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Front Cover: Lee-side exposure of a fossil parabolic dune viewed from the Grahams Harbour side (west) of North Point, San Salvador, Bahamas. These Holocene carbonate eolianites have been assigned to the North Point Member of the Rice Bay Formation (Carew and Mylroie, 1995). The eolian cross-stratification dips below present sea level, proving that late Holocene sea-level rise is real. Top of the dune is about 7 meters above the sea surface. Photo by Al Curran.

Back Cover: Dr. Noel P. James of Queen's University, Kingston, Ontario, Canada, keynote speaker for this symposium. Noel is holding a carving of a tropical fish created by a local artist and presented to him at the end of the symposium. Photo by Al Curran.

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A CORE-BASED DEPOSITIONAL INTERPRETATION OF COCKBURN TOWN, SAN SALVADOR ISLAND, BAHAMAS

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ABSTRACT

Little is known about the subsurface geology of San Salvador Island. Four cores (as deep as 15 m) taken from the area of Cockburn Town offer a unique opportunity to study depositional environments and sea level events occurring on the western shore of the island in the late Pleistocene. In these cores there is a major paleosol separating Sangamon (isotope stage 5e) deposits of the Cockburn Town Member of the Grotto Beach Formation from pre-Sangamon deposits. Corals below the paleosol are significantly more altered than those above. The paleosol is interpreted to be the paleosol identified at the top of the Owl's Hole Formation, thus separating the Cockburn Town Member above the paleosol from pre-Sangamon (Owl's Hole Formation) sediments below. Stratigraphy is based on the Carew and Mylroie (1995) model.

In each core there are shallowing-upward depositional sequences which repeat above and below the paleosol, a trend expected in Bahamian deposition. Shallowing upward sequences are either capped by a paleosol within the cores (for the pre-Sangamon deposits) or by an exposure surface in the case of the Cockburn Town Member (Sangamon deposits) above the paleosol. Depositional environments within each core also generally repeat above and below the buried paleosol. This paleosol is encountered at a lower depth (9 m) in the core at the Cockburn Town shoreline and at shallower levels (1 m) in the inland cores. This creates allostratigraphic packages in cross-section, which suggest lateral accretion of sediment to the island margin. At the base of the most inland core a second major paleosol was encountered at 13 m below mean high water. Only 20 cm was penetrated by the drill.

In cross section, reef-dominated environments repeat in the two cores at Cockburn Town fossil reef, lagoon and dune-dominated environments repeat in the Cockburn Town dump core (1 km inland to the east) and lagoon and beach environments alternate in the core farthest inland (1.5 km) at Observation Tower Road. The major difference between the Sangamon and pre-Sangamon depositional environments is one of magnitude - magnitude of scale, energy and available accommodation space.

Pre-Sangamon deposition occurred in a broader, less well protected lagoon, with higher energy reaching the beach (at least 1.5 km inland) to create the very coarse, strongly laminated beach deposits that dominate 6 m of the most inland core. Thick lagoon sediments appear 1 km inland and 0.75 km from the beach of the most inland core. Pre-Sangamon reefs are discontinuous and less robust. They are probably patch reefs providing less protection to the back reef lagoon and distant shore. This broader,

less sheltered Pre-Sangamon lagoon provided a larger area for carbonate production, higher energy, and a larger volume of accommodation space. Sangamon deposition, in contrast, occurred behind a substantial barrier reef which reduced energy in the lagoon but encouraged carbonate production. However, with a beach only half a km distant, available accommodation space was reduced.

INTRODUCTION

Much is known about the surface geology of San Salvador Island (Figure1), but there has been little opportunity to look at rocks of the subsurface beyond what could be reached in road cuts, caves, and banana holes. One 180 meter deep core was extracted in 1967 from the northern shore of the island. The study of that core emphasized diagenesis and dolomitization of the limestone (Supko, 1970). Lost recovery in the first 10 m of drilling obscured facies changes in the near-surface. The 4 cores of our study offer an excellent opportunity to view events and sediments recorded in the shallow subsurface.

