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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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FORAMINIFERAL ASSEMBLAGES AND REEF-SEDIMENT PETROGRAPHIC CRITERIA AS EVIDENCE FOR RELATIVE DISTANCE FROM SHORE FOR PLEISTOCENE REEFS, SAN SALVADOR, BAHAMAS: PRELIMINARY RESULTS

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ABSTRACT

Pleistocene reefs in the Bahamas are recognized by the abundance of *in situ* coral heads and coarse coral debris. Determination of fossil reef type with regard to location on the shelf is usually based primarily on dominant coral taxa and reef geometry. In this study, modern reef sediment samples including foraminiferal death assemblages are examined in an attempt to provide an actualistic model against which such fossil reefs may be evaluated.

Key foraminiferal taxa in shallow water are soritids such as *Archaias angulatus* and the attached rotaliine *Homotrema rubrum*, which is most abundant at Gaulins Reef on the windward side of the island. Deeper water faunas (not previously studied on San Salvador) are diverse but include *Amphistegina* and several genera of textulariines. Grain aggregates are common in lagoonal settings including patch reefs, and polished grains are abundant locally in these settings. The combination of characteristics found in the sediment at the Cockburn Town fossil reef is most compatible with those found in patch reefs, but the reef could also have been a relatively low-energy bank barrier reef not separated very far from lagoonal grass beds, as might be expected on the western side of the island.

INTRODUCTION

Pleistocene (Sangamonian) reefs on San Salvador, Bahamas, such as the Cockburn Town and Sue Point fossil reefs, are recognized by the abundance of *in situ* coral heads and coarse coral debris. The fossil reefs occur in shallowing-upward sequences, typically consisting of the fol-

lowing facies: lagoon, reef, shallow subtidal, storm, beach, and eolianite (White et al, 1984; Schmidt et al., 2004). Determination of reef type in terms of position on the shelf and geometry (e.g., patch reef vs bank barrier reef) is not self evident for fossil reefs. Such determinations have been made based on dominant coral taxa, reef geometry, and stratigraphic sequence. However, coral taxa are not always diagnostic for a given reef type, facies geometry is often not well known for fossil reefs, and stratigraphic successions are not necessarily simply progradational. Another approach in the study of fossil reefs is the analysis of reef sediment including its foraminifera.

Investigations of live benthic foraminiferal populations (e.g., Martin, 1986; Hallock and Peebles, 1993) as well as studies of death assemblages (e.g., Liddell et al., 1987; Martin, 1988; Martin and Liddell, 1988) have allowed broad zones (biofacies) to be recognized in spite of post-mortem transport and the persistence of robust tests such as those of *Archaias angulatus* (Martin, 1986). In general, miliolines, especially the penetroplids and soritids (including *Archaias*), dominate in back-reef lagoons, whereas rotaliines such as *Amphistegina* and *Planorbulina* are more common in the fore-reef slope (Martin, 1988). These broad zones have been further refined by Hallock and Glenn (1986) and applied to the interpretation of ancient depositional facies.

The foraminifera of the outer Bahamian islands are not well known (Culver and Buzas, 1982; Hart, 1986). On San Salvador, taphonomic studies have been carried out on selected species by Peebles and Lewis (1988, 1991). Distributional studies of San Salvador foraminifera are limited to the interior lakes (Bowman, 1982; Bowman and Teeter, 1982; Diaz and Fluegeman, 1993) and to

near-shore, marine environments. Haynes (1991) studied foraminiferal death assemblages in a 40 x 75 m area off Dump Reef, and Beck (1991) examined a 48 x 50 m area in Graham's Harbor at Cut Cay. In both of these studies, assemblages were influenced by habitat (substrate type), even though the areas studied were small and near shore. In contrast, Geissler et al. (2000) found the foraminiferal tests in Rice Bay (to a distance of 155 m from shore) to be essentially homogeneous as a result of sediment redistribution despite the presence of sand flats, sea-grass beds, and reefs along the transects studied. San Salvador's mid- to outer-shelf foraminifera have not been previously discussed.

The present study makes use of sea-floor sediment samples taken at reefs and other environments from near shore to shelf edge in an attempt to propose a model that may be useful in interpreting fossil reefs. Unlike in many prior studies, fragments are included as well as whole tests, and agglutinated foraminifera and those cemented to a hard substrate (e.g., *Homotrema*) play an important role. Because of the small number of samples used and the relatively small number of reefs studied, the results are preliminary.

OBJECTIVES AND METHODS

The objectives of this study were (1) to examine the sea-floor sediment and its death assemblage of large benthic foraminifera at each of the primary reef types found at San Salvador, (2) to identify useful criteria for distinguishing among these reef types based on these properties, and (3) to test the actualistic model obtained by applying it to sediment from the Pleistocene Cockburn Town Reef in a preliminary attempt to determine its relative distance from shore and water depth. The four reef types as defined for purposes of this study are illustrated in Figure 1; the major reefs examined are shown in Figure 2.

Sea-floor sediment was collected by SCUBA divers using one-pint, plastic containers. Most samples were taken during 2000-2001, but some samples from prior studies were also used due to availability and to provide historical perspective. Former sea-floor samples include some

taken in Grahams Harbor for echinoid remains; exact locations and water depths are given in Schein and Lewis (2001). A few additional samples were taken from Cockburn Town reef and added to those collected in past years.

Sediment samples were dry sieved at half-phi intervals and the 0 phi interval (1.00 to 1.41 mm) was used for petrographic and foraminiferal analysis. Consequently, some elongate foraminifera (e.g., *Clavulina*) may have escaped this preliminary analysis. One hundred grains were counted and used as an estimate of percent of polished grains, aggregate grains, and other distinctive grain types. Approximately 100 or more foraminifera were picked and identified to genus using standard references, primarily the Treatise on Invertebrate Paleontology (Loeblich et al., 1964) and Loeblich and Tappan (1988). Reference was also made to taxa reported in previous Caribbean studies. The taphonomic condition of each specimen was recorded in one of four categories: pristine (fresh test, similar to that of living individuals), slightly altered (e.g., only a few chambers broken), altered, and greatly altered (including fragments). Additional notes included the presence or absence of original color and the mode of taphonomic alteration. Rare taxa, those representing only a few percent of one or two samples, were not included in the final analysis.

