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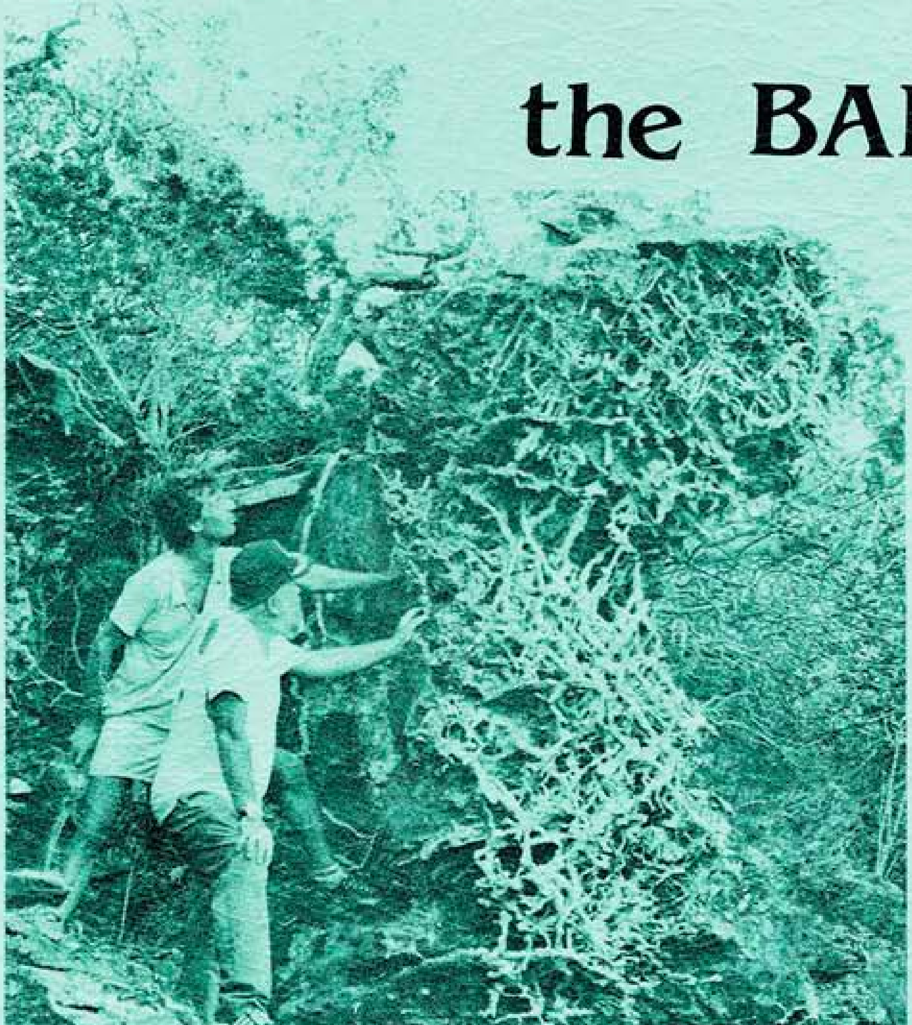

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A SHALLOWING-UPWARD SEQUENCE IN A PLEISTOCENE CORAL REEF AND ASSOCIATED FACIES, SAN SALVADOR, BAHAMAS

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Abstract

The Sangamon-age Cockburn Town fossil coral reef complex displays a vertical sequence of facies from coral reef and closely associated subtidal carbonate sands, through beach calcarenites, to eolianites. This upward change reflects a progressive lowering of sea level and the eventual emergence of the reef complex into a subaerial environment. The contact between upper beach sediments and eolianites is at +4 m providing a minimum for the sea level high stand. Essentially in situ Acropora palmata suggests a sea level of at least 5 to 6 m above present. These values are similar to Sangamon-age high stands reported from New Providence, the northern Bahamas, and Bermuda.

Northerly flowing longshore currents deposited trough cross-bedded carbonate sands around and over coral heads, and this implies the existence of ancient San Salvador during development of the coral reef complex. Land lying to the east of the reef also is indicated by westerly dipping beach bedding. A large-scale, westerly dipping, tabular cross-bedded set of calcarenite records the effects on the Cockburn Town fossil reef of a major storm or hurricane.