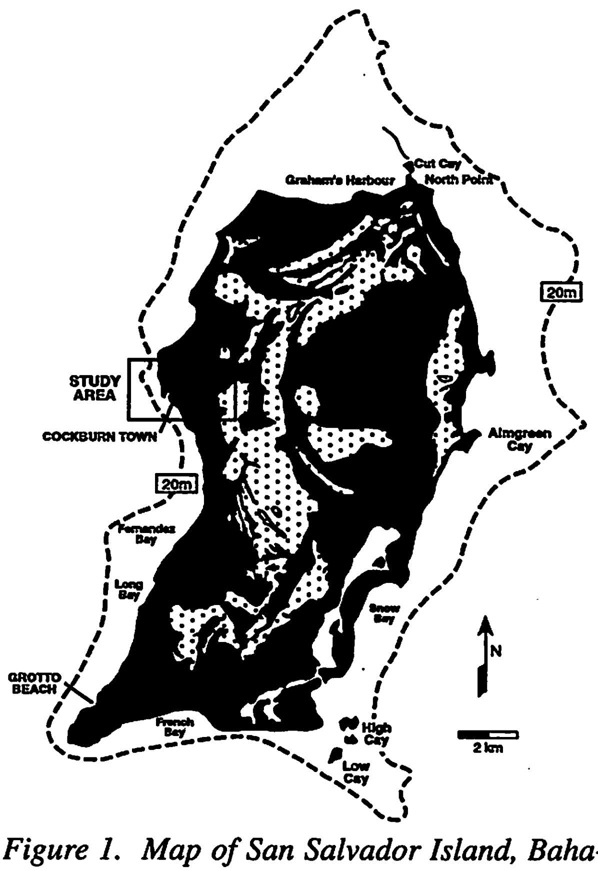

Figure 1. Map of San Salvador Island, Bahamas, showing the study area.

The 4 cores of this study were extracted in 1996 and 1997 using a SCARID wireline drill which produced a 5 cm diameter core. The cores were split and studied under a binocular microscope to record depositional features, sedimentary structures and sediment composition. Thin sections were made, with good coverage for two cores (96-C and 97-1) but only sporadic coverage on the other cores (97-2 and 97-3). Thin section analysis specifically looked at grain composition, sedimentary textures and fabrics. A level loop survey was conducted to determine relative elevations of the cores and to tie them to mean high water. A hand held GPS unit provided relative distances and orientations for mapping the cores.

Two cores (96-C and 97-3) are located 13.5 m apart on the quarry floor at Cockburn Town fossil reef (Figure 2). Core 97-2 is one km east of Cockburn Town reef, in the floor of a quarry cut into dunes. The quarry now serves as a town dump. Core 97-1 is 1.44 km northeast of 96-C and 97-3, just south of the airport runway. It was extracted from a low-lying area near the north-western edge of Little Lake.

RELEVANT GEOLOGY OF THE STUDY AREA

Located on the eastern edge of the Bahamas carbonate platform, San Salvador Island rises in arcuate dune ridges to form an island approximately 21 km long by 12 km wide. Carew and Mylroie (1985, 1987,1995) and Hearty and Kindler (1993) developed stratigraphic models for the surface geology of San Salvador, and Curran and White (1985, 1995) and White et al. (1997) provided detailed interpretations of the Cockburn Town fossil reef complex. Surface rocks of San Salvador consist of late Pleistocene and Holocene carbonate rocks originating from reef, lagoon, shoreface and

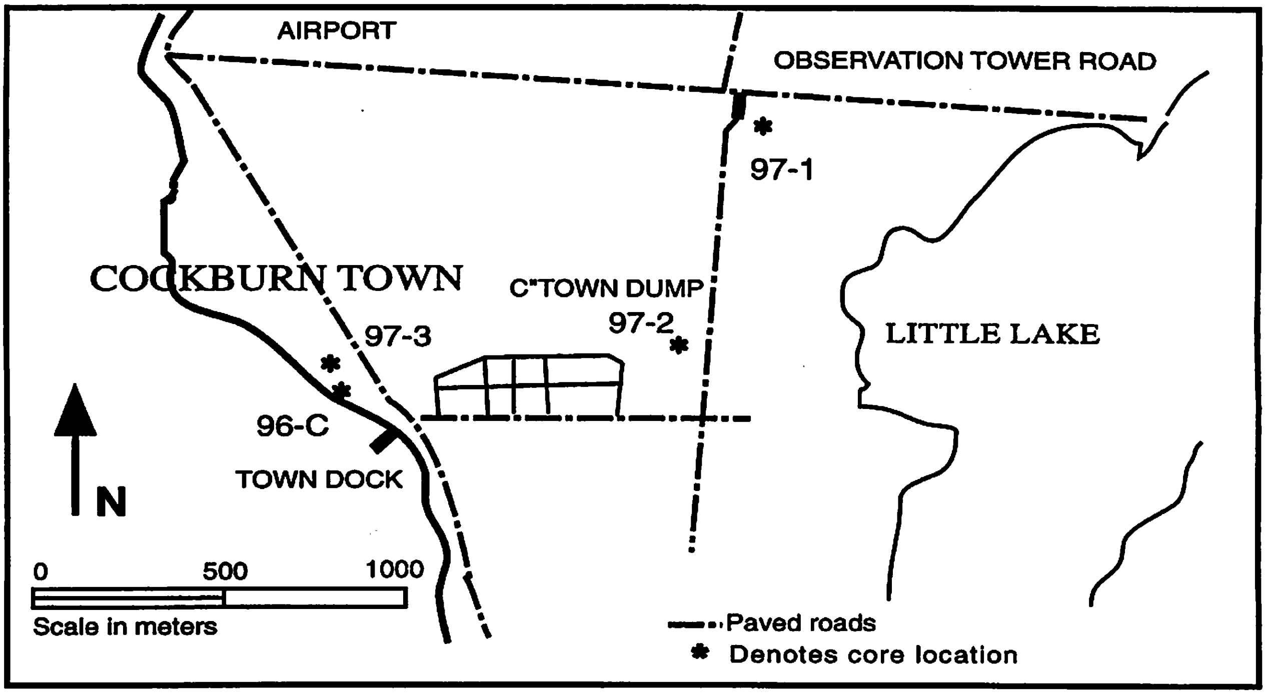

Figure 2. Map of Cockburn Town and study area, showing locations of the 4 cores.

eolian dune environments, with paleosols, caliche crusts and karst features generally punctuating the stratigraphy. Topographic highs occur as a series of arcuate dunes formed between preexisting highs and lakes fill many of the low areas between the dune ridges (Carew and Mylroie, 1995). The varied stratigraphy is dominated by complex lateral and vertical fluctuations of depositional environments which are linked to even minor changes in sea level (White et al., 1997).

