# PROCEEDINGS OF THE 11$^{TH}$ SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

**Edited by**
**Ronald D. Lewis and Bruce C. Panuska**

**Production Editor:**
**Ronald D. Lewis**

Gerace Research Center
San Salvador, Bahamas
2004

Front Cover: Close-up view of a patch-reef coral head in Grahams Harbor, north of Dump Reef. As shown here, Caribbean shallow-water reefs have declined since the mid-1980s and are now largely overgrown by fleshy green macroalgae and a variety of encrusting organisms. See Curran et al., "Shallow-water reefs in transition," this volume, p. 13. Photograph by Ron Lewis.

Back Cover: Dr. A. Conrad Neumann, University of North Carolina, Chapel Hill, NC, Keynote Speaker for the 11th Symposium and author of "Cement loading: A carbonate retrospective," this volume, p. xii. Photograph by Mark Boardman.

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**ISBN 0-935909-72-9**

# CHRONOLOGY AND DIAGENESIS OF PLEISTOCENE, REEF-DOMINATED, SHALLOWING-UPWARD SEQUENCES AT COCKBURN TOWN, SAN SALVADOR, BAHAMAS

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## ABSTRACT

X-ray diffractometry and petrography disclose the diagenetic signatures of late Quaternary sea-level events within a core and hand samples retrieved at Cockburn Town, San Salvador, Bahamas. The 15-meter core and stratigraphically-overlying facies in outcrop encompass two stacked, shallowing-upward sequences made up of lagoon, reef, beach, and eolian dune sediments that are capped by red, micritic paleosols. Sediments deposited during the Sangamon (oxygen isotope substage 5e) interglacial highstand at approximately 125,000 years ago comprise the upper shallowing-upward sequence, which has undergone limited alteration during one phase of submergence and emergence. The lower shallowing-upward sequence was deposited during a pre-5e highstand and has undergone significant diagenesis during at least two phases of submergence and emergence.

Both sequences contain reef facies that are dominated by the scleractinian coral *Acropora cervicornis*. *A. cervicornis* fossils are commonly overgrown by an encrusting variety of the coralline algae *Neogoniolithon* sp. Within two separate zones of the upper reef facies, *Neogoniolithon* sp. is in turn overlain by micrite that formed via microbial mediation (i.e., 'microbialites').

Diagenesis of both shallowing-upward sequences occurred within the marine, freshwater phreatic, vadose, and post-vadose freshwater phreatic zones, with principal diagenesis occurring during residence in meteoric environments. Macroscopic indicators of diagenesis include coral 'chalkification,' vuggy porosity, and the presence of crusts at unconformity horizons. Petrographic diagenetic features include neomorphic fabrics, vugs, moldic porosity, and cement that includes acicular, bladed, and equant crystals, drusy infillings, whisker, and meniscus forms.

X-ray diffractometry indicates a general trend of mineralogical alteration from aragonite to calcite with increased core depth, which is consistent with macroscopic and petrographic features. X-ray diffractometry analysis of similar components from each of the two reef facies reveals alteration of sand and *Neogoniolithon* sp. that increases with age, and uneven diagenetic trends within *A. cervicornis* that are attributed to variable fluid paths within the coral's highly-porous branches.

## INTRODUCTION

Eustatic sea-level change throughout the Quaternary Period has exerted the primary control on Bahamian depositional settings and produced a complex sedimentary record on San Salvador. Sea-level change has also prompted fluctuations between nearshore marine and meteoric diagenetic environments that have left characteristic petrographic and geochemical signatures on San Salvador's carbonate sediments. This study investigates a core (assigned the number 97-3) and overlying outcrop samples to determine the mineralogy and petrographic features of two shallowing-upward sequences that immediately underlie and encompass the prominent fossil reef exposed near Cockburn Town on the western side of San Salvador (Figure 1). The purpose of this research is to characterize these sequences with emphasis on the contrasting diagenetic features of their reef sediments and apply these characterizations to clarification of the area's late Quaternary geological history.

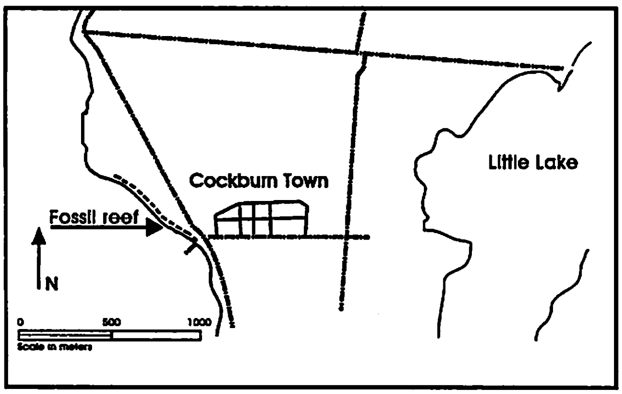


*Figure 1. The Cockburn Town area.*

## PREVIOUS RESEARCH

Maximum Quaternary sea level occurred during the oxygen isotope substage 5e (Sangamon interglacial) highstand (Shackleton and Opdyke, 1973). Curran and White (1985) determined that the Cockburn Town Fossil Reef developed during this highstand, and they extensively described, mapped, and compiled facies diagrams of the Cockburn Town outcrop's 5 meters of vertical section. Curran and White also interpreted the reef proper as a bank barrier reef situated seaward of a lagoon and located about 450 meters offshore. Chen et al. (1991) used $^{234}U/^{230}Th$ mass-spectrometric techniques to date pristine aragonite from corals on the Cockburn Town reef and Great Inagua Island. Their results indicated that the substage 5e highstand occurred from about 132 to 119 ka. Recent studies show that a brief (~1500 year) sea-level lowstand and depositional hiatus occurred during the 5e highstand (e.g., Wilson et al., 1998).

Four cores were retrieved by the junior authors during 1996 and 1997 from sites trending inland from the Cockburn Town reef. These cores contain a variety of near-shore sediments that indicate shallowing-upward sedimentation on the western side of San Salvador during the late Pleistocene (Gose et al., 1999). Further documentation and characterization of the area's shallowing-upward sequences involved a preliminary x-ray diffraction study of core 97-3 by Boardman and Carney (1999). The results of their mineralogical assessment showed overall alteration from aragonite to calcite with increased core depth (Figure 2).