The diagenetic sequence from submarine aragonite to freshwater vadose low-Mg calcite cements reflects the emergence of the reef complex and shows no evidence of subsequent immersion in marine waters. The sparsity of phreatic freshwater diagenetic effects may be due to a post-Sangamon rapid fall in sea level similar to that recorded for the same time on Bermuda. Calichification of all the facies of the reef complex and the development of rhizocretions resulted from extensive subaerial exposure and the growth of a vegetative cover respectively.

Introduction

Excellent exposures of a Pleistocene coral reef occur along a 650 m stretch of the western coast of San Salvador in the

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vicinity of Cockburn Town. A map and geologic profiles of the fossil reef are included in Curran and White (A Field Guide to the Cockburn Town Fossil Coral Reef, this volume).

Adams (1983) mentioned the fossil reef in his general account of the geology of San Salvador, and Moshier et al. (1979) provided an abstract of preliminary analyses of the corals and facies of the reef. Studies of trace fossils found in calcarenites associated with the reef were reported by Curran (1983, 1984). Amino acid racemization dating of *Chione cancellata* and *Acropora cervicornis* from the reef gave ages of 120,000 to 140,000 years and 75,000 to 130,000 years respectively (Carew, 1983). The fossil corals and associated facies form a single shallowing-upward sequence produced during a progressive lowering of sea level (White et al., 1984). San Salvador is either tectonically stable or subsiding slowly, perhaps at approximately the 3 m per 125,000 years found on Andros Island (Garrett and Gould, 1984). In either case, the presence of *in situ* fossil corals up to 2 m above present mean sea level implies a higher stand of sea level that correlates with the well-known Sangamon interglacial sea level rise of 125,000 years ago.

The excellent exposures of the well-preserved fossil coral reef and associated facies (Curran and White, this volume) provide an unusual opportunity for a detailed study of a Pleistocene reef, which will add significantly to our knowledge of the geology of San Salvador and the Bahamas. In the immediate vicinity of the Cockburn Town fossil reef there are precisely surveyed bench marks, related to accurately measured mean sea level (Adams, 1983). These provide a convenient datum plane for topographic surveying and comparison of former sea level elevations, which could serve as a standard for San Salvador and neighboring Bahamian islands.

The Shallowing-Upward Sequence

Field observations at the reef site clearly show an upward sequence of lithologies ranging from *in situ* fossil corals through shallow subtidal and beach calcarenites to eolianites. Lateral interfingering of subtidal coral rubblestone and calcarenites with adjacent coralstone on one hand and beach deposits on the other demonstrates contemporaneous development of different facies. Nevertheless, the overall vertical sequence can only be explained as having been deposited during a progressive lowering of sea level, accepting that there is no evidence for vertical uplift of the area. These lithologic relationships are illustrated by the profiles in Curran and White, Figs. 1, 2, 4, 5, and 7 (this volume).

Fine examples of *in situ* corals (Curran and White, Figs. 3a-c, and 8d, this volume) occur in the fossil reef up to 2 m above present mean sea level (MSL). *Acropora palmata* essentially in growth position, although perhaps collapsed, is found up to +2 m (Curran and White, Fig. 6c, 8b, this volume). Comparison with modern *A. palmata* growing on the shelf around San Salvador suggests a minimum sea level of +5 to 6 m at the time of growth. Coral rubblestone commonly occurs adjacent to and partly overlying the coralstone (Curran and White, Fig. 6a, this volume).