The physical stratigraphy of San Salvador, as developed by Carew and Mylroie (1985, 1987, 1995), begins with the Owl's Hole Formation (eolianite) which is capped by a terrarossa paleosol. Above the Owl's Hole is the Grotto Beach Formation which is divided into the French Bay Member (lower unit) and the Cockburn Town Member (upper unit). The top of the Cockburn Town Member forms the upper limit of Pleistocene rocks on the island and is topped by either erosional surfaces or paleosols which separate it from Holocene sediments. Holocene sediments are divided into the North Point Member (lower member) and the Hanna Bay Member (upper member).

CORE DESCRIPTIONS AND INTERPRETATIONS

The following descriptions and interpretations are brief and list only major components and observations of the sediments in the cores. Cores are described from the base up.

Core 96-C: Cockburn Town Fossil Reef

Core 96-C from the Cockburn Town Fossil Reef is 9 m long (Figure 3). The bottom 2.7 meters of the core is composed of well preserved heads of *Montastrea cavernosa, M. annularis, Siderastrea sp.* and *Diploria sp.*, as large as 20 cm and in growth position (Figure 4). Encrusting coralline algae was incorporated into the bases of *M. annularis* and *Siderastrea sp.* in the sand-dominated lower portion of the unit. This may indicate coralline algae colonized and encrusted sandy areas early in the reef's

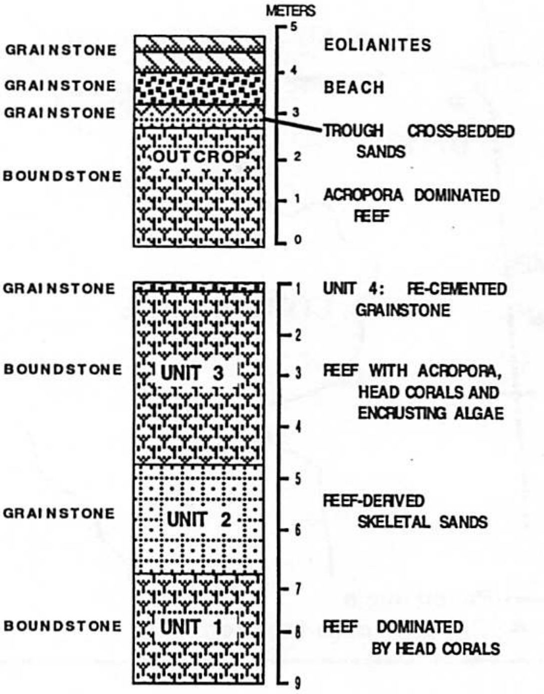

Figure 3. Core 96-C lithology and depositional environments (includes lithology and depositional environments for the Cockburn Town fossil reef outcrop from White et al., 1997).

Figure 4. Photo of massive Montastrea cavernosa at 8.3 m in Core 96-C.

growth, providing a favorable platform for coral growth (James, 1983). Coral density and diversity increase upward, indicating reef growth towards a more mature community.

Above the coral unit is 2.4 m of reef-derived skeletal sand. The sand is skeletal grainstone with varied sorting and rounding and large amounts of *Halimeda lacrimosa, H. copiosa* and *H. opuntia* in both broken and unbroken segments. Pieces of encrusting algae are also present along with whole and broken gastropod and bivalve shells, worm-tube bundles, crustacean claws, echinoid pieces, and *Homotrema rubrum.* Coral is absent in this unit. These sandy, reef-derived sediments could have accumulated at the boundary between the reef and lagoon, or on a sandy bottom between two reef communities (James, 1983; Pichon, 1981).

The contact between unit 2 and unit 3 is gradual, with corals becoming increasingly dominant as heavily algae-encrusted *Montastrea annularis* and *Diploria sp.* give way to large, 6 cm diameter branches of *Acropora sp.* which dominate at the top of the unit. There is the occasional presence of *M. annularis*, and fragments of *Millipora alcicornis* and *Eusimilia fastigiata.* Coralline algae commonly encrusts *Acropora cervicornis*, appearing on the side of the branches corresponding to the upward direction in the core, indicating the reef is in growth position. Unit 3 is 3.85 m thick.

At the top of the core there is a 2 cm veneer of loosely consolidated, well-rounded, well-sorted grainstone. In thin section ooids and peloids are the most abundant grains and cement is only present at grain contacts. Grains are medium sand size and appear to be similar to loose sand grains lying on the surface of the drilling site. Since this unit is on the excavated floor of the quarry, it is probably composed of reworked, recemented grains eroded from the outcrop 15 m away.