FORAMINIFERAL TAXA

As no general guide is available to the foraminiferal taxa of San Salvador or any of the outer Bahamian islands, a brief description is given below for each of the principal taxa found. Technical terms are kept to a minimum for the benefit of nonspecialists, and features discussed are those seen using a low-power light microscope and in thin sections.

Suborder Textulariina

The principal agglutinated foraminifera of the Suborder Textulariina found in this study are *Placopsilina*, *Dusenburyina*, and *Valvulina*. *Liebusella*(?) is minor but may be an important indicator taxon.

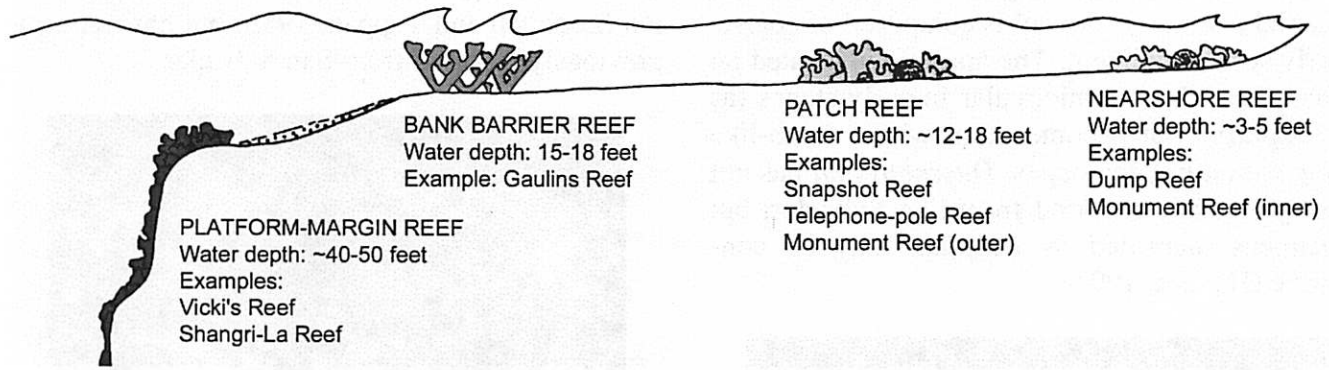


Figure 1. A schematic composite of the major types of living reefs found at San Salvador as used in this paper. Nearshore reefs typically begin within 10 meters of shore and include true fringing reefs. Patch reefs are irregular in shape and are variable in their position within the lagoon, commonly lying between 50 and 250 meters from shore. Bank barrier reefs are linear and are located offshore, but in shallow, high-energy waters. A broad, gently sloping fore reef may separate these reefs from the shelf edge. Platform-margin reefs are found at the shelf edge and extend down the "wall."

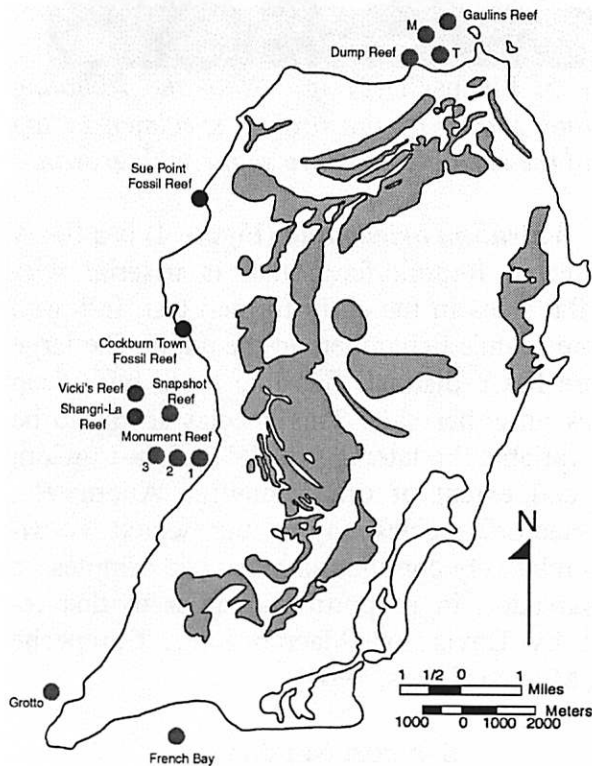


Figure 2. San Salvador, showing the major modern and fossil reefs examined. Two additional sites on the north side of the island are echinoid sites used in a previous study: (T) Tripneustes (grass bed) and (M) Meoma (sand flat). Map from Greenstein et al., 1998, with modifications.

Placopsilina(?) sp. (Figure 3) is a small, elongate foraminiferan found cemented to grains of sediment, typically beginning on one side and ending on the other, and frequently cementing two or more grains together. Its test is made up of relatively fine-grained and well-sorted sediment compared to the other taxa in this data set. The uniseriately arranged chambers are rounded, and this, along with its meandering habit, gives the test a segmented-worm-like appearance. The aperture is typically a basal slit rather than the circular, terminal aperture described in Loeblich and Tappan (1988); hence, this identification is provisional. *Placopsilina* has not been reported previously from San Salvador, but is fairly common offshore.