In many cases coral rubblestones, and in some places coralstones, are flanked and overlain by medium to coarse, commonly shelly, calcarenites with abundant trough cross-bedding. Some of these calcarenites occur as channel fill sediments (Curran and White, Fig. 8a, this volume) and in general were deposited as small sinuous crested dunes by northerly flowing currents. Trace fossils including Ophiomorpha sp., believed to be produced by the burrowing activities of callianassids, are well preserved in some of the calcarenites (Curran, 1983, 1984; Curran and White, Figs. 2, 3d, this volume). Comparison with modern Callianassa sp. burrows from the shelf sands around San Salvador indicates minimum water depth of 1 m during the formation of Ophiomorpha sp., and an entirely subtidal environment. Interbedded with the trough cross-bedded calcarenites there is at least one set of steeply dipping tabular cross-beds up to 1 m thick in places (Curran and White, Figs. 6b, 7, and 8c, this volume). The tabular cross-beds dip in a westerly direction essentially perpendicular to the currents that produced the trough cross-beds which surround them, and they were deposited by a single sedimentation event. The trough cross-bedded calcarenites were deposited by northerly flowing, perhaps longshore, currents that appear to have been the normal ongoing sand-transporting mechanism in this area. This system was interrupted by a large-scale storm event, perhaps a hurricane, that deposited the high angle tabular cross-bedded sands; perhaps by overwash of an emergent sand shoal or by currents reflected off a more substanial island (ancient San Salvador). The northerly flowing currents may have been produced by wave refraction around the south end of the island. Wave refraction also may have created the high energy conditions indicated by the presence of A. palmata in the fossil reef, whch was located on the leeward side of the postulated island.

Calcarenites with westerly dipping, low angle cross-beds and associated beachrock clast breccias progressively overstep the subtidal calcarenites. These are the deposits of a westerly facing and westward migrating beach, suggesting a contemporaneous emergent sand shoal or island to the east. The beach facies passes upward into fine-grained eolianites with abundant rhizocretions, clearly demonstrating the existence of a vegetated dune system on an ancient island. The upper beach-eolianite contact is at +4 m, indicating a maximum sea level height at this time and also providing a minimum of +4 m for the sea level high stand during the development of the Cockburn Town fossil reef. Cutting through all facies of the reef are numerous caliche dikes, which formed after emergence of the entire reef complex.

Rock and Grain Types

The overwhelming majority of the calcarenites found in the reef complex are oosparites with some further classification to bio-oosparites, peloosparites, and intraoosparites where fossil fragments, peloids, and intraclasts are important grain components respectively. Coralstones are biolithites;

biosparites and biomicrites form the matrix of some coral rubblestones.

Floral grains include green calcareous algae, mainly Halimeda, and fewer red calcareous algae, mostly Goniolithon. Faunal types include Foraminifera, especially milioloids but also some textularids and rotalines; gastropod, bivalve, and coral fragments; echinoderm plates; tunicate spicules; and rare bryozoans. Non-skeletal grains include intraclasts, ooids, superficial ooids, peloids, and pellets. Of particular interest is the presence of Favreina (Fig. 13), fecal pellets produced by Callianassa sp., the same animal believed to have produced the Ophiomorpha sp. trace fossils found in some subtidal calcarenites. Thus, two lines of evidence converge to show the existence of Callianassa sp. in sands adjacent to the reef.

Diagenesis

Submarine aragonite cements occur *in situ* only in coralstones and coral rubblestones below +2.5 m. Intragranular acicular aragonite occurs within Halimeda plates, benthic foraminifers, Favreina, gastropods (Fig. 1), and coral corallites (Figs. 2-4). Aragonite also occurs as dense isopachous rims around grains in oomicrites from the matrix of coral rubblestone.

Freshwater vadose cements post-date the submarine aragonite in rocks below +2.5 m and were the first cements to form in the shallow subtidal, beach, and dunal calcarenites above this elevation. Meniscus low-Mg calcite, as determined by electron microprobe analyses, occurs commonly (Fig. 5) and in many cases displays a characteristic pore rounding (Figs. 6, 7), first described by Dunham (1971). Equant calcite occurs as partial, irregular to sometimes isopachous crusts around grains, with considerable variability seen within single thin sections. The unevenness of this cementation is emphasized by grain size differences, with finer-grained sediments being better cemented than coarser ones. Calcite also occurs within intragranular pores and follows acicular aragonite where the earlier submarine cement is present (Figs. 1, 4). Calcite syntaxial overgrowths occur around echinoderm plates in some of the more completely cemented sparites (Fig. 8).

Alveolar texture, a ramifying network of dense micrite, occurs in intergranular pore space (Fig. 9) where it postdates the meniscus calcite, and within coral pore space. The irregular pore space created by the interconnecting walls of micrite contains whisker calcite (Fig. 10), and whisker calcite and microsparite (Fig. 11). Associated with the alveolar texture are *Microcodium* (Fig. 12) and abundant rhizocretions.