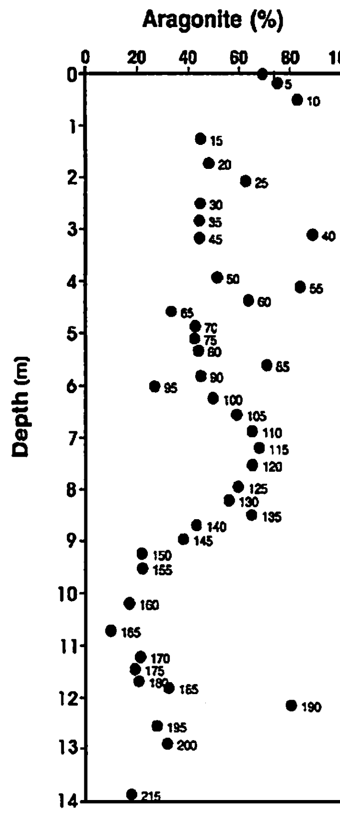


*Figure 2. X-ray diffractometry results for core 97-3. Data-point numbers correspond to core pieces from which samples were taken for analysis (modified from Boardman and Carney, 1999).*

## METHODS

Core 97-3 is approximately 15 meters in length and was retrieved from the floor of a previously quarried area at the Cockburn Town Fossil Reef. The coring procedure was performed with a hydraulically-powered drill rig based on the SCARID design of Hubbard et al. (1986).

Thirty-six thin sections were prepared from core and outcrop samples and examined under a polarizing microscope. Quantitative analysis (300-point counts) was performed on 21 thin sections.

X-ray diffraction analysis was performed on one core piece from each of this study's two reef facies. Each piece contained similar features, including transverse cross sections of *Acropora cervicornis* branches, coralline algae, and areas of relatively loose sand grains. A total of eight samples were retrieved from four corresponding areas on each of the two core pieces: (1) the approximate centers of *A. cervicornis*, (2) internal sites near the edge of each coral, (3) the coralline algae encrusting the coral, and (4) the sandy areas between branches. The x-ray diffraction was performed at Miami University in Oxford, Ohio.

## RESULTS

Core 97-3 and the Cockburn Town reef outcrop represent two stacked, shallowing-upward sequences of lagoon, reef, beach, and eolian dune sediments capped by a red micritic paleosol. These facies have been numbered one through nine and their relative positions diagrammed on Figure 3. Point count results for these facies are shown in Table 1.