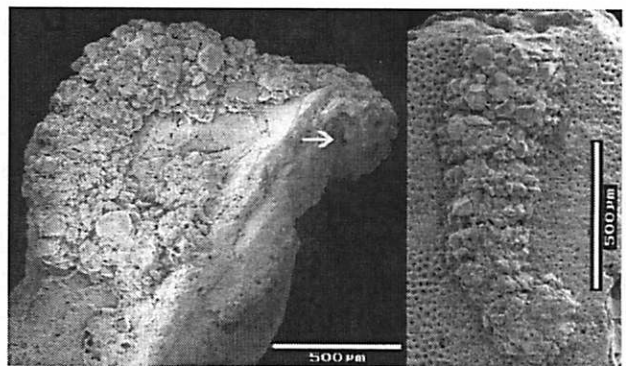


Figure 3. *Placopsilina*(?) sp., an attached textulariine living cemented to grains such as the Halimeda segment at right. Arrow (left) points to slit-shaped aperture.

Dusenburyina sp. (Figure 4) has a large (up to 5 mm long), straight to slightly curved, uniserial test. Its thick wall is composed of coarse, poorly sorted sediment. The aperture is located on a distinct neck, is semicircular in early stages (as in *Reophax*), but becomes oval with a tooth-like invagination in later stages. *Dusenburyina* has not been previously reported from San Salvador, but specimens identified as *Reophax* may be congeneric (Haynes, 1991).

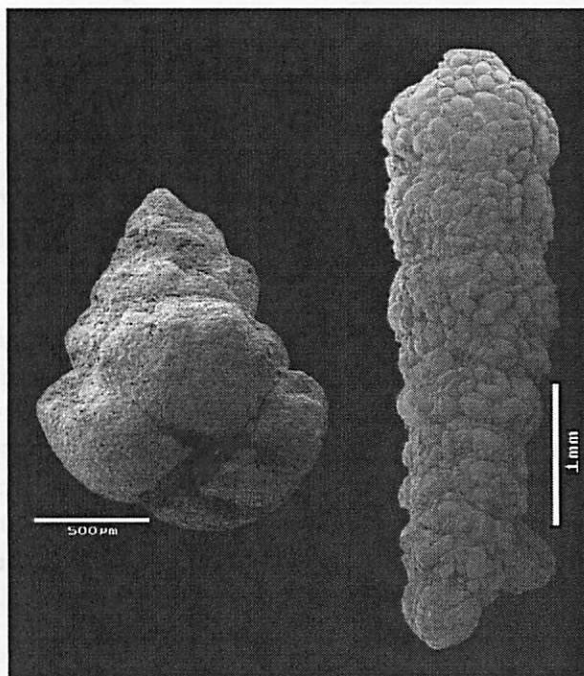


Figure 4. *Valvulina oviedoiana* (left) with the much larger *Dusenburyina* sp. (right).

Liebusella(?) sp. (Figure 5). This taxon is a “short and stubby,” uniserial foraminiferan with a pupa-like to slightly hour-glass longitudinal profile. It can be distinguished from *Dusenburyina* by its stout, rather than tapering outline, slightly smaller size, lack of pronounced curvature, finer-grained test, and the absence of a neck. Its aperture also differs from that of *Dusenburyina* in its later chambers, where it consists of several slits, centrally located on the face of the terminal chamber. Earlier chambers may have a rounded, oval, to triradiate aperture. The test interior contains pronounced radiating partitions (Figure 5). *Liebusella* and closely related taxa have a coiled early test, and it is not clear whether or not the San Salvador species does; thus assignment to this genus is tentative until further, more detailed stud-

ies can be done. *Liebusella* has been reported from the Holocene of Cuba and the Gulf of Mexico (Loeblich and Tappan, 1988) but has not been previously reported from San Salvador.

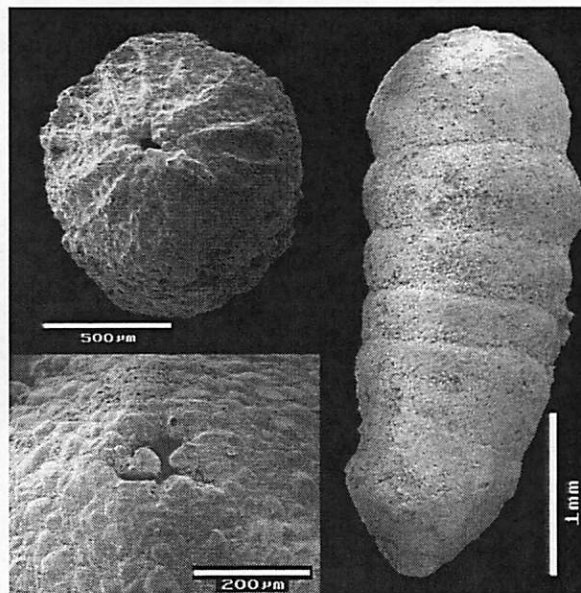


Figure 5. *Liebusella*(?) sp. Note the radiating partitions shown by the broken specimen at top left and the variable aperture shape with growth.

Valvulina oviedoiana (Figure 4) is a finely agglutinated foraminiferan that is triserial with three flat sides in the early formed test, followed by more rounded chambers in the adult. The large aperture has a distinct, flap-like tooth with deep notches on either side. This species seems to be quite variable in lateral profile (height-to-width ratio) and extent of ornamentation. Alternately, more than one species may be represented. *Valvulina* is relatively common in grass-bed samples on San Salvador, in proportions similar to that reported by Davis for Alacran Reef, Campeche Bank, Mexico (Davis, 1964).

Suborder Miliolina

By far, the most abundant taxa in the Suborder Miliolina are *Archaias* and *Cylcorbiculina*. *Cornuspiramia* is important at some sites, and *Quinqueloculina agglutinans*(?) is present in small numbers. *Laevipeneroplis* and *Sorites* were also recovered but were so rare that they were not used in the data set.