The Cockburn Town fossil outcrop continues the depositional history started in the core with a 0.5 m head of *Montastrea cavernosa* and more *Acropora cervicornis* exposed immediately above the core site.

Core 97-3: Cockburn Town Fossil Reef

Core 97-3 is 14.75 m long (Figure 5). The base of this core is dominated by 2.4 m of burrowed lagoonal packstone. Peloids, whole and broken mollusk pieces and algae grains are common, and grains show poor or mixed rounding and sorting. There is a coarsening-upward trend in the lagoonal sediments. A 30 cm interval of coarse, reef-derived skeletal grains with heavily altered *Montastrea annularis*, *Siderastrea sp.* and other small corals common to lagoons is present.

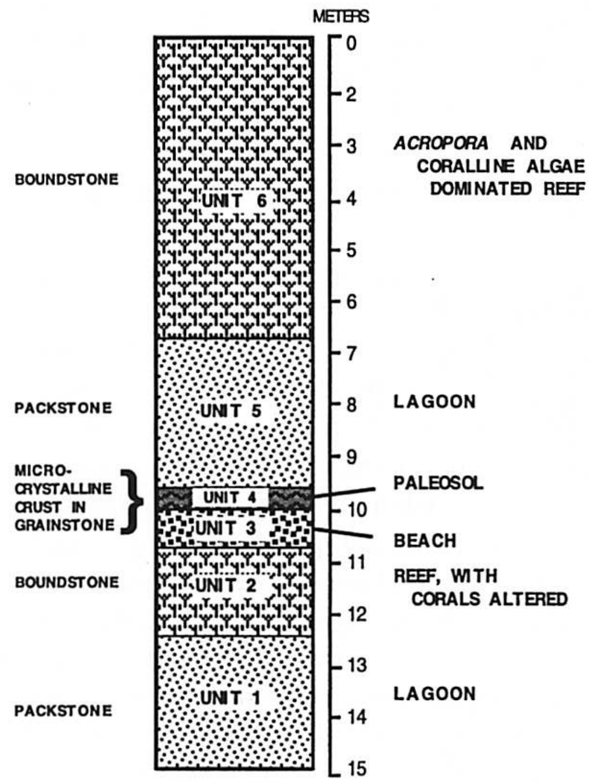

Figure 5. Core 97-3 lithology and depositional environments.

Two meters of coral dominated reef, with reef-derived skeletal sands surrounding the coral framework occur above the lagoonal sediments. Branching *Acropora cervicornis* dominates at the base, but transitions gradually to mound corals such as *Porites asteroides* and *Montastrea annularis*. All corals in this unit are heavily altered. *A. cervicornis*, altered to a consistency of chalk, is almost unrecognizable by internal septa morphology (Figure 6). Instead, dense coralline algae rims define branch shape around the altered, chalk-like interiors of the *A. cervicornis*. Where the coral framework dominates, the sediment is a boundstone and is a grainstone where skeletal sands dominate. The limited vertical accumulation indicates this is probably a patch

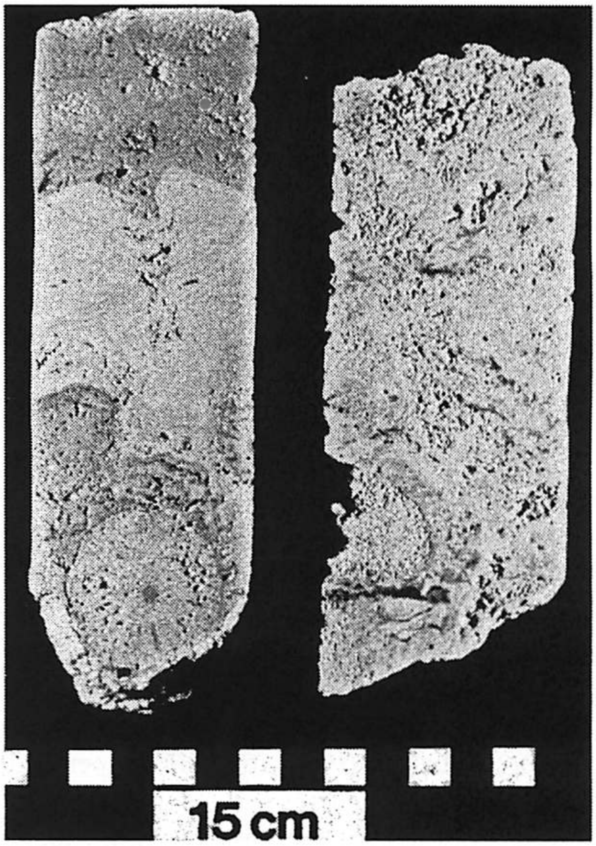

Figure 6. LEFT: Well-preserved Acropora cervicornis branch encrusted with coralline algae (gray), fine-grained drape (white) and reef derived sand (top) from above the paleosol. RIGHT: Altered, chalky-textured A. cervicornis from below the paleosol showing dense rim of coralline algae around branch.

reef, or a reef limited in growth by shallowing water.