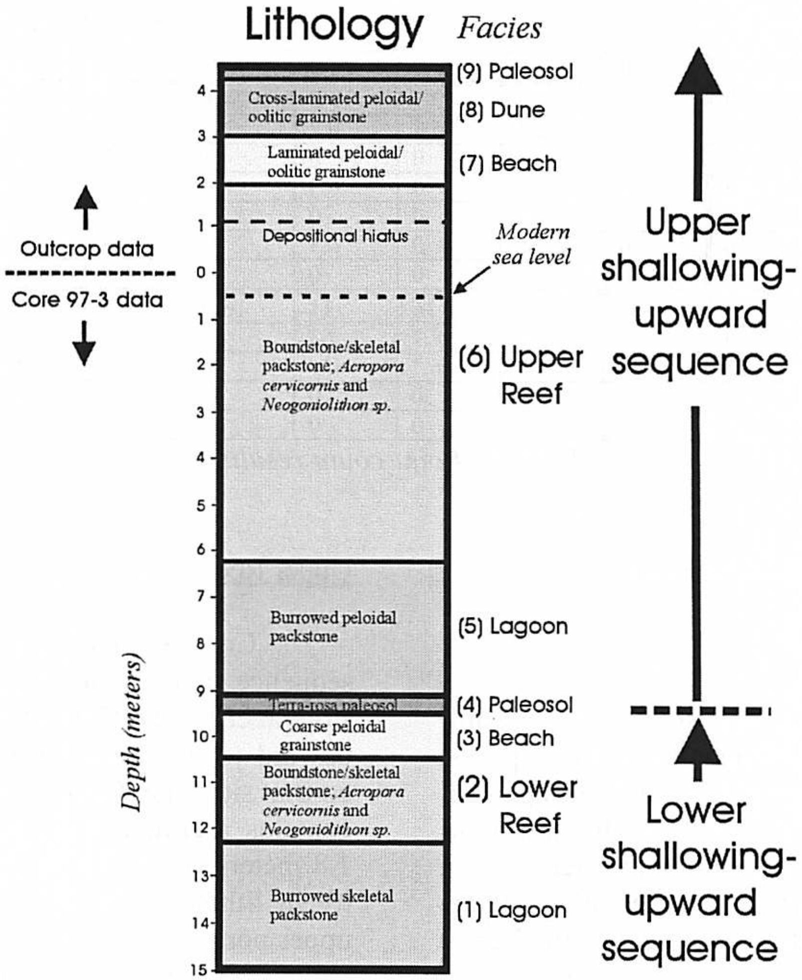


*Figure 3. Composite section of core 97-3 and overlying facies.*

| Facies Number | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 4 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Facies Name | Lagoon | | Reef | | | | | | Beach | Paleosol | |
| Elevation (m) | -14.35 | -14 | -12.1 | -11.8 | -11.5 | -11.15 | -10.8 | -10.75 | -10.2 | -9.45 | -9.3 |
| Thin Section # | 219 | 215 | 189 | 185 | 176 | 169 | 165b | 165a | 160 | 154 | 151 |
| % Ooids | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 4.3 | 1.7 |
| % Peloids | 0 | 0 | 3.3 | 3.3 | 0 | 0 | 6 | 0 | 27 | 22.3 | 17 |
| % Clasts | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.7 | 1 | 2.7 |
| % Coral | 0 | 0 | 28 | 23.7 | 61.3 | 40 | 18.7 | 27.7 | 0 | 0 | 0 |
| % Coralline algae | 25 | 3.7 | 20 | 25.7 | 18 | 17 | 11.3 | 33.7 | 2.7 | 22.3 | 4.3 |
| % *Halimeda* sp. | 0.3 | 3 | 2 | 11.7 | 0 | 0 | 1 | 1.7 | 16.7 | 3.7 | 3.3 |
| % Molluscs | 0 | 1 | 2 | 11.7 | 0 | 0 | 0.3 | 0 | 2 | 3.3 | 2 |
| % Echinoderms | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 |
| % Miliolid forams | 0 | 0 | 1.3 | 1 | 0 | 0 | 0.7 | 0.3 | 1.7 | 0.3 | 0.3 |
| % Penerop forams | 0 | 1.3 | 0.3 | 0.7 | 0 | 0 | 0.7 | 0 | 1.3 | 1.7 | 0 |
| % Porosity | 49.3 | 17.7 | 7 | 11.3 | 2.3 | 11 | 16 | 8.3 | 22.7 | 11 | 10 |
| % Mud | 14 | 65.7 | 27.3 | 5.7 | 18.3 | 18.3 | 29.3 | 8 | 0 | 0 | 0 |
| % Fine xl cement | 10.3 | 7.3 | 6.3 | 13.3 | 0 | 7.3 | 15 | 16.7 | 20.3 | 30 | 52.3 |
| % Lg blocky cement | 1 | 0.3 | 2.3 | 1.3 | 0 | 6.3 | 1 | 3.7 | 0 | 0 | 6 |
| % Acicular cement | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Facies Number | 5 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| Facies Name | Lagoon | Reef | | | | | | | Beach | Dune |
| Elevation (m) | -6.3 | -6.05 | -4.35 | -3.45 | -2.85 | -0.75 | 1.2 | 2.1 | 3.5 | 4.2 |
| Thin Section # | 101 | 95b | 59 | 43 | 35 | 12a | 002 | 003 | 006 | 008 |
| % Ooids | 12.3 | 0 | 0 | 0 | 0.3 | 0.7 | 1.3 | 6 | 4 | 23.3 |
| % Peloids | 34.3 | 0 | 10 | 0 | 3.3 | 3 | 24.3 | 19.3 | 14.3 | 39.7 |
| % Clasts | 0.3 | 0 | 0 | 0 | 0 | 0 | 2.3 | 4.7 | 10.3 | 4.7 |
| % Coral | 0 | 23.7 | 6.3 | 53.7 | 0 | 24.3 | 0 | 0 | 0 | 0 |
| % Coralline algae | 1 | 9.7 | 2.7 | 5.3 | 0.7 | 2.7 | 1 | 0 | 0 | 0 |
| % *Halimeda* sp. | 3 | 0 | 0.7 | 0 | 0 | 0 | 3.7 | 2.7 | 28.3 | 1 |
| % Molluscs | 1.3 | 0.3 | 2 | 0 | 0.3 | 1.7 | 13 | 9 | 9.3 | 0.7 |
| % Echinoderms | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| % Miliolid forams | 0 | 0 | 0 | 0 | 0.3 | 0 | 2.3 | 0 | 1 | 0.3 |
| % Penerop forams | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0 | 2 | 0 |
| % Porosity | 9 | 24 | 8 | 16 | 11 | 16.7 | 6.3 | 4.7 | 13 | 6.7 |
| % Mud | 12.3 | 5.3 | 48 | 18.7 | 53 | 17 | 30 | 38.7 | 0 | 0 |
| % Fine xl cement | 23 | 37 | 22.3 | 6.3 | 31 | 31 | 14 | 14.3 | 17.7 | 23.7 |
| % Lg blocky cement | 1.7 | 0 | 0 | 0 | 0 | 3 | 1 | 0.7 | 0 | 0 |
| % Acicular cement | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*Table 1. Point-count results*

## Reef Facies Descriptions

### Lower Reef

Core 97-3's lower shallowing-upward sequence contains a boundstone/skeletal packstone reef facies (Gose et al., 1999) designated as facies 2. The fauna is dominated by *Acropora cervicornis,* which is typically encrusted in layers up to 2 cm thick by the coralline algae *Neogoniolithon* sp. Mud indicated by the Table 1 point-count results is largely confined to micrite intercalated with and overlying the *Neogoniolithon.*

### Upper Reef

Core 97-3's upper shallowing-upward sequence contains a boundstone/skeletal packstone reef facies (Gose et al., 1999) that extends upward to the ground surface. Adjacent to the coring site, the Cockburn Town reef outcrop contains a similar lithology to an elevation of 1.8 meters above that of the core. This continuity in lithology indicates that the outcrop and upper portions of core 97-3 can be combined as facies 6. Previous studies (e.g., Curran and White, 1985) indicate that this facies was deposited as a bank barrier reef with a north-south trending crest.

The outcrop's diverse assemblage of coral fossils contrasts with the dominance of *A. cervicornis* at the top of core 97-3. *A. cervicornis* fossils in the core have branch diameters up to ~8 cm that are commonly overgrown by *Neogoniolithon* sp. Within two separate zones of the facies, the encrusting algae are in turn overlain by micrite (up to 5 cm thick) with a macroscopic appearance of clean, white laminae that follow the contours of the underlying coralline algae (Figure 4). Petrographically, this well-indurated micrite appears as weakly laminated aggregations of peloids and dark matrix that commonly surround encrusting rotaliid foraminifera (Figure 5).

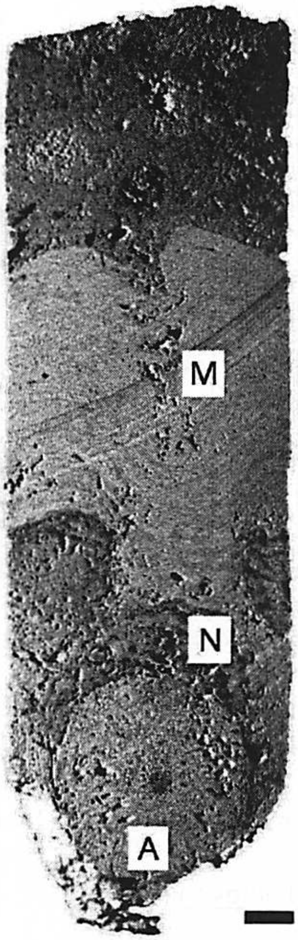


*Figure 4. Upper reef core piece containing the coral-coralline algae-micrite sequence. An* Acropora cervicornis *branch (A) is encrusted by the coralline algae* Neogoniolithon *sp. (N) that is turn overlain by micrite (M) with wavy laminae. Note the single axial corallite diagnostic of* A. cervicornis *that is visible as a small gray area toward the coral's center. Scale bar is 1 cm.*

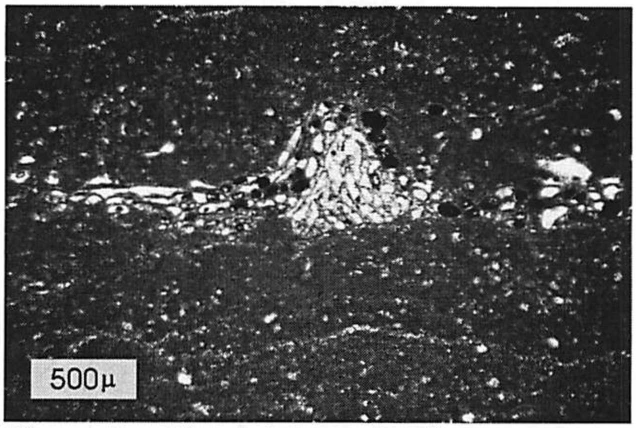


*Figure 5. Photomicrograph of an encrusting rotaliid foraminiferan within laminated micrite.*

## Diagenesis

The lower shallowing-upward sequence has undergone greater alteration than the upper shallowing-upward sequence. Petrography indicates considerable recrystallization of primary aragonite grains and micrite matrix. This alteration, combined with development of low-Mg calcite cements, accounts for the shift of core 97-3's mineralogy towards calcite with increased core depth (Figure 2).