***Cornuspiramia* spp.** (Figure 6). It is not obvious that *Cornuspiramia* is a foraminiferan at all because of its small size, branching habit, and indistinct chambers. It appears as a tube, branching repeatedly at high angles, with all branches about the same diameter. Cemented to shell fragments and other sediment grains, it can be recognized by its bright white color, its irregular margin at the attachment surface, and the fact that the upper part of the chambers are often broken away to form a u-shaped channel. The branch diameter of most specimens is typically approximately 75 μm ; overall test size may reach several mm. This species may be *C. antillarum*, which is known from Jamaica. Much smaller sizes suggest at least one other species in the San Salvador fauna.

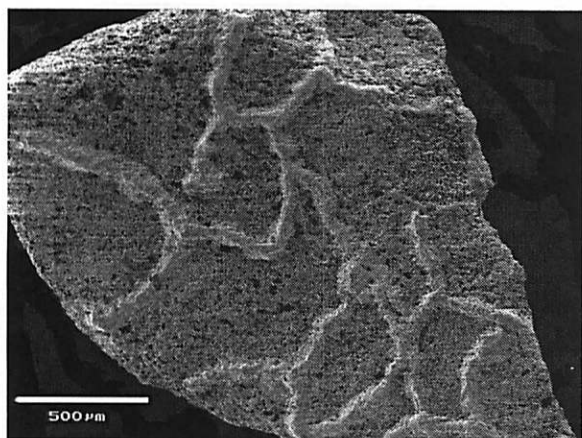


Figure 6. *Cornuspiramia* sp., probably *C. antillarum*, cemented to a worn *Halimeda* segment.

Archaias angulatus (Figure 7). Like other members of the Family Soritidae, *Archaias* has a very large, discoidal test. The test outline varies widely with growth stages from an ammonoid-like, planispirally coiled initial stage, to the markedly asymmetrical shape shown in Figure 7, ending in a more nearly circular outline in the largest individuals. The symbiotic protists in its protoplasm typically give this species a bluish green coloration in living specimens. Dead tests are robust due to the thickened central area and the relatively thick test wall; therefore *Archaias* is prevalent in many death assemblages (Martin, 1986).

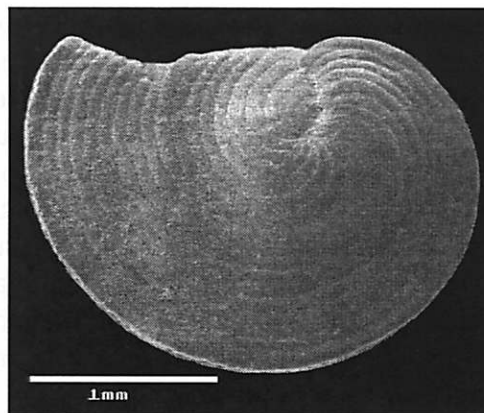


Figure 7. *Archaias angulatus*.

Cyclorbiculina compressa (Figure 8) is another large soritid that is very abundant at San Salvador. Like *Archaias*, it is brightly colored by its symbionts in life. The largest tests are well over 2 mm wide, have a coin-shaped appearance caused by the annular growth of the final chambers. Smaller tests without these annular chambers can be confused with those of *Archaias angulatus*, but have a central area that is somewhat smaller and not as thick, and the outer area is typically thinner and tends to have a fluted appearance (Figure 8). The relatively thin test wall contributes to rapid post-mortem breakdown of the test, making altered tests difficult to distinguish from those of *Archaias* in many cases.

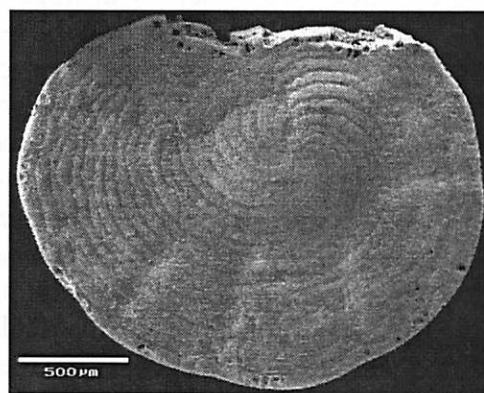


Figure 8. *Cyclorbiculina compressa*. Note fluted outer portion of test and easily broken perimeter.

Suborder Rotaliina

The Suborder Rotaliina is represented by *Amphistegina*, which is relatively rare in my data set, and by large numbers of *Homotrema* and *Planorbulina*.

Amphistegina gibbosa (Figure 9) is easily recognized by the test's distinctive shape and its highly vitreous luster. The test outline is essentially circular; in profile, it is strongly (but unequally) biconvex: the thick central portion thins rapidly to a sharp edge at the rim. The smooth surface is only lightly etched with complex sutures between chambers arranged in a spiral pattern. Live specimens are distinguished by their brown color, which appears to be lost relatively rapidly after death.

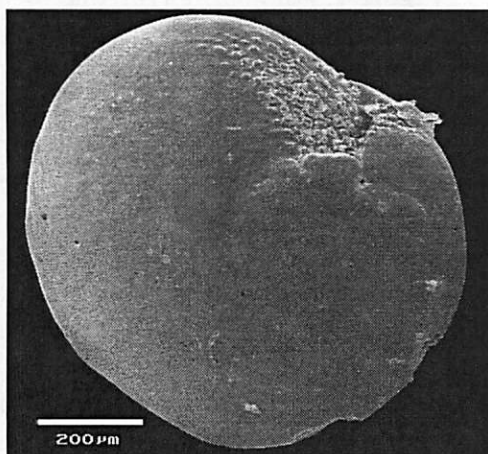


Figure 9. *Amphistegina gibbosa*.