Although many corals retain their original aragonitic composition, some show partial neomorphic replacement by calcite (Fig. 14), as do some mollusk shell fragments.

In rare instances there is a later calcite spar that postdates the whisker calcite and microsparite in the alveolar texture pore space and the earlier vadose meniscus calcite (Fig. 7).

Diagenesis and Sea Level Change

Clearly the Cockburn Town coral reef grew under marine conditions, thus it is not surprising to find submarine syntaxial aragonite cement in coral corallites. Similarly, well developed isopachous aragonite on matrix grains in coral rubblestone indicates extended exposure to marine waters. Post-aragonite freshwater vadose cementation demonstrates the subsequent change of environment of the corals and associated coral rubble to non-marine conditions. The absence of well developed freshwater phreatic cements suggests that the change from marine to non-marine conditions was rapid, and occurred without the development of a long-lived freshwater phreatic lens. A very rapid fall in sea level under stable tectonic conditions on Bermuda following the Sangamon interglacial is indicated by Harmon et al. (1983). Presumably sea level fell as rapidly elsewhere, including San Salvador.

Above +2.5 m no submarine cements have been found, and the first cements are vadose meniscus and equant low-Mg calcite. The presence of some isopachous calcite rims and syntaxial overgrowths around echinoderm plates indicates phreatic-like conditions; however, these are very patchy and suggest scattered saturated sediment lens within the freshwater vadose zone. Such conditions are best developed in finer-grained sediments where lower permeability might be expected to increase the chances of local saturation.

Prolonged subaerial exposure of the reef complex caused calichification most similar to that found in irregular

Figure 1: Acicular aragonite cement on interior of a gastropod shell. Remaining intragranular pore space filled by coarse calcite spar.

Bar scale = 100 micrometers

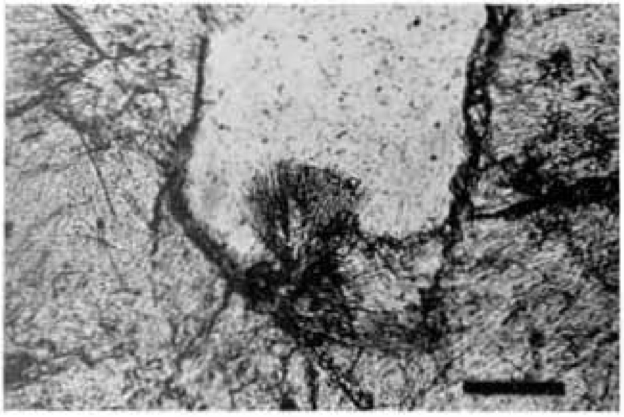


Figure 2: Acicular aragonite growing within a coral corallite.

Bar scale = 100 micrometers

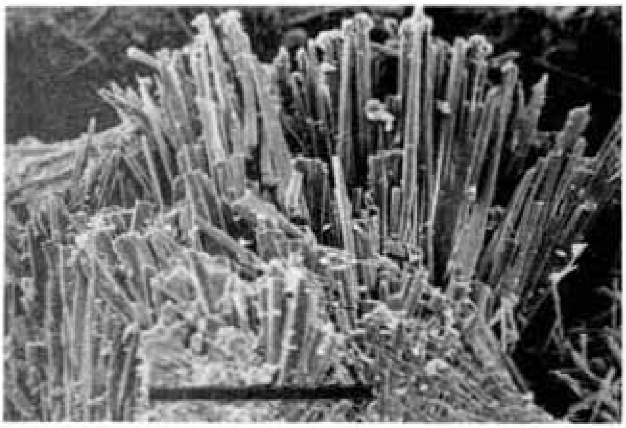


Figure 3: SEM photograph of aragonite growing within a coral corallite.