The upper-most corals of this reef are overlain by 85 cm of coarse, well-rounded, well-sorted, laminated skeletal grainstones with beach bubbles in the sediment. Fine-grained orange and brown clay-sized particles occupy intergranular spaces, highlighting the laminations. This grainstone unit is interpreted to be a beach of moderate energy near a source of organic material, which may have washed down and infiltrated the laminated sands.

Unit 4 contains sediments similar to the beach, but slightly finer. The 35 cm section contains dark brown, laminated, microcrystalline crusts with clasts of platy, clay-sized material which may be organic matter filling root molds from plants. The unit is interpreted to be beach or back-beach sediments on which a paleosol formed during subaerial exposure.

Unit 5 is 3 m of coarse sand, composed of peloids and reef-derived skeletal and coral fragments. There are burrows and articulated bivalves, particularly in the lower portion. Root molds present in the lower part of unit 5 indicate sea grasses may have grown there. At the top of the unit, burrows disappear and pieces of *Acropora cervicornis* become more prevalent. This unit is interpreted to be a lagoon near a reef.

Acropora cervicornis pieces dominate the entire 6.2 m of unit 6. The coral framework is composed of well-preserved *A. cervicornis* heavily encrusted with coralline algae and a fine-grained, finely laminated drape. Encrustation appears exclusively on the upper branch surfaces of the *A. cervicornis* (Figure 6), building perched sediments as thick as 10 cm. Reef-derived skeletal sand fills spaces between the coral framework. Geopetal features and encrusting algae indicate that this reef is in growth position.

Cockburn Town Fossil Reef Outcrop

The Cockburn Town fossil reef complex is exposed near cores 96-C and 97-3 (Figure 3). The studies of Curran and White (1985) and White et al. (1997) tell us the base of the outcrop represents a bank or barrier reef with the reef crest marked by the presence of *Acropora palmata* at the top of the reef unit. Reef growth occurred approximately 131 to 119 thousand years ago and is linked to the Sangamon interglacial highstand, oxygen isotope stage 5e (Chen et al., 1991). Based on the position of *A. palmata*, an excellent sea level indicator, sea level would have reached about 6 m above the present level. The shore was estimated to be 450 m to the east of the reef (Chen et al., 1991). The reef was drowned quickly by a regressive sequence of sediments (rubble, cross-bedded shoreface sands, then eolian dunes) from a prograding shoreline, which are associated with falling sea levels at the onset of Wisconsin glaciation about 119 thousand years before present. The extremely well preserved nature of the corals and their preservation in near-growth position is attributed to this quick burial. More recent research (White et al., 1997) found evidence in the reef portion of the outcrop that there was a period of rapid sea-level fall followed by resumed reef growth at about 126-125 thousand years ago.

Core 97-2: Cockburn Town Dump

Core 97-2 from the Cockburn Town Dump is 10.16 m long (Figure 7). The base of core 97-2 is dominated by 7.5 m of lagoonal packstone with abundant and diverse marine fossils. Whole and fragmented mollusks, forams, echinoid pieces, and root molds are common. There are horizons rich in *Goniolithon sp.* Extensive burrowing, pellet groupings, crustacean pieces and clumps of organic material indicate intense biologic activity. Sediment is generally poorly sorted and poorly rounded throughout, but a two meter thick section of fine-grained, well-rounded and well-sorted sands (excepting whole and fragmented mollusks), abruptly appears 2 m above the base. Unit 1 is interpreted to be a lagoonal environment sup-

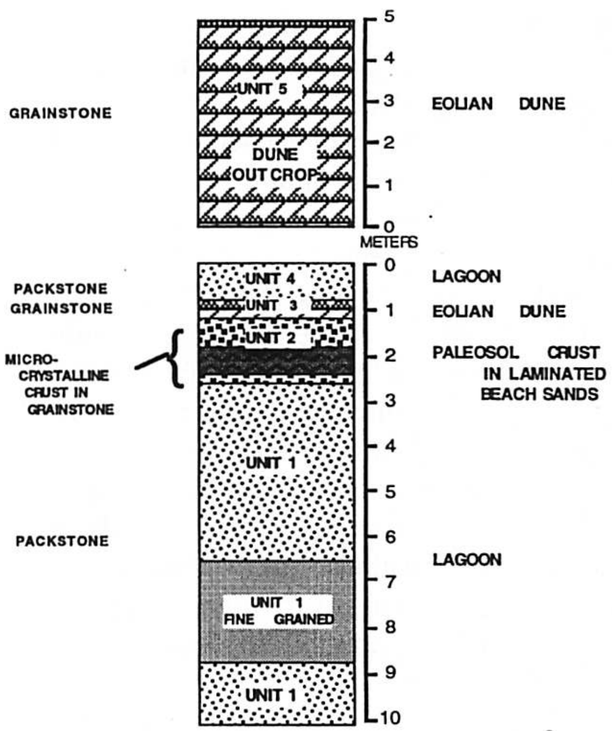

Figure 7. Core 97-2 lithology and depositional environments.