Planorbulina spp. (Figure 10). This taxon is characterized by a disc-shaped, attached test composed of bulbous chambers with large pores. Two basal, rimmed apertures occur on the test periphery, one on either side of each late-formed chamber, but are not conspicuous with light microscopy. An organic membrane colors the central part of the test brown in well-preserved specimens. The presence of both brown and reddish specimens may indicate that more than one species is present in the fauna. *Planorbulina* tests with a flat side are found free in the sediment, where they have been dislodged from their attachment surface. Unusually thick tests lacking a flat side were apparently dislodged early in life, and those that were attached to small rod-like substrates have wrapped around these structures and taken on rounded test shapes. *Acervulina* is also known from the San Salvador fauna, but its chamber margins more irregular and it lacks apertures.

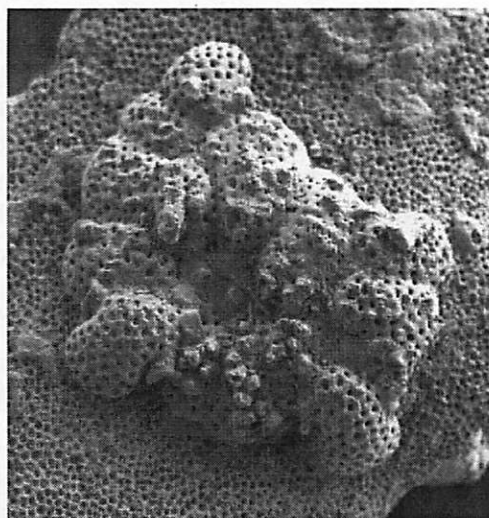


Figure 10. Immature specimen of *Planorbulina* sp. cemented to *Halimeda*. Field of view approximately 2 mm wide.

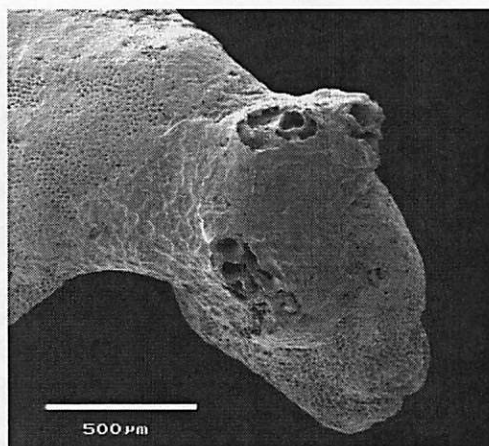


Figure 11. *Homotrema rubrum*. A nearly complete specimen cemented to the *Halimeda* at left. Note distinctive cellular porosity where broken.

Homotrema rubrum (Figure 11) is an easily recognized, yet bizarre foraminiferan. It is always found cemented to hard substrates during life and colored a bright red. Test morphologies include encrusting, hemispherical, and globose (Elliott, et al., 1996) with some specimens bearing projections that give the test the appearance of a tree-stump. Broken specimens and fragments found in the sediment eventually lose their red color, but are recognized by their distinct porosity, which is seen at several scales due to coarse perforations, unusually large apertures, and the cavities formed by broken tubular projections.

FORAMINIFERAL ASSEMBLAGES

Most Caribbean large benthic foraminifera are either attached to benthic plants and algae by their pseudopodia during life or are cemented to hard substrates. The two sites examined from the outer grass beds and sand flats of Grahams Harbor are dominated by the phytal taxa *Archaias*, *Cyclorbiculina*, and *Valvulina* (Figure 12). The relatively high percentage of pristinely preserved specimens, some with the original coloration still intact, indicate that these samples are reflective of the live populations. Representative foraminiferal assemblages of the 4 reef types studied are shown in Figure 13, the initial actualistic model. Each of the shallow-water reefs (nearshore reefs, patch reefs, and bank barrier reefs) are dominated by a combination of the *Archaias*, *Cyclorbiculina*, and *Homotrema*. Foraminifera found in the platform-margin reefs of Fernandez Bay are quite different from the lagoon assemblages: they are more equitable, and textulariines are relatively more abundant and diverse than in the other assemblages. They include the (apparent) indicator taxa *Amphistegina*, *Placopsilina*, *Dusenburyina*, and *Liebusella*(?).

The samples studied from Gualins Reef are distinct because of the dominance of *Homotrema* fragments. Additional specimens were picked from one sample to see what the composition of the assemblages was exclusive of *Homotrema*. The results show that *Archaias* and *Cyclorbiculina* still do not dominate the assemblage (they total approximately 30%) when *Homotrema* is removed, and most of these specimens are highly altered. A sediment sample collected in 1986 shows that the dominance of *Homotrema* in the sediment (over 80%) has persisted through a period of years. Similarly, data from samples taken at Snapshot Reef in the 1980s and early 1990s are consistent with the findings shown in Figure 13. The dominance of *Homotrema rubrum* in a bank barrier reef on the windward side of the island is not surprising (see MacKenzie et al., 1964), but it is worth noting that the species also occurs in abundance in near-shore environments on San Salvador: it is not restricted to an outer shelf setting.

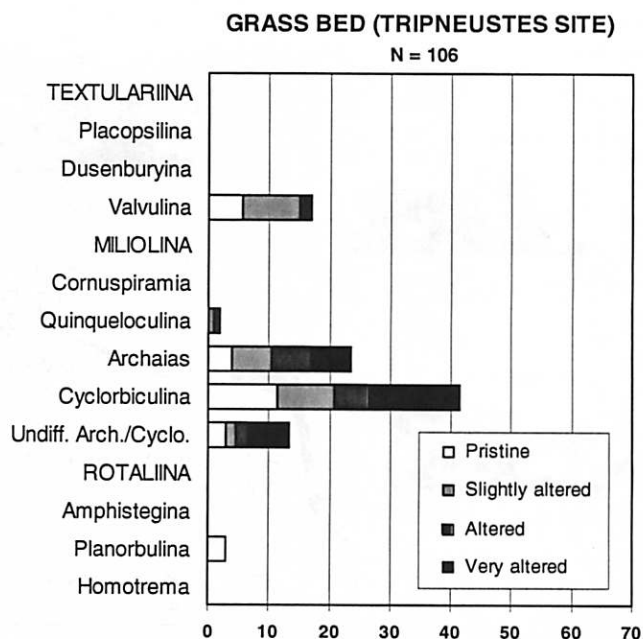


Figure 12. Foraminiferal assemblage from grass-bed site in Grahams Harbor; water depth ~ 3 m.

