

**GROWTH AND DEPOSITIONAL FACIES
OF A WINDWARD REEF COMPLEX
(Nonsuch Bay, Antigua, W.I.)**

**FACIES BIOCONSTRUITS ET BIODÉTRITIQUES
D'UN COMPLEXE RÉCIFAL AU VENT
(Nonsuch Bay, Antigue, Petites Antilles)**

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ABSTRACT

The history of a Caribbean windward reef complex (bank barrier, patch, and fringing reef) is revealed in eight core holes across Nonsuch Bay, Antigua. This complex (up to 16 m thick) is established on Oligocene limestone and contains five reef facies: fore-reef talus, fore-reef coral heads, fore-reef *A. palmata*, back-reef rubble, and back-reef sediments. Ten radiocarbon dates indicate that about 5,000 years B.P. the bank barrier reef consisted of an *A. palmata* community with a seaward accumulation of fore-reef talus debris. In the subsequent 2,000 years, a well-developed coral-head community (accumulation rates of up to 4.6 m/1000 years) thrived seaward of the *A. palmata* community and the back-reef sediments (maximum accumulation rate of 5.6 m/1000 years). In the last 3000 years the *A. palmata* facies has prograded seaward over the coral-head facies. Today, the limited accumulation of this shallow *A. palmata* community (0.9 m/1000 years) indicates that much of this coral is being transported shoreward and is providing rubble to the reef-crest and shallow back-reef. Because of space limitations, this material has been accumulating at a rate of only 0.7 m/1000 years. The cored patch reef rests on an Oligocene erosional high and consists of an *A. palmata* community 6745 years old. It gives way to *A. cervicornis* and coral head communities that formed a loose back-reef sediment facies trapping large quantities of fine sediment (overall accumulation rate of 2.2 m/1000 years). The fringing reef consists of a similar facies (accumulation rate of 1.6 m/1000 years) capped by a thin *A. palmata* section. Submarine lithification appears primarily in the fore-reef coral head and *A. palmata* facies, where it forms microcrystalline crust/infill rims on corals. Traces of multicyclic board and cemented pavement limestone were found in the back-reef rubble facies directly shoreward of the reef crest. As in many other reef areas, this submarine cement is predominantly magnesium calcite (18.52 - 15.1 mole percent Mg CO₃), with minor traces of acicular aragonite, generally in coral skeletal cavities.

RESUME

Huit sondages réalisés dans la baie de Nonsuch, île d'Antigue, Petites Antilles, permettent de reconstituer l'histoire d'un ensemble récifal (récif barrière, pâtés coralliens et récifs frangeants). D'une épaisseur de 16 m, cet ensemble repose sur un calcaire oligocène et comprend 5 facies coralliens : un talus prérécifal, une zone prérécifale à pâtés coralliens, un récif externe à *Acropora palmata* et une pente externe détritique, à sédiments plus fins. D'après 10 datations au radiocarbone, il y a 5000 ans environ, le récif barrière était constitué par un biotope à *Acropora palmata* avec, du côté océan, un talus prérécifal formé par l'accumulation de débris coralliens. Pendant les 2000 ans suivants, un biotope à pâtés coralliens bien développés (taux d'accumulation jusqu'à 4,6 m par 1000 ans) a cru activement en avant du biotope à *A. palmata* et des sédiments de la face interne du récif (taux d'accumulation maximum de 5,6 m par 1000 ans). Au cours des 3000 dernières années, le faciès à *A. palmata* a progressé vers l'océan sur le faciès à pâtés coralliens. De nos jours, la croissance relativement faible de cette communauté à *A. palmata* (0,9 m par 1000 ans) indique qu'une grande partie des éléments coralliens correspondants est transportée vers le rivage et alimente en matériaux détritiques le front récifal et la zone d'arrière récif peu profonde. L'exiguité de l'espace disponible permet l'accumulation de ces matériaux à un taux de 0,7 m par 1000 ans. Les pâtés coralliens forés reposent sur une surface d'érosion oligocène et représentent un biotope à *A. palmata* âgé de 6745 ans. Il cède la place à des biotopes à *A. cervicornis* et à pâtés coralliens qui forment un faciès sédimentaire meuble en arrière du récif contenant une importante fraction de sédiments fins (taux d'accumulation total de 2,3 m par 1000 ans). Le récif frangeant présente un faciès de même type (taux d'accumulation de 1,6 m par 1000 ans) surmonté d'une mince couche d'*A. palmata*. La lithification sous-marine intervient surtout dans la zone prérécifale à pâtés coralliens et dans le faciès à *A. palmata* où se forment des couches et des remplissages microcristallins. Des traces de dalles calcaires alternativement cimentées ou perforées s'observent dans le faciès détritique grossier juste en arrière du front récifal. Comme dans de nombreux sites récifaux, le ciment marin consiste surtout en calcite magnésienne (18,5 à 15,1 mole % MgCO₃) avec des traces d'aragonite en aiguilles, le plus souvent localisé dans les cavités du squelette corallien.