Bar scale = 100 micrometers

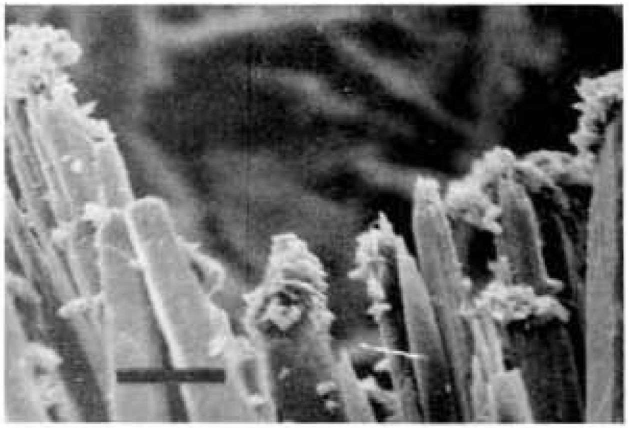


Figure 4: Higher magnification SEM photograph of Fig. 3. Calcite crystals growing on sharp terminations of aragonite.

Bar scale = 10 micrometers

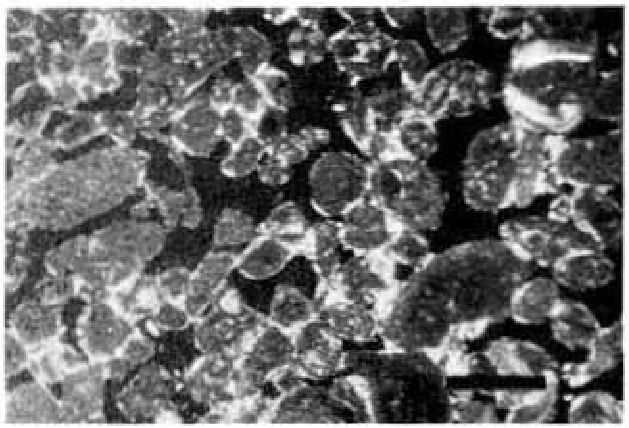


Figure 5: Meniscus calcite cement at grain contacts.

Bar scale = 500 micrometers

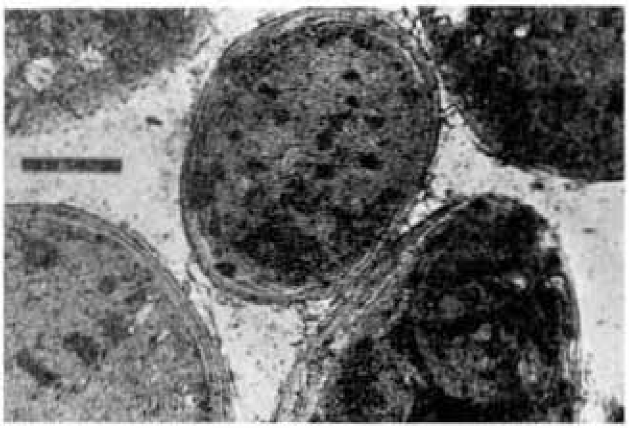


Figure 6: Meniscus calcite cement with pore-rounding which reflects shape of air-water interface at time of precipitation

Bar scale = 100 micrometers

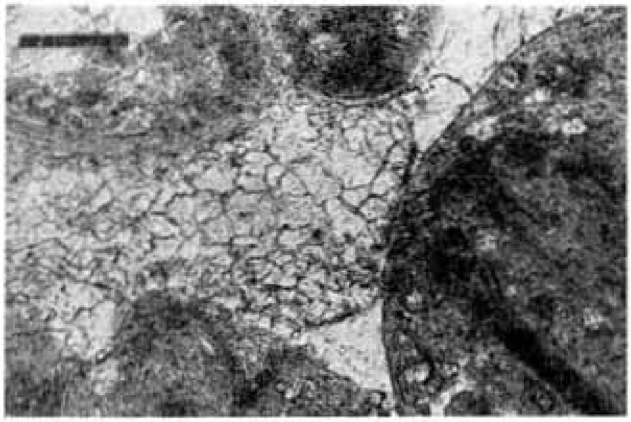


Figure 7: Meniscus calcite cement with pore-rounding separated from later, finer calcite cement by thin layer of micrite.