Attempts were made to locate other examples of healthy bank barrier reefs on the west edge of Graham's Harbor but to no avail. A poorly developed bank barrier(?) reef off Grotto Beach was sampled (Figure 14) and is very similar to a French-Bay sample (not shown). In these instances, soritid tests and fragments outnumber *Homotrema* remains. It seems that bank barrier reefs are somewhat variable in their foraminiferal death assemblages, probably depending on the energy regime and the proximity of live populations.

PETROGRAPHIC CRITERIA

Representative grain-size analyses of the major sites studied is shown in Figure 13. The well sorted sediment of Snapshot Reef is accompanied by a large percentage of highly polished grains. Snapshot reef and other mid-shelf reefs and lagoonal environments are also characterized by a high percentage of multi-grain aggregates. In the case of Snapshot Reef, these cemented aggregates are often highly polished, indicating periods of calm between periods of active wave surge. Figures 15 and 16 compare the study sites in Grahams Harbor and Fernandez Bay in terms of polished grains and grain aggregates.

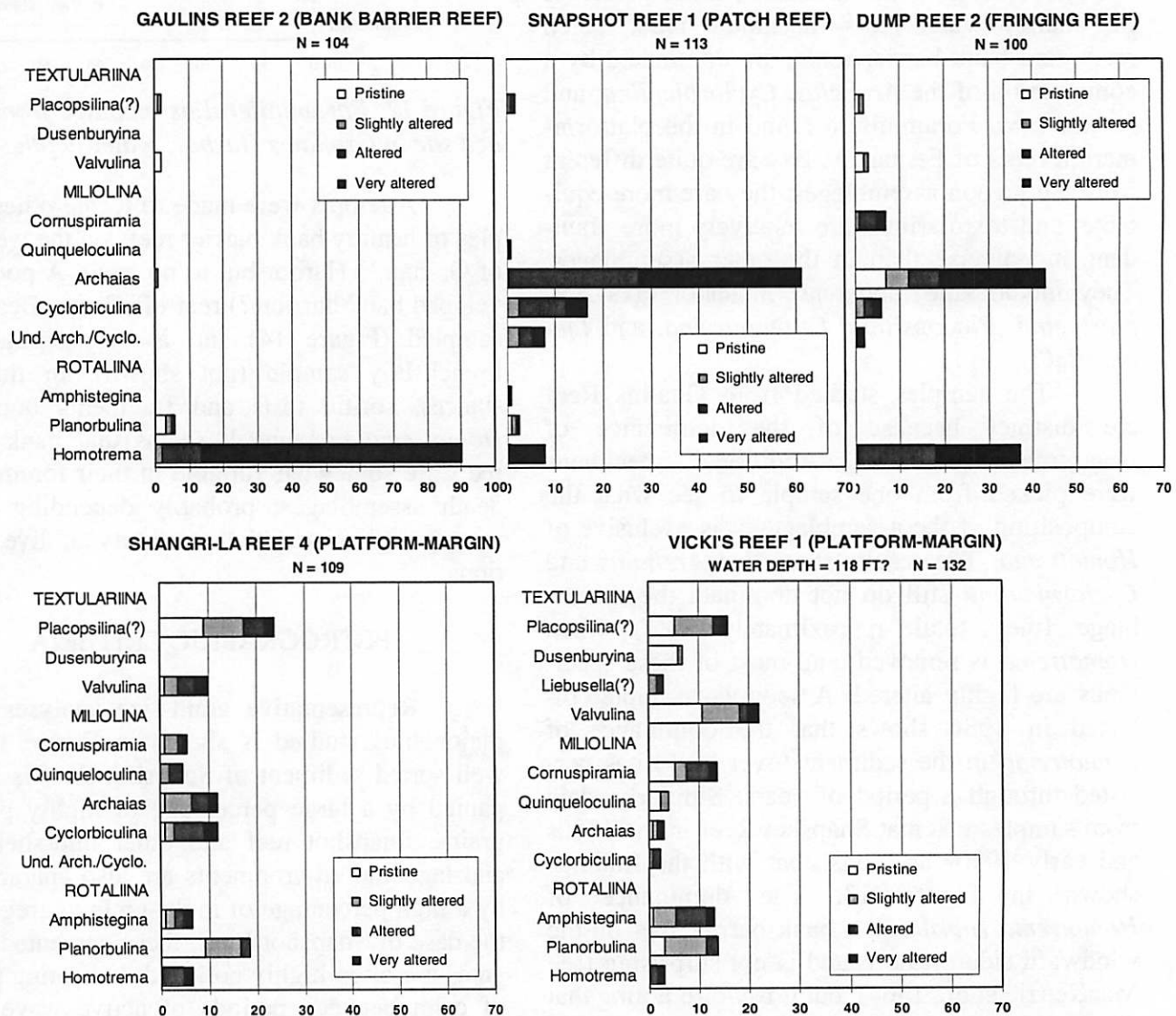
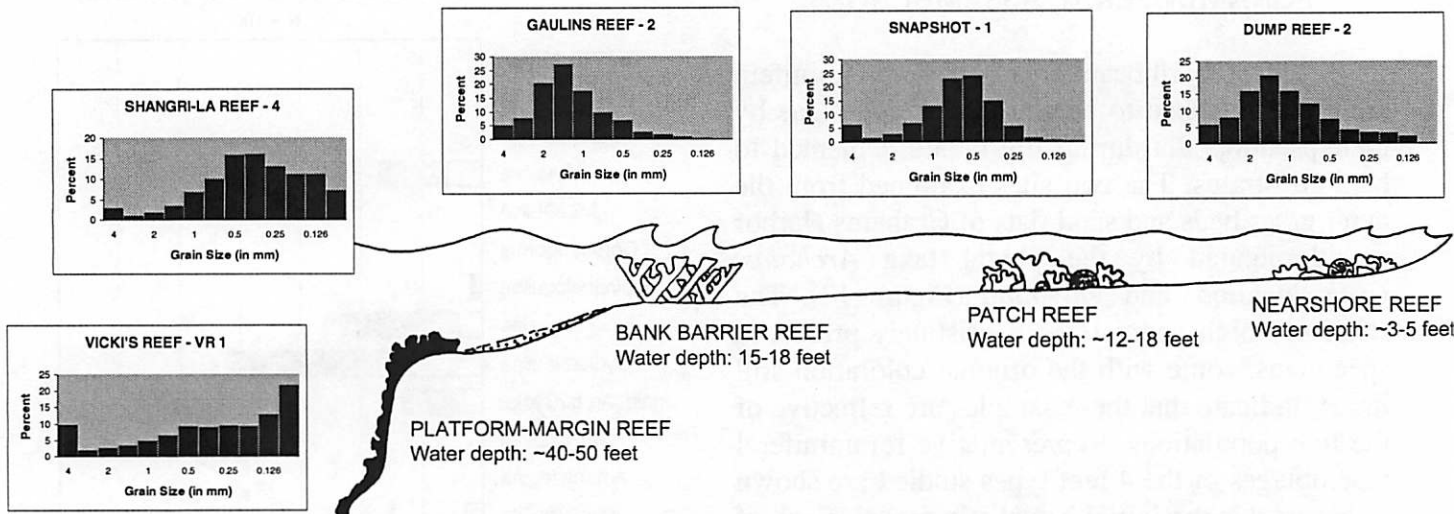