INTRODUCTION

Nonsuch Bay is located on the windward east coast of Antigua, a small (280 sq km) island in the Caribbean Lesser Antilles (Fig. 1). This bay, which has a maximum depth of 24 m, is encircled by Oligocene limestone cliffs landward and a bank-barrier reef seaward, which protects its many small patch and fringing reefs (Multer and Weiss, 1980). To gain an insight into the growth history of this windward reef complex, in March 1983 we drilled eight core holes along a transect extending from the bank-barrier reef through a lagoon patch reef and on to the fringing reef off Conk Point (Fig. 1). The cores were collected

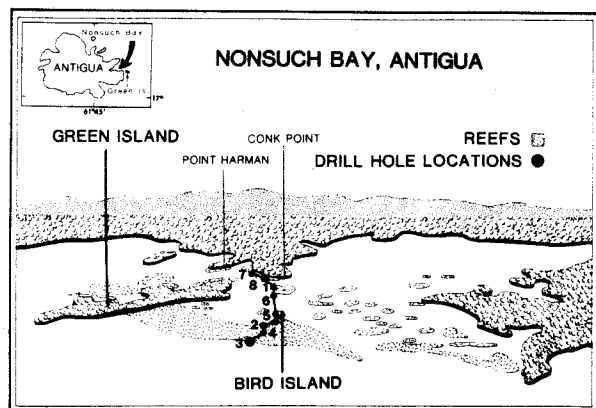


Figure 1: Sketch of an oblique view of Nonsuch Bay showing locations of eight drill holes along a transect across a bank-barrier, patch, and fringing reef.

with a hydraulic submersible drill following the procedures described by Macintyre (1978). Core analyses were performed in the National Museum of Natural History's Sedimentology Laboratory, and radiocarbon dating was completed by R. Stuckenrath at the Smithsonian Radiation Biology Laboratory.

PRESENT-DAY REEF COMMUNITIES

The present-day reef assemblages and bottom characteristics of the three types of reef areas crossed by the study transect are briefly described below.

Bank-Barrier Reef

The bank-barrier reef is about 1,000 m wide. Its shallow fore reef is a poorly defined spur and groove system (up to 7 m of relief) almost entirely covered by thickets of *Acropora palmata*, except for some scattered colonies of *Montastrea annularis*, *Diplora strigosa*, *Agaricia agaricites*, and *Porites astreoides*. Seaward, the *A. palmata* community gives way to an octocoral and coral-head pavement (depths of 12 to 15 m), which marks the inner edge of this broad windward shelf.

Shoreward of the spur and groove zone, the almost exposed reef crest consists of coral-rubble fields that are encrusted with crustose coralline algae. These fields occur in elongate mounds (up to 1 m of relief) extending perpendicular to the reef trend. Linearly oriented *A. palmata* and the hydrocoral *Millepora complanata* survive in the troughs, whereas the crests of these shallow

mounds are commonly coated by the colonial zoanthid *Palythoa caribaeorum*.

Landward of the reef crest, numerous patches of coral buildups (up to 5 m of relief) are scattered over a sand and rubble bottom. For the most part, these localized buildups are formed by *M. annularis*, along with some *P. astreoides* and *M. complanata*, which are generally dominant in areas close to mean low sea level. The inner edge of this barrier-reef complex is dominated by mounds of *Porites porites* and thickets of *Acropora cervicornis* and *Acropora prolifera*. Adjacent to Bird Island, the bank barrier coalesces with a rubble pavement and a sand and *Thalassia* reef flat to form a fringing reef. Elsewhere, the reef communities give way to the sediment floor of the lagoon.

Patch Reefs

The patch reefs rise up from depths of about 20 m on the lagoon floor of Nonsuch Bay. The tops of these patches consist of rubble flats surrounded at their outer edges by scattered growths of *Porites porites*, *Millepora* spp., *A. palmata*, and *A. prolifera*. The steep debris slopes are characterized by large fragile colonies of *Millepora alcicornis*.

Fringing Reefs

The sand beaches and adjacent reef-flat rubble--with its scattered growths of *P. porites* and *Neogoniolithon strictum* are rimmed with *M. complanata* communities. Here and there, these communities grade into a narrow *A. palmata* zone at a depth of about 0.3 m below mean low sea level. At depths of 1 to 2 m, the *A. palmata* zone is followed by extensive fields of *P. porites*, which extend to steep talus slopes.

SUBSURFACE DATA

Reef cores and bathymetric and topographic relief indicate that the Holocene reef section in Nonsuch Bay is at least 17 m thick and is established on the high-relief erosional surface of Oligocene limestones. Five reef facies can be identified in the reef sections (see Fig. 2).