Bar scale = 100 micrometers

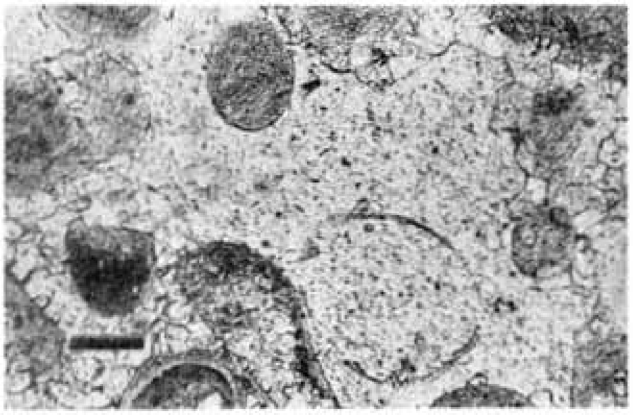


Figure 8: Syntaxial overgrowth around echinoderm extends to engulf nearby grains.

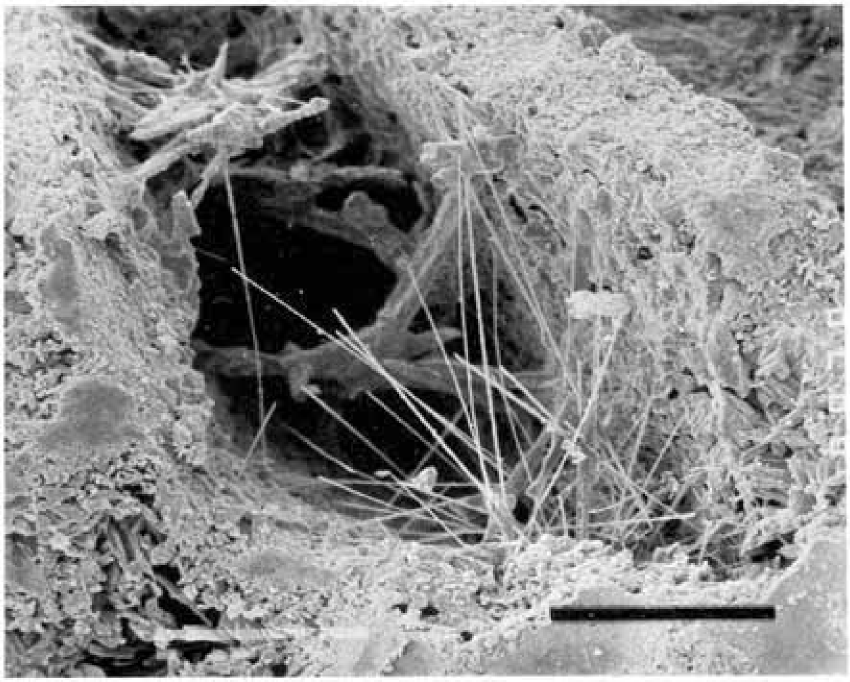
Bar scale = 200 micrometers

Figure 9: Alveolar texture in intergranular pore space.

Bar scale = 200 micrometers

Figure 10: SEM photograph of whisker calcite within the pore space of alveolar texture.