Figure 11. Grain size analyses (top) and representative foraminiferal death assemblages from the reef types studied.

GROTTO REEF 1 (BANK BARRIER REEF?)

N = 108

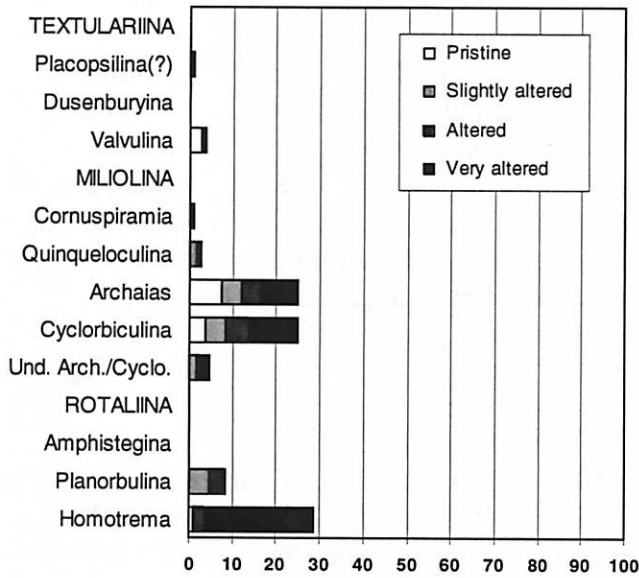


Figure 14. A poorly developed bank barrier(?) reef off Grotto beach, southwestern San Salvador. A similar assemblage was sampled at French Bay.

COCKBURN TOWN REEF

In a trial application of the preliminary model, a loose sediment sample was taken from Cockburn Town fossil reef from the stratigraphic position shown in Figure 16. Friable portions were picked for foraminifera, grain aggregates, and polished grains, although some grain aggregates were overcoated and had to be confirmed by thin-section study (Figure 17). The fine-grained, pelleted fabric of the sediment suggests that the sediment *in-situ* rather than transported into the framework of the reef from elsewhere. The assemblage of foraminifera recovered from the sample is represented in Figure 18. Although the total number of foraminifera recovered to date is low, the assemblage does not seem to be dominated by *Homotrema* as is that of Gaulins Reef; cursory examination of other samples supports this view. The high percentage of grain aggregates (over 50%) and polished grains (20%), as well as the apparent dominance by *Archaias* seems to make the Cockburn Town reef more comparable with a mid-shelf patch reef (see Schmidt et al., 2004) than with Gaulins Reef (compare White et al., 1984). However, the reef could also have been a relatively low-energy bank barrier reef not separated very far from lagoonal grass beds and their abundant *Archaias* populations, as might be expected on the western side of the island.

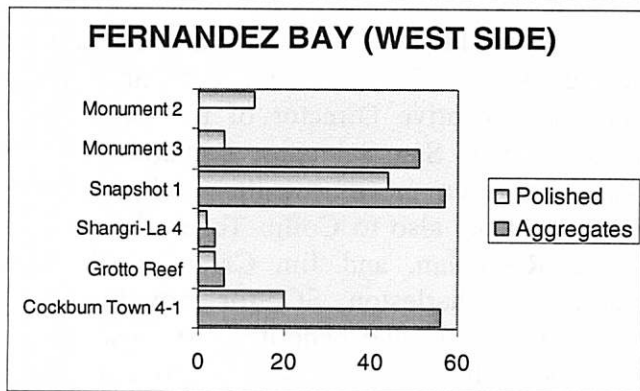
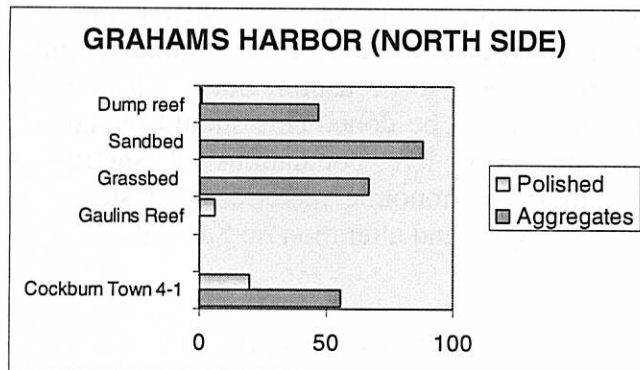


Figure 15. Percent of polished grains and grain aggregates in Grahams Harbor (above) and Fernandez Bay (below).