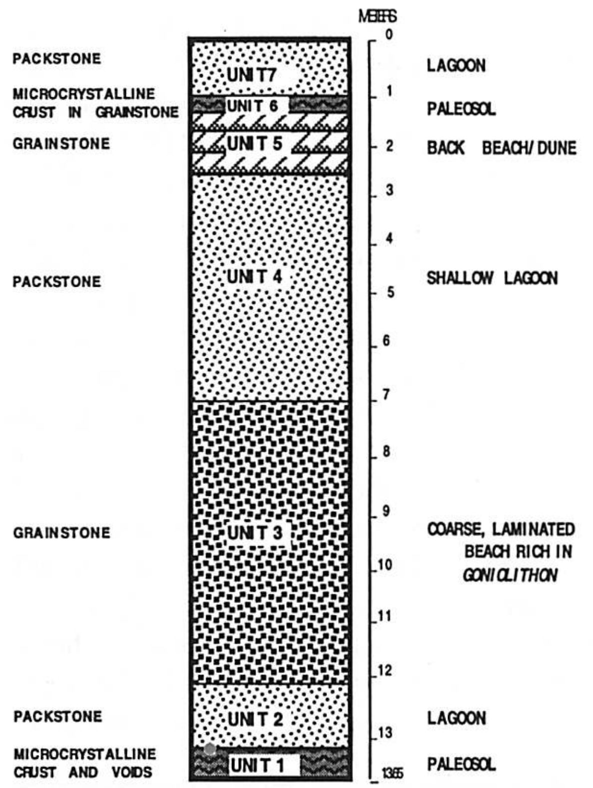

Figure 8. Core 97-1 lithology and depositional environments.

porting abundant mollusks, burrowing organisms, and sea grasses.

The sediments of unit 1 grade into 1.4 meters of sand with medium and coarse grain size and variable to good sorting and rounding. The base of unit 2 has faint laminations. Dark brown, microcrystalline, laminated crusts bisect 80 cm of this unit and fining-upward sequences 20 cm thick can be seen in the grainstone. Grains are composed of forams, red algae, echinoid pieces and mollusk fragments. The unit is interpreted to be shore-face deposits with imbedded laminated paleosol crusts.

Unit 3 is a 50 cm thick grainstone, with grains that are fine sand-sized, very well sorted and rounded. In thin section ooids, peloids, forams and algae grains are abundant. There are low-angle laminations and cross-bedding. This unit is interpreted to be dune deposits, a continuation of the shoreface deposits of unit 2.

Above the dune is an 80 cm lagoonal packstone deposit, with abundant and diverse marine fauna. Mollusks are abundant and sediments are punctuated by dark brown root molds and intense burrowing. Fragments of *Goniolithon sp.* are also present. Grains are fine to lower medium sand size and are poorly sorted.

Five meters west of the surface of the drill site is a 6 m outcrop of cross-bedded dunes. The contact between the lagoon of unit 4 and the dune of unit 5 was not observed. Hand samples taken from the outcrop are very well sorted peloid and ooid grainstones of fine sand size. There are no marine fossils and laminations are produced by minute changes in grain size. Sorting and fining increase upward in the outcrop. This unit is a grainstone almost identical to the sediment in unit 3 in the core.

Core 97-1: Observation Tower Road

Core 97-1 from Observation Tower Road is 13.65 m long (Figure 8). Twenty cm of a paleosol, formed on exposed lagoonal deposits, was recovered at the base of core 97-1. The material is so dense that drilling was halted. Microcrystalline laminated crusts are found in the bottom and the contact with unit 2 above is an irregular surface with blackened grains (as large as 2 cm) of lagoonal sediments (Figure 9). The lagoonal material of unit 1 is microcrystalline and gastropod rich.

Above the paleosol is 1.3 m of lagoonal sediment. There are voids and mollusk molds with drusy yellow or pink crystal coatings and the color changes from dark pink to white towards the top of the unit. One very altered 10 cm *Montastrea annularis* occurs in the unit. Thin sections show micritized sediments with abundant grains composed of peloids, red algae, forams, coralline algae and mollusks. The lagoon sediment coarsens upward from fine-grained to coarse with faint laminations at the top. Unit 2 also becomes less muddy upwards, changing from a packstone at the base to a grainstone at the top.

Unit 3 is 5.2 m of very coarse grainstone with peloids, whole *Goniolithon sp.* segments, *Halimeda sp.* pieces, red algae grains and broken mollusk fragments (Figure 10). The unit is strongly laminated with some shell-hash layers and beach bubbles at the very top. Sediment shows moderate to good rounding and sorting. Angles of the laminations range from 4 to 22 degrees and generally steepen toward the top. A 1.5 m section in the middle of unit 3 is slightly less coarse, contains more whole fossils, and shows faint laminations and cross-bedding. The unit is interpreted as a very high energy beach with the middle section showing lower shoreface characteristics.

Unit 4 is 4.5 m of lagoonal packstone

Figure 9. Photo of blackened grain at the surface of the lower paleosol in Core 97-1 (13 m below mean high water).