Bar scale = 100 micrometers



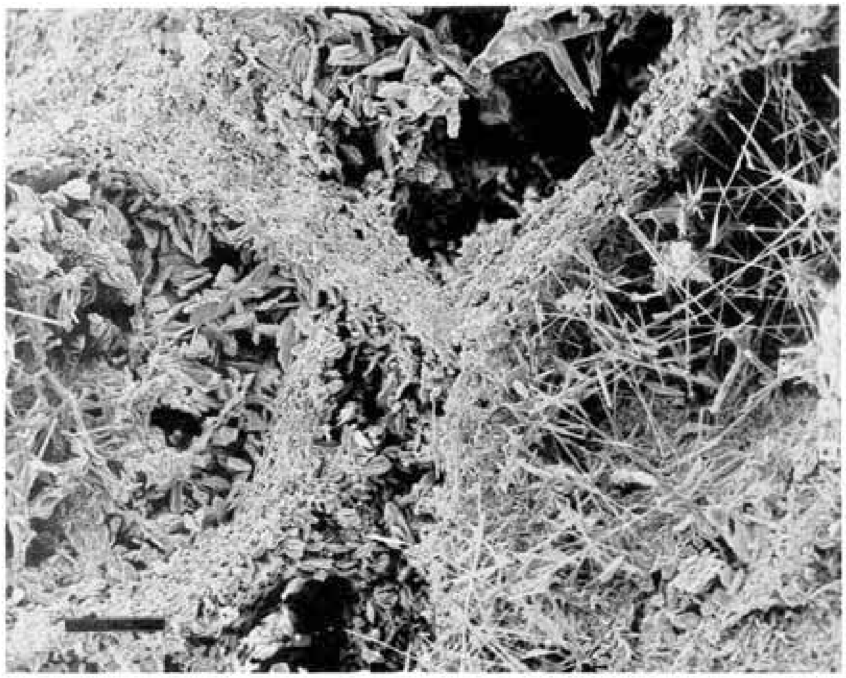


Figure 11: SEM photograph of whisker calcite and microsparite within pore space of alveolar texture.

Bar scale = 100 micrometers

Figure 12: Microcodium with ring of petal-shaped calcite prisms.

Bar scale = 200 micrometers

Figure 13: Favreina - fecal pellet of Callianassa sp.

Bar scale = 200 micrometers

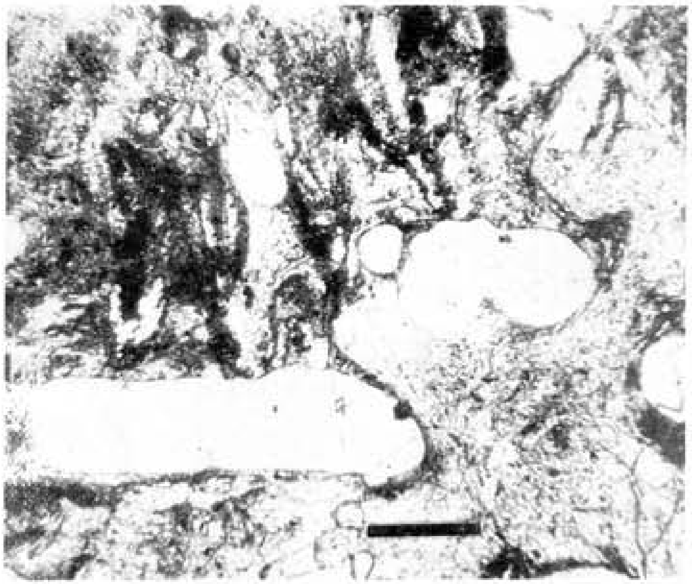


Figure 14: Replacement of aragonitic coral by neomorphic equant calcite

Bar scale = 200 micrometers

unlaminated alteration zones described from Barbados by Harrison (1977), and from Florida by Conglio and Harrison (1983). Observed microscopic features characteristic for this zone include: alveolar texture, whisker calcite, microsparite, and Microcodium. All facies of the reef complex contain these features, confirming the fall in sea level indicated by other field and petrographic evidence.

There are no marine cements that postdate the freshwater vadose cements or calichification textures, suggesting that there has been no marine inundation of the rocks of the Cockburn Town reef since the end of the Sangamon interglacial. The scant evidence of a late-stage equant calcite cement that post-dates the alveolor textures raises the interesting possibility of a later freshwater phreatic event. This could be accomplished by a sea level rise of perhaps 1 m or so above present that raised a phreatic lens, or by significantly increased rainfall. Future work will explore this possiblity in more detail.

Conclusions

1. The vertical distribution of lithologies, fossils, trace fossils, sedimentary structures, and cement types is consistent with a progressive shallowing of sea water and eventual emergence of the Cockburn Town fossil reef and associated facies.

2. The upper beach-eolianite contact at +4 m provides a minimum sea level for the development of the reef complex.

Essentially *in situ* *Acropora palmata* suggests a sea level at least 5 to 6 m above present.

3. Assuming subsidence of 3 m in the 125,000 post-Sangamon years, sea level stood at least some 8 to 9 m above present levels during the growth of the reef. Similar sea level high stands for the Sangamon interglacial are reported from many locations, including New Providence (Garrett and Gould, 1984), the northern Bahamas (Neumann and Moore, 1975), and Bermuda (Harmon et al., 1983).