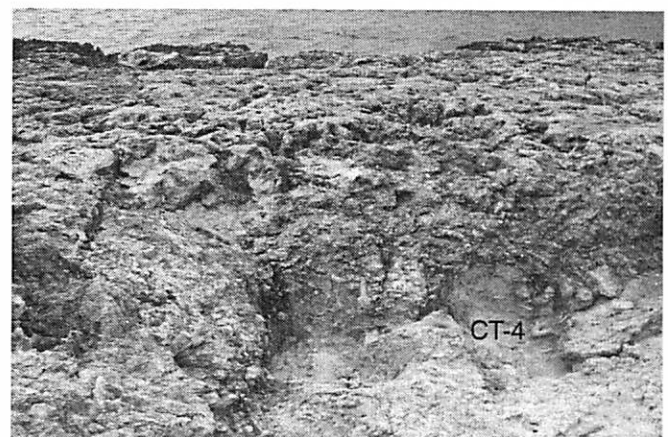


Figure 16. Cockburn Town reef viewing west. The position of the sample is shown at "CT-4."

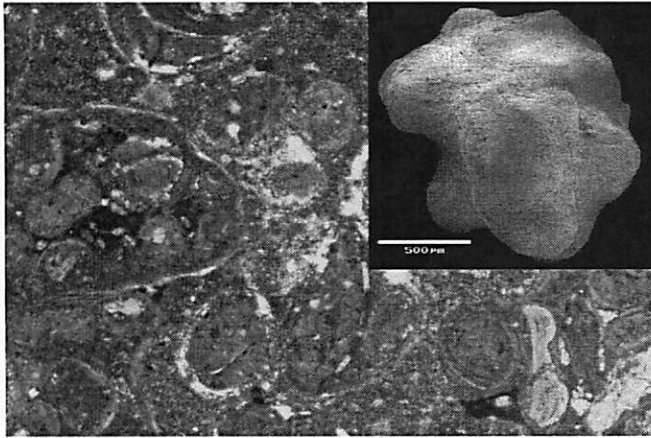


Figure 17. Thin-section and SEM of grain aggregates from the Pleistocene Cockburn Town reef. Note fine-grained pellet rich fabric of reef sediment.

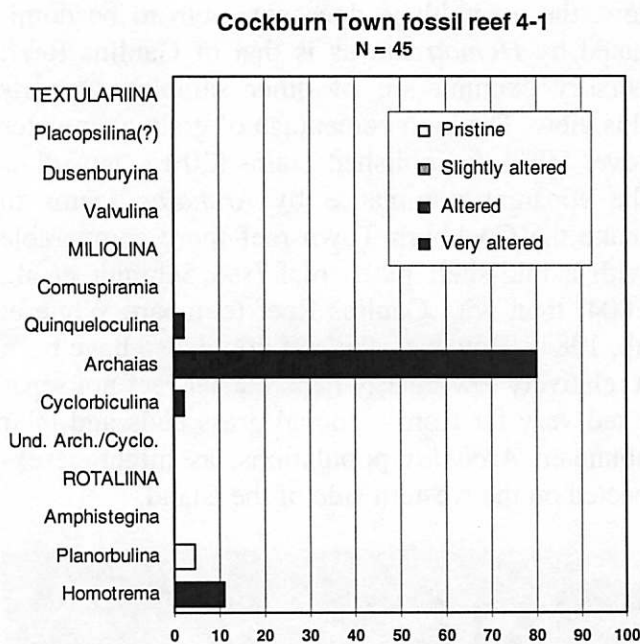


Figure 18. An *Archaias*-dominated foraminiferal assemblage from Cockburn Town reef.

CONCLUSIONS

In the data set examined, textulariine foraminifera are most prevalent in the assemblages found at platform-margin (wall) reefs, Fernandez Bay. These include *Placopsilina*(?), *Dusenburyina* sp., and *Liebusella*(?), none of which have been reported from San Salvador previously.

Homotrema rubrum dominates foraminiferal assemblages at Gaulins Reef, a high-energy

bank barrier reef on the northeast side of the island. It is also found in abundance at bank barrier(?) reefs at the southeastern end of the island (Grotto and French Bays), but it is found in near-shore reefs as well.

Lagoonal grass-bed assemblages are dominated by the soritids *Archaias angulatus* and *Cyclorbiculina compressa*, as are (at least some) patch reefs (e.g., Snapshot Reef). Initial sampling at the Cockburn Town fossil reef indicates that it was a patch reef, based on the abundance of *Archaias* and grain aggregates, but the reef could also have been a relatively low-energy bank barrier reef not separated very far from the lagoonal grass-bed source of these particles.

At the present time, certain specific reefs on San Salvador, such as Snapshot Reef and Gaulins Reef, can be recognized easily by their distinctive sediment characteristics and foraminiferal assemblages, and these have persisted through nearly 2 decades of sampling. Recognition of reef types, and the relative distance from shore that this implies, based on sediment samples is more challenging. Foraminiferal assemblages including taphonomic data, polished grains, and grain aggregates are among the sediment characters that appear to be useful, but much more research needs to be done. This should include the distribution of live populations of shelfal foraminifera, taphonomic histories, and studies of grain transport and alteration on San Salvador.

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