The presence of cement averages 11.3% (mean) in the lower shallowing-upward sequence and 22.4% in the upper shallowing-upward sequence (Figure 6A), suggesting that early cement within the lower sequence has undergone dissolution and/or recrystallization to neospar. The outlier on Figure 6A at the intervening paleosol reflects the development of cement during extended meteoric exposure.

Secondary porosity has developed as a result of both fabric-selective and non-fabric-selective dissolution. Results of point counting suggest that porosity is relatively consistent (generally from 0 – 20%) within both shallowing-upward sequences (Figure 6B). However, these results were taken from point counts of thin sections from well-lithified samples within the lower sequence, whereas macroscopic inspection reveals that sediments from the lower

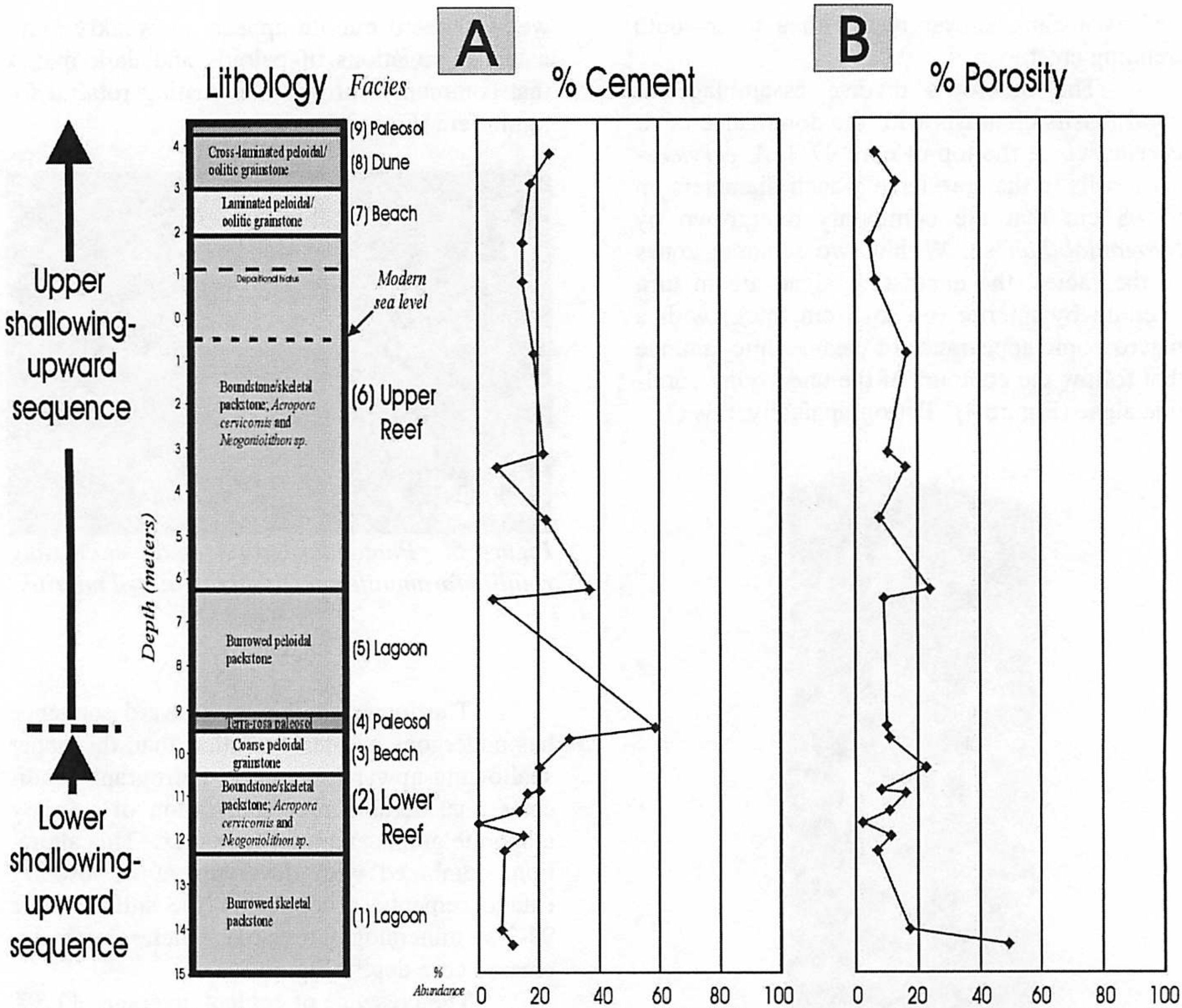


*Figure 6. Graphs of percent cement (A) and percent porosity (B) within core 97-3 and overlying facies.*

sequence are generally friable and rubbly as a result of extensive dissolution.

Lower Reef (Facies 2)

The reef sediments that comprise facies 2 have undergone significant diagenesis. Overall petrographic features of the facies include neomorphism, vug development, and cementation, with rare occurrence of multigenerational forms. The facies' abundant *Acropora cervicornis* fossils have been altered by various degrees of chalkification. Other diagenetic features of coral within the facies include voids lined by fine crystalline or blocky cement, acicular cement with parallel crystals infilling voids, and coral recrystallization to calcite (Figure 7A). Diagenetic features of coralline algae include neomorphism, vugs, fractures, and varying amounts and microtextures of cement.