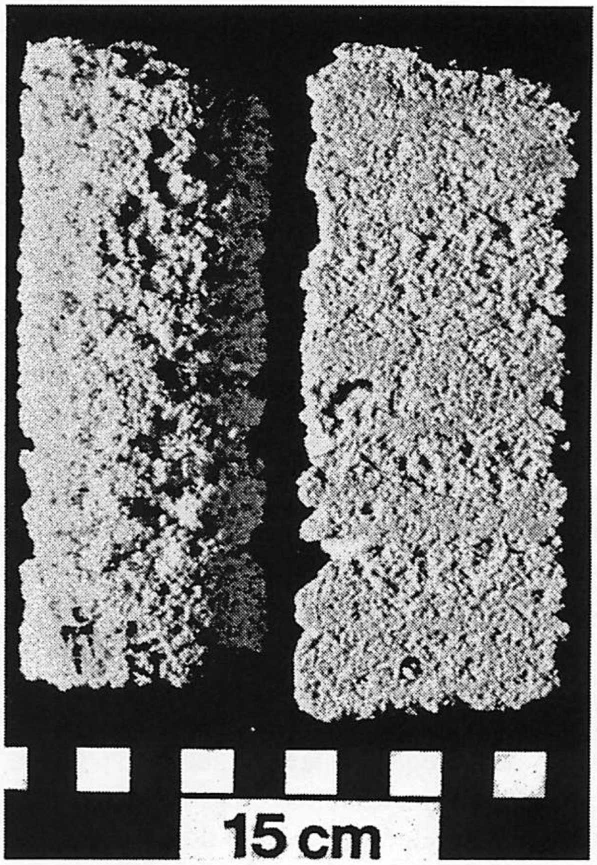

Figure 10. Photo of coarse, laminated beach sands from Core 97-1.

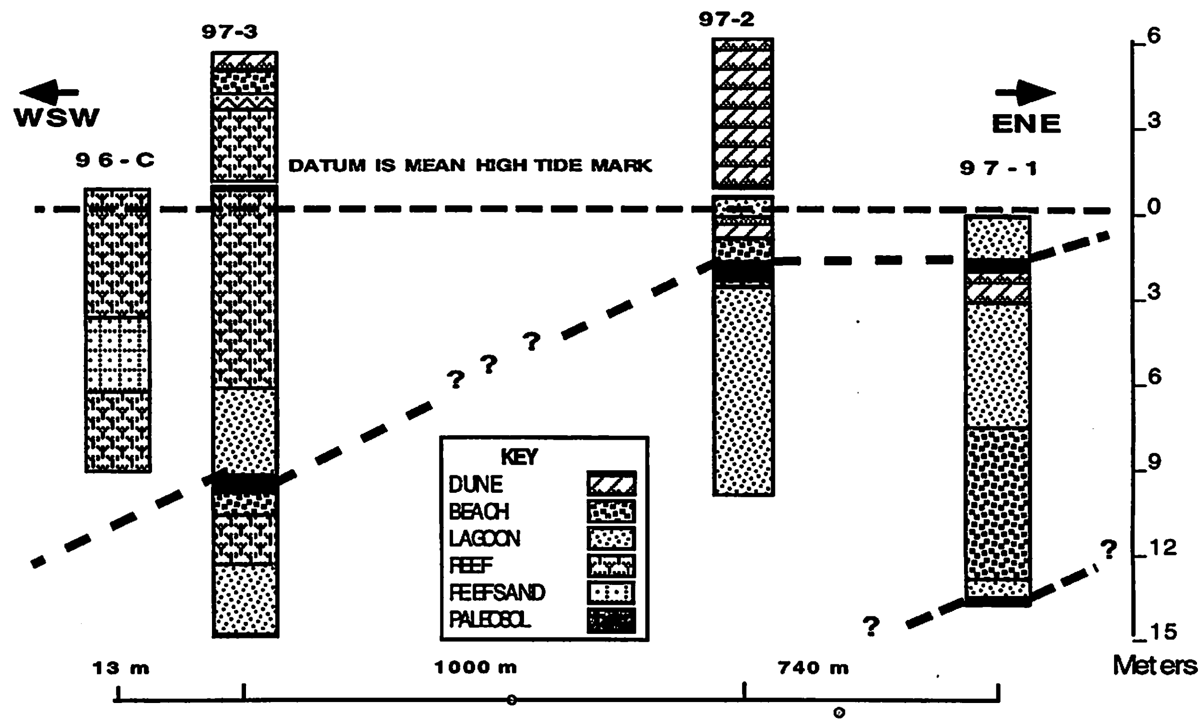

Figure 11. Profile of the 4 cores and depositional cross-section.

rich in *Halimeda sp.*, mollusks, worm tubes and forams. Grain size is variable, but decreases from coarse to medium sand-sized upwards. Unit 4 is heavily burrowed with areas of root molds and pockets of organic matter.

Unit 5 is a 120 cm thick grainstone with well-rounded and well-sorted sediments. The bottom 20 cm is medium sand-sized with layers of broken and abraded shells. Above this, sediment is devoid of marine fossils and laminations and fines from medium to very fine sand-size. Grains are cemented at grain contacts. Unit 5 is interpreted as a back beach, grading to dunes.