4. Transportation of subtidal sands by northerly flowing longshore currents implies the existence of proto-San Salvador Island with wave refraction around its south end. Beach bedding dips westerly implying land, or at least an emergent sand shoal, to the east of the reef.

5. The growth of *Acropora palmata* in the reef shows greater wave activity at the location 125,000 years ago than occurs immediately offshore now. This may have been caused by strong wave refraction around the south end of proto-San Salvador.

6. The large-scale tabular cross-bedded set indicates that at least one major storm or hurricane is recorded in the sedimentary deposits of the reef complex.

7. The diagenetic sequence shows that there has been no second immersion in marine pore waters; however, a sea level rise of 1 to 2 m above present could be accommodated. Some scarce evidence of late-stage calcite spar cement could represent such a post-Sangamon high stand, or, alternatively, could have been caused by increased rainfall.

8. The sparsity of freshwater phreatic diagenetic effects may reflect a rapid post-Sangamon sea level fall of the same order as that reported from Bermuda by Harmon et al. (1983).

9. Extensive subaerial exposure and vegetative cover led to calichification of the rocks and the development of rhizocretions.

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REFERENCES

Adams, R. W., 1983, General guide to the geological features of San Salvador in Gerace, D. T. (ed.), Field Guide to the Geology of San Salvador (Third Edition): San Salvador, Bahamas, CCFL Bahamian Field Station, p. 1-66.

Carew, J. L., 1983, Geochronology of San Salvador in Gerace, D. T. (ed.), Field Guide to the Geology of San Salvador (Third Edition): San Salvador, Bahamas, CCFL Bahamian Field Station, p. 160-172.

Conglio, M. and Harrision, R. S., 1983, Holocene and Pleistocene caliche from Big Pine Key, Florida: Canadian Petroleum Geology Bulletin, v. 31, p. 3-13.

Curran, H. A., 1983, Guide to trace fossils in the Pleistocene carbonate rocks of San Salvador, Bahamas in Gerace, D. T. (ed.), Field Guide to the Geology of San Salvador (Third Edition): San Salvador, Bahamas, CCFL Bahamian Field Station, p. 146-159.

Curran, H. A., 1984, Ichnology of Pleistocene carbonates of San Salvador, Bahamas: Journal of Paleontology, v. 58, p. 312-321.

Curran, H. A. and White, B., 1984, Field Guide to the Cockburn Town Fossil Coral Reef: this volume.

Dunham, R. J., 1971, Meniscus cements in Bricker, O. P. (ed.), Carbonate Cements: Johns Hopkins University Studies in Geology, no. 19, p. 297-300.

Garrett, P. and Gould, S. J., 1984, Geology of New Providence Island, Bahamas: Geological Society of America Bulletin, v. 95, p. 209-220.

Harmon, R. S., Mitterer, R. M., Kriausakul, N., Land, L. S., Schwarcz, H. P., Garrett, P., Larson, G. J., Vacher, H. L., and Rowe, M., 1983, U-series and amino-acid racemization geochronology of Bermuda: Implications for eustatic sea-level fluctuation over the past 250,000 years: Paleogeography, Paleoclimatology, Paleoecology, v. 44, p. 41-70.

Harrison, R. G., 1977, Caliche profiles: Indicators of near-surface subaerial diagenesis, Barbados, West Indies: Canadian Petroleum Geology Bulletin, v. 25, p. 123-173.

Moshier, S. O., Cassa, M. R., Dunn, M. J., Dhiold, J., Kissling, D. L., Polasek, J. F., and Warzeski, E. R., 1979, Stratigraphy and facies of a Pleistocene fringing reef at Cockburn Town, San Salvador: Geological Society of America Abstracts with programs, v. 11, p. 206.

Neumann, A. C. and Moore, W. S., 1975, Sea level events and Pleistocene coral ages in the Northern Bahamas: Quaternary Research, v. 5, p. 215-224.

White, B., Kurkjy, K. A., Curran, H. A., and Besom, K. A., 1984, A shallowing-upward sequence in a Pleistocene coral reef and associated facies, San Salvador, Bahamas: American Association of Petroleum Geologists Bulletin, v. 68, p. 539.