Upper Reef (Facies 6)

The diagenetic components of facies 6 are dominated by fine crystalline cement. Whisker cement indicative of vadose zone diagenesis commonly occurs near the top of the facies. Primary pores contain rare complete infillings of acicular cement (Figure 7B). Other diagenetic features include an irregular distribution of vugs that contain a variety of cements, including linings of fine crystalline fabrics, lin-

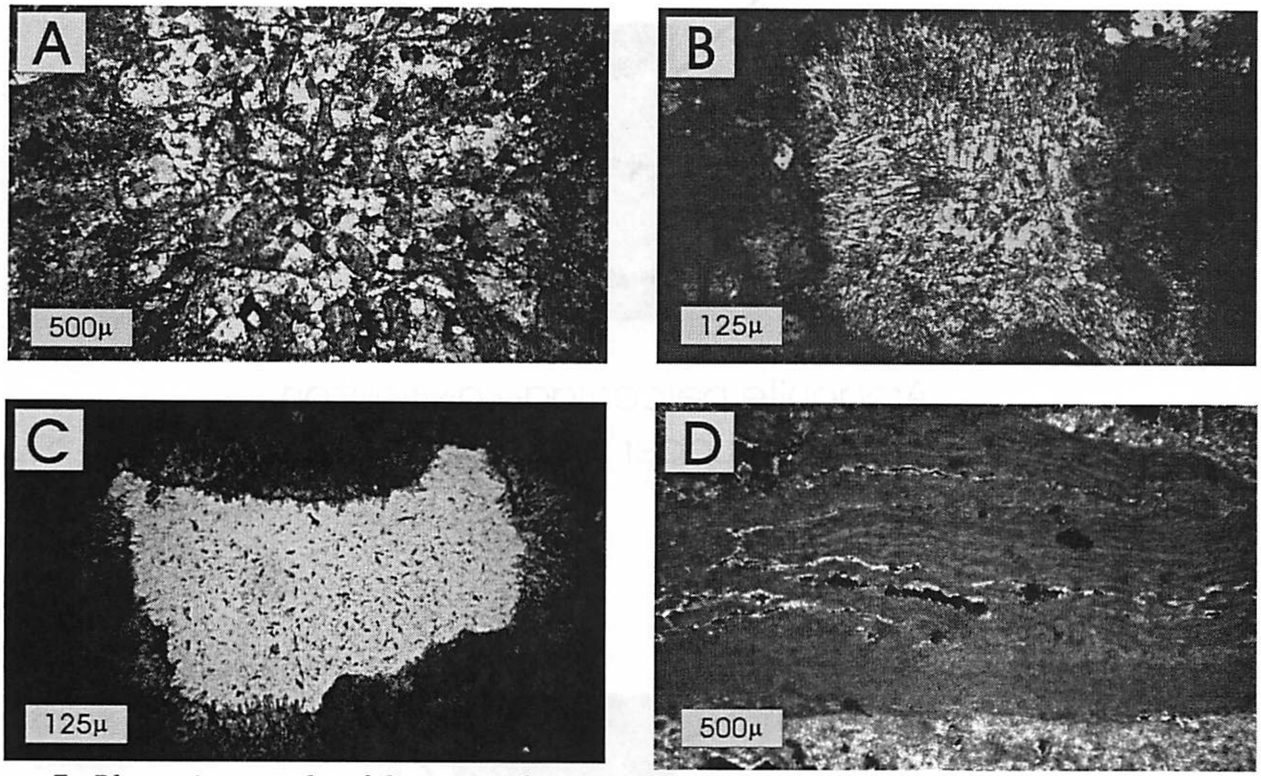


*Figure 7. Photomicrographs of diagenetic features within core 97-3's reef sediments. A) Recrystallized corallite. Note that the calcite crystals (light areas) do not cross-cut the coral septae (linear dark areas). This mosaic is diagnostic of coral alteration within vadose environments (Pingitore, 1976). B) Pore completely filled with acicular cement. C) Pore sparsely lined with acicular cement. D) Coralline algae containing vugs lined with fine crystalline cement (cross-polarized light).*

ings of acicular cement (Figure 7C), and complete infillings of bladed spar. Some areas of coralline algae contain linear voids that are both lined and completely filled with fine crystalline cement (Figure 7D). Peloidal sediments are commonly cemented by fine crystalline cement. Areas near the top of the facies contain fine crystalline cement with a meniscus fabric indicative of vadose conditions. Other examples of cement occurring at point contacts may be meniscus cement or the product of leaching of more extensive cement. Neomorphism occurs throughout the facies with mud having altered to microspar, and corals and molluscs having altered to neospar.

X-ray Diffractometry

This study's x-ray diffractometry analysis (Figure 8) was performed to bring greater resolution to Boardman and Carney's (1999) results (Figure 2). Because of the trend of increased alteration with core depth, samples from the upper reef were expected to contain more aragonite that those from the lower reef. Aragonite percentages for red algae and sand indeed show greater alteration in the lower reef that is consistent with expectations. However, the results for *Acropora cervicornis* were unexpected: the aragonite content within the center of *A. cervicornis* from the upper reef has been reduced to 87%, while the edge of the coral has maintained a high aragonite content (97%). This indicates that alteration within *A. cervicornis* does not always proceed inward from the margin. Within the sample from the lower reef, the center of *A. cervicornis* has maintained an aragonite content of 100% despite partial dissolution. The unexpectantly low result of 67% for the chalky edge of the coral likely reflected from sampling that incorporated high-Mg calcite from the adjacent red algae.