Grainstones of unit 6 (50 cm thick) are bisected by microcrystalline, laminated crusts at the base, but have root molds, clumps of organic material, a mottled appearance and an interlocking contact with the unit above. Blackened grains are found in this mottled section. Unit 6 is interpreted to be a paleosol in fine-grained sediment, probably a continuation of the dune deposit of unit 5.

Unit 7 consists of fine-grained lagoonal (or possibly lake) packstone, rich in whole mollusks but no other recognizable fossils. The unit has root molds and orange organic material filling voids at the top and terminates at a karst surface.

DISCUSSION AND CONCLUSIONS

While paleosols cannot be used as a conclusive means to correlate deposits, in cores so closely spaced they do provide a useful tool to correlation when combined with other clues (Boardman et al., 1995). They also provide strong evidence of major exposure events. At the fossil reef we encounter a paleosol at 9.4 m. Core 96-C, 13.5 m away, only reached 9 m and did not encounter a paleosol. Over a km away, at cores 97-1 and 97-2, the first paleosol is encountered at about 1 m depth (Figure 11). As we might expect, the reef and lagoon environments located at the western shoreline yield to lagoons, beaches and dunes inland. When the lateral distribution of environments is considered, it is possible to accept this paleosol as continuous between all cores. The shallower position of the paleosol in the inland cores and the appearance of an even earlier paleosol creates an impression of inclined allostratigraphic packages in cross-section, suggesting lateral accretion of sediment packages to the island margin. This conforms to the lateral accretion model of island building (Vacher, 1973).

If the paleosol is indeed continuous, relating these cores to the established stratigraphy of San Salvador (Carew and Mylroie, 1985, 1987, 1995) is relatively straightforward. This paleosol clearly underlies the Cockburn Town fossil reef and associated lagoon. The outcrop was deposited during the Sangamon interglacial period (oxygen isotope stage 5e) and is the type section for the Cockburn Town Member of the Grotto Beach Formation (Curran and White, 1985; White et al., 1997; Chen et al., 1991). The paleosol therefore separates Sangamon from pre-Sangamon deposits, making it equivalent to the paleosol at the top of the Owl's Hole Formation. Sediments in the cores below this paleosol would then be analogous to those of the Owl's Hole Formation, and deposition would be associated with oxygen isotope stage 7 (ca. 220 ka), 9 (ca. 320 ka) or 11 (ca. 410 ka) (Carew and Mylroie, 1995). The thick paleosol at the base of core 97-1 would then correlate to the base of the Owl's Hole Formation and be associated with lowstands of stage 8, 10 or earlier.

Sediment packages preserved in the cores are shallowing-upward sequences that terminate in paleosols. Thick lagoon and beach deposits, perhaps associated with deposition during stillstands, are overlain by eolianites, often related to the regressive phase (Carew and Mylroie, 1995). During stillstands, reefs would also create thick deposits as they grew rapidly to sea level. Viewed together, these shallowing-upward sequences probably represent depositional packages of stillstand, followed by regressive phase deposits, and bounded by paleosols representing long (~ 100,000 year) periods of exposure during sea level lowstands (Carew and Mylroie, 1995; Boardman, et al., 1995).

Shallowing sequences and even specific environments are repeated vertically above and below the paleosol in each core (Figure 11). In core 97-3, lagoon sediments give way to reefs, which are then covered by shoreface deposits and a paleosol. Above the paleosol the lagoon and reef are repeated and the entire prograding sequence of the Cockburn Town fossil reef continues the shallowing sequence, terminating with the current exposure surface at the top of the outcrop. At core 97-2, thick lagoon sediments are capped by beaches, then by dunes imbedded with a paleosol crust. Above the paleosol, lagoons are again superseded by dunes and the modern exposure surface. Core 97-1 contains alternating lagoon and beach sediments topped by a paleosol in the upper-most dune unit. The cycle then starts over above the paleosol, with lagoon sediments truncated by a karst exposure surface.

There are, however, differences in the lateral distribution of environments below the paleosol versus above it. The very thick lagoon of core 97-2 and beach of core 97-1 indicate there was significant accommodation space available and the extremely coarse, laminated beach of 97-1 suggests a very high energy beach capable of transporting and depositing large quantities of coarse sediment. The beach in this pre-Sangamon lagoon is at least 1.5 km from the patch reefs, indicating a very broad lagoon. The greater area of submerged shelf would also generate more carbonate material to build thick deposits of shallow water sediments. In summary, the lagoon of the lower formation was broader, less well protected, and thus had more accommodation space and higher energy reaching the shore.

This scenario is contrasted with the Sangamon depositional system where the well-established barrier reef, only 450 m from shore (Chen et al., 1991), would have provided significant protection to the back reef and shore. The lagoon would have been protected from ocean swell and wave energy, enhancing lagoon filling and producing a lower energy beach. With limited accommodation space and a more protected environment for carbonate production, it is no wonder that the prograding subaerial sediments were able to quickly drown and preserve the Cockburn Town reef.

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