. These are identical to, although narrower than, features found in the Cockburn Town fossil coral reef on San Salvador Island where they were named caliche dikes (Curran and White, 1985).

We have not yet obtained absolute ages from any of the Inagua sequence rocks. The well-developed paleosols, and the fossil corals found *in situ* well above present sea level certainly indicate a pre-Holocene age. The fossil corals occur at least 2 m above present sea level and correspond to Sangamon-age corals found at similar elevations on San Salvador, Bahamas (Curran and White, 1985). This suggests a probable Sangamon age of approximately 125,000 years for the Inagua rocks.

It is not yet possible to reconstruct a firm paleogeography of the study area. Consideration of Figure 12 shows that to the south beach deposits and eolianites are at the same elevation as corals and subtidal sediments farther north. However, it is not known whether or not these facies were contemporaneous. If they were, then the

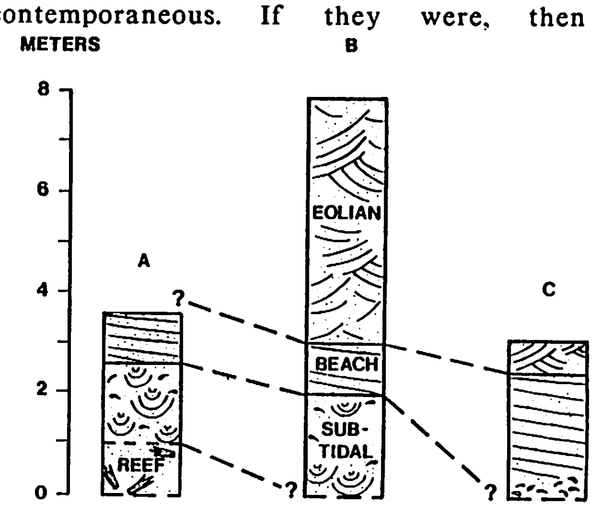


Fig. 12. Comparison and correlation of sections A, B, and C.

geography would have been that of an island in the south mantled by wind-blown sand, bordered to the north by a lagoon with patch reefs, and farther offshore, a bank/-barrier coral reef. Another possibility is that when the reef was flourishing in the north, the area to the south was covered by deeper water, and any subtidal sediments formed there reside at a subsurface level. The beachrock clasts found in the subtidal sands in the northern area show proximity to a beach, and lend support to the contemporaneous presence of an island in that area and to the first paleogeographic scenario suggested above.

Although the fossil corals have been exposed to the freshwater zone, they have retained their original aragonite composition. A similar situation exists in the rocks of the Cockburn Town fossil coral reef (White and others, 1984), and in the Hogsty Reef of the Bahamas (Pierson and Shinn, 1985). This preservation may be due to the aridity of the climate.

CONCLUSIONS

1. The sequence of rocks found in southwest Great Inagua represents a change from subtidal to terrestrial environments due to lowering sea level, probably as a consequence of the onset of Wisconsinan glaciation.
2. The excellent preservation of the fossil corals was facilitated by their burial beneath subtidal, beach, and eolian sands. These fossil corals are now exposed above present sea level, and they probably are of Sangamon age.
3. Preliminary paleogeographic reconstruction suggests a south-to-north change from an island with dunes, to a lagoon with coral patch reefs, to a bank/barrier coral reef.
4. On emergence, all facies became part of an island, which was colonized by plants and where soils developed.
5. Preservation of the original coral aragonite, despite emergence into the freshwater zone, may be due to the aridity of the climate.

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