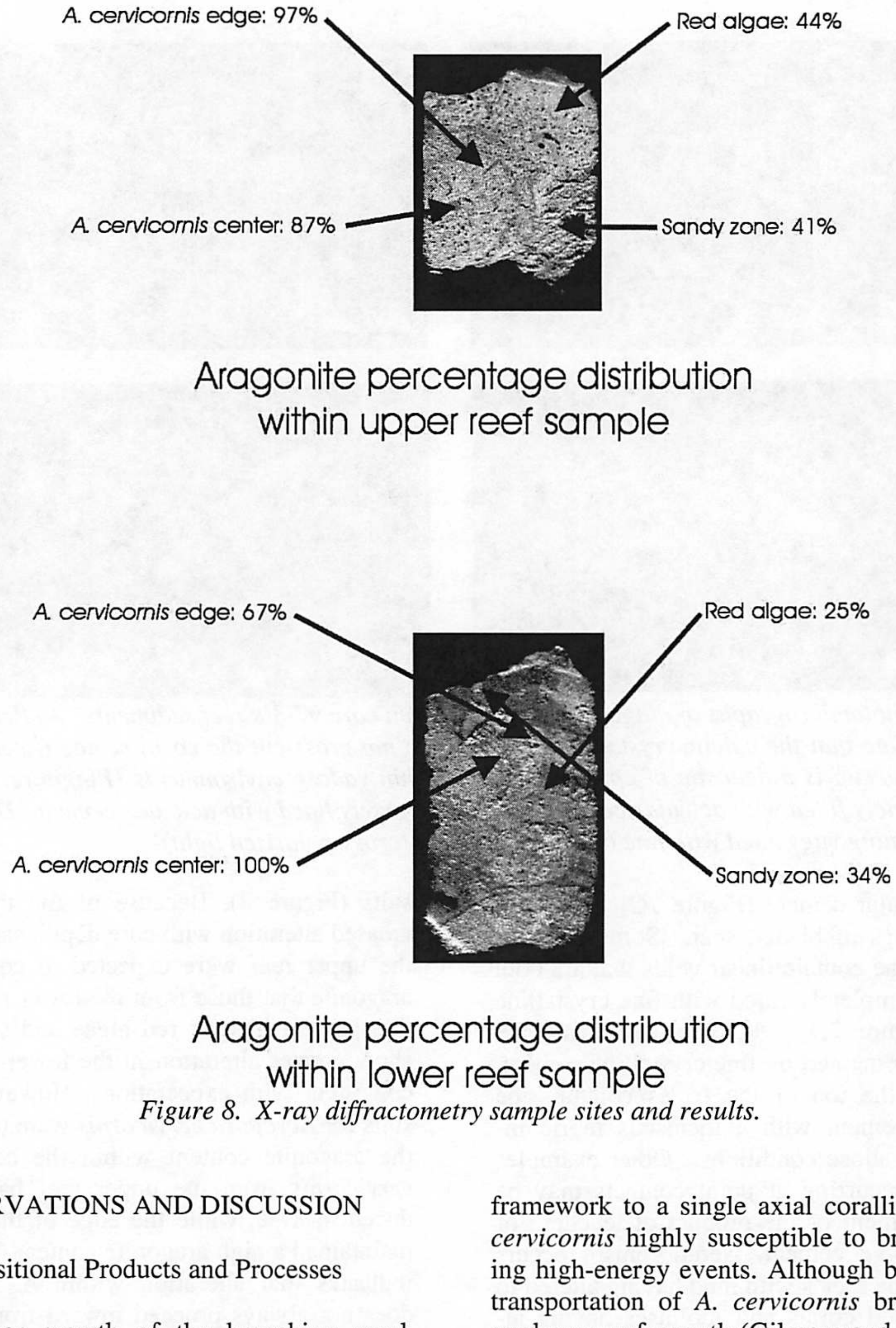


*Figure 8. X-ray diffractometry sample sites and results.*

## OBSERVATIONS AND DISCUSSION

### Depositional Products and Processes

Linear growth of the branching coral *Acropora cervicornis* ('staghorn coral') is perhaps the most rapid among all scleractinian corals (Gladfelter et al., 1978). This rapid growth is reflected in the high porosity within young branches that undergo subsequent infilling as they lengthen (Bucher et al., 1998). High skeletal porosity and limitation of the internal branch framework to a single axial corallite render *A. cervicornis* highly susceptible to breakage during high-energy events. Although breakage and transportation of *A. cervicornis* branches may seed new reef growth (Gilmore and Hall, 1976), such events are often fatal to the colony fragment (Greenstein and Moffat, 1996). Dead *A. cervicornis* branches can, however, provide suitable surfaces for encrustation by other organisms that commonly include coralline red algae (Jones and Hunter, 1991; Greenstein and Moffat, 1996; Humphrey, 1997).

The coralline alga *Neogoniolithon* sp. commonly grows well in shallow, moderate to high energy areas of pronounced light intensity (Adey and Macintyre, 1973; Hattin and Warren, 1989; Humphrey, 1997) typical of settings that facilitate *A. cervicornis* growth. The occurrence of *Neogoniolithon* sp. all around *A. cervicornis* branches within facies 2 and facies 6 suggests that algal encrustation occurred either on corals in upright growth position or on broken coral branches that underwent periodic movement on the sea floor.

Filamentous cyanobacteria may have influenced deposition of laminated peloidal mudstones ['microbialites' *sensu* Burne and Moore (1987)] that overlie the algae-encrusted corals in facies 6. One occurrence of the coral, coralline algae, microbialite sequence is within a <1 m-thick zone on the exposed portion of the Cockburn Town reef outcrop. Jones and Hunter (1991) described the sequence and attributed microbialite development to the trapping and binding of micrite by filamentous cyanobacteria in turbid, low-energy lagoonal waters. They further surmised that the coral, coralline algae, microbialite sequence resulted from a progressive drop in light and energy levels that accompanied regressive conditions during a sea-level fall.

A similar sequence also dominates the 2.4-m to 4.8-m depth range within core 97-3 (Figure 4). The top of this zone occurs approximately 3 meters below the outcrop examples. This position indicates that the deposition of this coral, coralline algae, microbialite sequence occurred during conditions of stable reef growth and sea-level highstand rather than regression.

Several features indicate that the microbialites within facies 6 accreted as well-indurated surfaces: (1) their domical to columnar geometries that would be unlikely to have formed and held their structural integrity as soft substrates, (2) the presence of foraminifera that exclusively encrust rigid surfaces (Perrin, 1994) and later became encapsulated within the microbialites (Figure 5), and (3) the presence of internal borings. Because *A. cervicornis* has a low sediment tolerance (Hubbard and Pocock, 1972; Kendall et al., 1985), its abundance throughout facies 6 suggests that the coral, coralline algae, microbialite sequence was deposited in an environment low in turbidity. Additionally, several microbialite features suggest an autochthonous sediment origin: (1) the paucity of grains of obvious allochthonous origin such as skeletal grains; (2) laminations that tightly follow the contours of the underlying encrusting algae and corals (settling of suspended mud would produce a smooth horizontal surface); and (3) peloids within the microbialites that have sizes, colors, and textures like those attributed to microbial mediation (e.g., Macintyre, 1985; Chafetz, 1986; Riding, 1991).

The peloids and micrite that comprise this study's microbialites therefore likely formed as autochthonous deposits via direct precipitation of calcium carbonate by cyanobacteria. Evidence that microbialites precipitated directly as well-lithified crusts indicates that the microbialites, and thus the entire coral, coralline algae, microbialite sequence, developed under the moderate to high energy and low turbidity conditions typical of reef environments.

*A. cervicornis* fossils having no apparent microbialite encrustations occur at the upper and lower limits of core 97-3's coral, coralline algae, microbialite zone. This constrained presence of microbialites within core 97-3 and the scarcity of microbialites on the exposed portions of the Cockburn Town reef suggest that microbialite formation on *A. cervicornis* branches is a rare event.

## Diagenetic Processes and Products

The variations in size and mineralogy of reef sediments, and their resultant differences in diagenetic susceptibilities, render this study's reef facies ideal for inferring the Cockburn Town area's diagenetic settings and sea-level history.

### Lower Reef (Facies 2)

Petrographic investigation reveals that facies 2 has undergone diagenesis in both marine and meteoric environments. Evidence of marine diagenesis occurs as trace quantities of aragonite and high-Mg calcite cements. Morphologies of these cements include fine crystalline, bladed, and radial fibrous high-Mg calcite, and acicular aragonite. Aragonite cement occurs in primary intraskeletal coral pores, and high-Mg calcite cements are present in both intragranular and intergranular pores.

The most visible effects of meteoric diagenesis include neomorphism, dissolution to varying extents, and precipitation of low-Mg calcite cement. Point counts of meteoric cement range up to 20.4% (Table 1). Meteoric cement morphologies include large blocky and fine crystalline forms with common overgrowths, drusy infillings, and overgrown bladed crystals.

Marine diagenesis. -- Evidence of early marine diagenesis occurs as aragonite and high-Mg calcite cements. Aragonite morphologies include acicular aggregates and radial fibrous textures, and high-Mg calcite occurs in microcrystalline and bladed forms. All are common marine phreatic cements (e.g., James et al., 1976; Longman, 1980; Marshall, 1983).

Acicular aragonite occurs as intraskeletal cement in primary coral pores. Macintyre (1977) observed that this cement forms within coral skeletal cavities during active coral growth. Microcrystalline high-Mg calcite also coats the walls of primary intraskeletal coral pores and is commonly overgrown by crystals of bladed spar. This morphology is similar to cements described by James et al. (1976) and Marshall (1983) and is attributed to early submarine cementation. Bladed crystal overgrowth may be due to continued growth on upper rhomb faces in micritic cements by high-Mg calcite (Longman, 1980; Pierson and Shinn, 1985).

Fine crystalline calcite also commonly occurs as first-generation cement coatings on skeletal grains and rarely as second-generation cements, overlying acicular aragonite, bladed spar, and equant spar.

Freshwater phreatic diagenesis. -- Meteoric diagenesis followed early marine diagenesis as indicated by common occurrences of blocky cement fabrics. Fine crystalline cement occurs as primary pore linings and is commonly overlain by sparry cement. Equant blocky cement is also present as large crystals. Meteoric alteration of facies 2 sediment is somewhat patchy, with preservation ranging from seemingly pristine corals to dissolution and neomorphic spar alteration. Much of this alteration occurred during residence of reef sediments in a freshwater phreatic environment at the margin of a meteoric lens underlying San Salvador.

Drusy cement is present in primary pores, and calcite spar with several generations of crystal growth occurs in other intergranular and intragranular voids. Bladed cement with overgrowths alongside larger crystals is also a possible indicator of freshwater phreatic diagenesis.

Vadose diagenesis. -- Subaerial exposure of facies 2 sediments occurred following final deposition of core 97-3's lower shallowing-upward sequence. Evidence of this vadose zone residence in facies 2 sediments occurs as the development of neomorphic fabrics (up to ~5%) and the dissolution of original microstructures (Longman, 1981).

Neomorphic fabrics occur in several types of facies 2 constituents. Micrite has neomorphosed to microspar and pseudospar. Neomorphism of aragonitic coral skeletons has replaced their original fabrics with calcite spar microtextures. Although the original skeletal microstructures are gone, coral skeleton outlines are clearly discernible against the surrounding matrix (Figure 7A). Pingitore (1976) demonstrated that such coral neomorphic features are indicative of vadose diagenesis, while corals altered under freshwater phreatic conditions develop a "cross-cutting" calcite fabric that extends into surrounding matrix.

Coralline algae thalli have neomorphosed into mosaics of fine calcite neospar. Some facies 2 neomorphosed sections appear to grade into sparry cement with crystal overgrowths. Vug development, indicative of vadose diagenesis (Longman, 1981), occurred via non-fabric-selective dissolution of facies 2 micrite, coralline algae, and corals. Absence of moldic porosity indicates that permeability, rather than allochem composition, controlled dissolution. Vugs contain varying extents and fabrics of cement, with a common occurrence of fine crystalline linings overlain by larger sparry cement.

Acropora cervicornis diagenesis. -- Young branches of *Acropora cervicornis* are highly porous. Branches undergo later infilling as the coral develops, producing significant variation in *A. cervicornis* skeletal porosity. Variation in primary porosity presumably renders *A. cervicornis* branches susceptible to wide degrees of alteration. Exposure to meteoric water is perhaps the primary control on *A. cervicornis* diagenesis because most of the scleractinian coral skeleton is composed of bundles of aragonite needles or fibers (e.g., James, 1974; Bathurst, 1975) that are unstable in meteoric water.

X-ray diffractometry revealed an aragonite percentage of 100% for *A. cervicornis* within core 97-3 piece 192 and 80% for *A. cervicornis* within core 97-3 piece 190, which is the apparent outlier at approximately 12 m depth (Figure 2). These high aragonite percentages reveal that, despite extensive physical alteration to a friable, chalky texture, *A. cervicornis* fossils within facies 2 have retained much of their original mineralogy. James (1974) demonstrated that this 'chalkification' of *A. cervicornis* arises from the partial meteoric dissolution of aragonitic skeletal fibers without subsequent precipitation of significant amounts of calcite. Such features indicate exposure to meteoric conditions of insufficient duration and intensity for total aragonite leaching and precipitation of calcite into a resultant mold. This condition is also shown by petrographic investigation of *A. cervicornis,* which reveals common remnant primary porosity. Additionally, the previously-described *A. cervicornis* fossils that have undergone recrystallization under vadose conditions further indicate that facies 2 was exposed to limited freshwater phreatic conditions, with most diagenesis occurring under vadose settings.

Neogoniolithon sp. diagenesis. -- Although coralline algae have undergone fracturing, patchy neomorphism, dissolution, and cementation, they have largely retained their microstructure, despite their primary high-Mg calcite mineralogy. Bathurst (1975) noted the seemingly paradoxical resistance of coralline algae to alteration and attributed it to wall structure, presence of organic sheaths, and crystal lattice stability.

Post-vadose freshwater phreatic diagenesis. -- Recognizable beach sediments do not overlie the intervening paleosol between core 97-3's two shallowing-upward sequences. This indicates that the rise in sea level following facies 2's subaerial exposure was relatively rapid. However, limited evidence suggests that facies 2 may have undergone brief post-vadose exposure to freshwater phreatic conditions. Neomorphic microspar and pseudospar is overlain by bladed cement, which in turn is overlain by large blocky crystals containing several zones of growth. If the neomorphic components of this sequence formed within vadose conditions as did neomorphism of *Acropora cervicornis*, then the overlying cements formed during the residence of facies 2 in a later freshwater phreatic setting. Other diagenetic features of facies 2 that may have developed in post-vadose freshwater phreatic conditions include vugs containing a variety of phreatic-derived cements. These cement fabrics include drusy infillings with central crystals containing several growth zones, and equant, blocky crystals that also commonly show zoned growth. These cements have occasionally developed amber coloration that may indicate the influence of overlying soils. Some crystals adjacent to these amber-colored cements show evidence of later solution that may have resulted from soil acidification of vadose fluids.

Upper Reef (Facies 6)

Alteration of facies 6 is not as extensive as that of other Pleistocene reefs exposed in tropical environments (e.g., James et al., 1976). Corals near the top of the facies have retained both their original aragonite mineralogy and fine morphological detail. This exceptional preservation, in part, reflects low mechanical disturbance likely resulting from a quick-burial episode before the regression at the end of the 5e highstand (White et al., 1984; Greenstein and Moffat, 1996).

The well-preserved features of facies 6 suggest limited exposure to freshwater phreatic conditions during regressive conditions after the 5e highstand, although sections of facies 6 have developed some features indicative of exposure to meteoric influences. Point-count results indicate a trace of marine cements and the presence of meteoric cement ranging from 6.3% to 37% (Table 1). Presence of a modern meteoric lens might have influenced the facies' increased alteration with depth.

Marine diagenesis. -- Early marine diagenesis is indicated by rare occurrences of bladed spar and acicular cement that range from sparse void coatings to complete infillings.

Freshwater phreatic diagenesis. -- Common occurrence of fine crystalline cement cementing peloids and lining voids reveals prior residence in freshwater phreatic conditions.

Vadose diagenesis. -- Diagenesis in vadose conditions is indicated by the development of vugs. Vadose cement fabrics include whisker cements, fine crystalline cement with meniscus fabrics, and other cement at grain point contacts, which may be either meniscus cement or the product of vadose leaching of previously precipitated freshwater phreatic cement.

Post-vadose freshwater phreatic diagenesis. -- Coralline algae contain linear vugs lined with fine crystalline cement. This cement may have precipitated within a freshwater phreatic environment following vug development under vadose conditions.

## HISTORY

The two shallowing-upward sequences described in this study represent two zones with separate depositional and diagenetic histories.

### Depositional History

The upper shallowing-upward sequence contains reef sediments that were deposited during the 5e interglacial highstand. The upper sequence is separated from the lower sequence by a well-developed paleosol; therefore, deposition of core 97-3's lower shallowing-upward sequence occurred during a pre-5e sea-level highstand. Sea-level fall then resulted in the formation of the intervening paleosol. Deposition resumed at the core site as the upper shallowing-upward sequence formed during the 5e highstand. Following the close of the 5e highstand, sea-level fall resulted in the development of the paleosol that overlies the upper sequence. The modern sea-level highstand has not been of sufficient elevation for renewed sedimentation at the Cockburn Town reef.

### Diagenetic History

#### Lower reef

During a pre-5e sea-level highstand, marine phreatic diagenesis of the lower reef occurred penecontemporaneous to deposition. Regressive conditions then resulted in further diagenesis of the lower reef sediments, initially while in a relatively brief freshwater phreatic setting, then during extended residence in the freshwater vadose zone. The paleosol that intervenes the two shallowing-upward sequences also developed during this vadose exposure. With sea-level rise at the onset of the 5e highstand, the lower reef sediments likely underwent a brief period of renewed freshwater phreatic diagenesis. Following immersion in the 5e highstand's marine phreatic environment, little or no diagenesis would have occurred within the lower reef due to sediment burial and stagnant pore waters. With post-5e sea-level fall, renewed freshwater phreatic diagenesis occurred within the lower reef, followed by diagenesis during extended residence under freshwater vadose conditions. Modern sea-level rise would have resulted in brief exposure to freshwater phreatic conditions, followed by the current residence of the lower reef under marine phreatic conditions. The lower reef facies presently resides under relative inactive marine phreatic conditions and is undergoing no appreciable diagenesis.

The complex diagenetic history of core 97-3's lower shallowing-upward sequence therefore includes multiple residences under freshwater phreatic conditions that have resulted in significant alteration of the reef facies.

Upper reef

During the 5e sea-level highstand, marine diagenesis of the upper reef began immediately after deposition. During sea-level fall at the end of the 5e interglacial, the facies underwent freshwater phreatic diagenesis, followed by diagenesis during extended residence under freshwater vadose conditions. The modern sea-level highstand has resulted in diagenesis under freshwater phreatic conditions for most of the upper shallowing-upward sequence except for the uppermost 5 meters of the sequence. This section includes the upper portion of the reef facies and the entire beach and eolian dune facies which, following their deposition, have always resided under vadose conditions. Presently, the upper shallowing-upward sequence resides under marine phreatic conditions except for the upper 2 meters of the reef facies and the overlying beach and eolian dune facies.

The history of the upper shallowing-upward sequence indicates that the majority of diagenesis in the upper reef has occurred during vadose exposure.

## ACKNOWLEDGEMENTS

We would like to thank Dr. Donald T. Gerace, Chief Executive Officer, and Vincent Voegeli, Executive Director of the Gerace Research Center, San Salvador, Bahamas, for an enjoyable and well-organized conference, the staff of the Gerace Research Center for their kindness and hospitality, and Drs. Ron Lewis and Bruce Panuska for their encouragement and dedicated work in chairing the 11th Symposium. We also thank Ruth Jewell and Jaime Kostelnik for assistance in collecting this study's x-ray diffractometry data. This research is part of David Schmidt's MS thesis at Wright State University and was performed with logistical support from the Gerace Research Center and partial financial support from the Wright State University Department of Geological Sciences.

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