Fore-reef talus.--This sediment facies appears only at the base of Hole 2. Recovery was poor, but it was possible to identify a section of *M. annularis* and *Porites* sp. rubble in a sand matrix.

Fore-reef coral heads.--Recovery was excellent in this facies, which appears to consist of a mixed coral-head assemblage dominated by *M. annularis*, *P. astreoides*, and *Montastrea cavernosa*. This facies makes up most of the framework of the bank-barrier reef.

Reef *Acropora palmata*.--Although the best-developed sections of this facies are found in the upper and windward sections of the bank-barrier reef, it also appears in short intervals in lower sections of Hole 5 (in the back reef) as well as in the lower sections of Hole 6 (the seaward hole in the patch reef) and in the top section of Hole 8 (the seaward hole of the fringing reef). By and large, this facies consists of a well-preserved *A. palmata* framework, which, in the outer reef sections, contains a variety of other reefal components, including *M. annularis*, *P. astreoides*, crustose coralline algae, *A. agaricites*, along with some *A. cervicornis*, *P. porites*, *Millepora* sp., and *Colpophyllia* sp.

Back-reef rubble.--This facies forms the uppermost sections of the three core holes drilled shoreward of the crest of the bank-barrier reef. Most of this material is extensively bored and encrusted by crustose coralline algae and foraminifera. It includes a wide variety of skeletal components, notably *M. annularis*, *P. porites*, *A. cervicornis*, *A. palmata*, *Millepora* sp., and *A. agaricites*.

Back-reef sediments.--As was expected, recovery was poor for this unlithified sediment facies, which dominated the innermost core hole of the bank-barrier reef (Hole 5) as well as the core holes in both the patch and fringing reefs. We recovered only small sections of coral heads here--primarily *M. annularis*, *Diploria* sp., and *Colpophyllia* sp.--along with fragments of *A. cervicornis*, *P. porites*, and *Millepora* sp.

STAGES OF REEF DEVELOPMENT AND ACCUMULATION RATES

Ten radiocarbon dates were obtained from unaltered skeletal carbonate of coral colonies--four from *M. annularis*, four from *A. palmata*, one from *Diploria* sp., and one from *M. cavernosa* (Table 1). A Libby half life of 5,568 years was used, and no corrections were introduced for $^{13}\text{C}/^{12}\text{C}$ ratios, or for secular atmospheric variations.

The positions of these radiocarbon dates on a minimum sea-level curve for the western Atlantic (Lighty et al. 1982) (Fig. 3) and the interpolated time-growth surface lines on the reef

SAMPLE NUMBER	DEPTH BELOW REEF SURFACE	RADIOCARBON DATE	ACCUMULATION RATE (m/1000 YRS)	REEF FACIES
CORE 2	0	PRESENT	0.92	FORE-REEF CORAL HEADS, REEF <i>A. palmata</i> AND BACK-REEF RUBBLE
H2-7	2.06	2245 ± 85	4.42	FORE-REEF CORAL HEADS
H2-38	10.32	4115 ± 65	4.62	FORE-REEF CORAL HEADS
H2-45	13.62	4830 ± 85		FORE-REEF CORAL HEADS
CORE 3	0	PRESENT	0.90	REEF <i>A. palmata</i>
H3-16	1.85	2065 ± 75		
CORE 4	0	PRESENT	0.98	BACK-REEF RUBBLE
H4-4	0.46	670 ± 75	1.77	REEF <i>A. palmata</i> AND FORE-REEF CORAL HEADS
H4-19	4.07	2705 ± 65		
CORE 5	0	PRESENT	0.78	REEF <i>A. palmata</i> AND BACK-REEF RUBBLE AND SEDIMENTS
H5-5	2.90	3710 ± 55	5.64	REEF <i>A. palmata</i> AND BACK-REEF SEDIMENTS
H5-13	12.04	5330 ± 90		
CORE 6	0	PRESENT	2.19	REEF <i>A. palmata</i> AND BACK-REEF SEDIMENTS
H6-14, 15	14.60	6745 ± 90		
CORE 7	0	PRESENT	1.63	BACK-REEF SEDIMENTS
H7-2	5.50	3365 ± 80		

TABLE 1. ACCUMULATION RATES, NONSUCH BAY, ANTIGUA

section (Fig. 2) were used to reconstruct the general stages of development of the Nonsuch Bay reef complex, which appears to be at least 7,000 years old. Because of somewhat poor penetration seaward of the reef crest, however, it is impossible to speculate about the initial stages of the bank-barrier reef. Nonetheless it seems clear that about 5,000 years B.P., the inner edge of the bank-barrier reef consisted of a deeper-water pioneer *A. palmata* fringing reef with a seaward accumulation of coral heads and fore-reef talus debris.

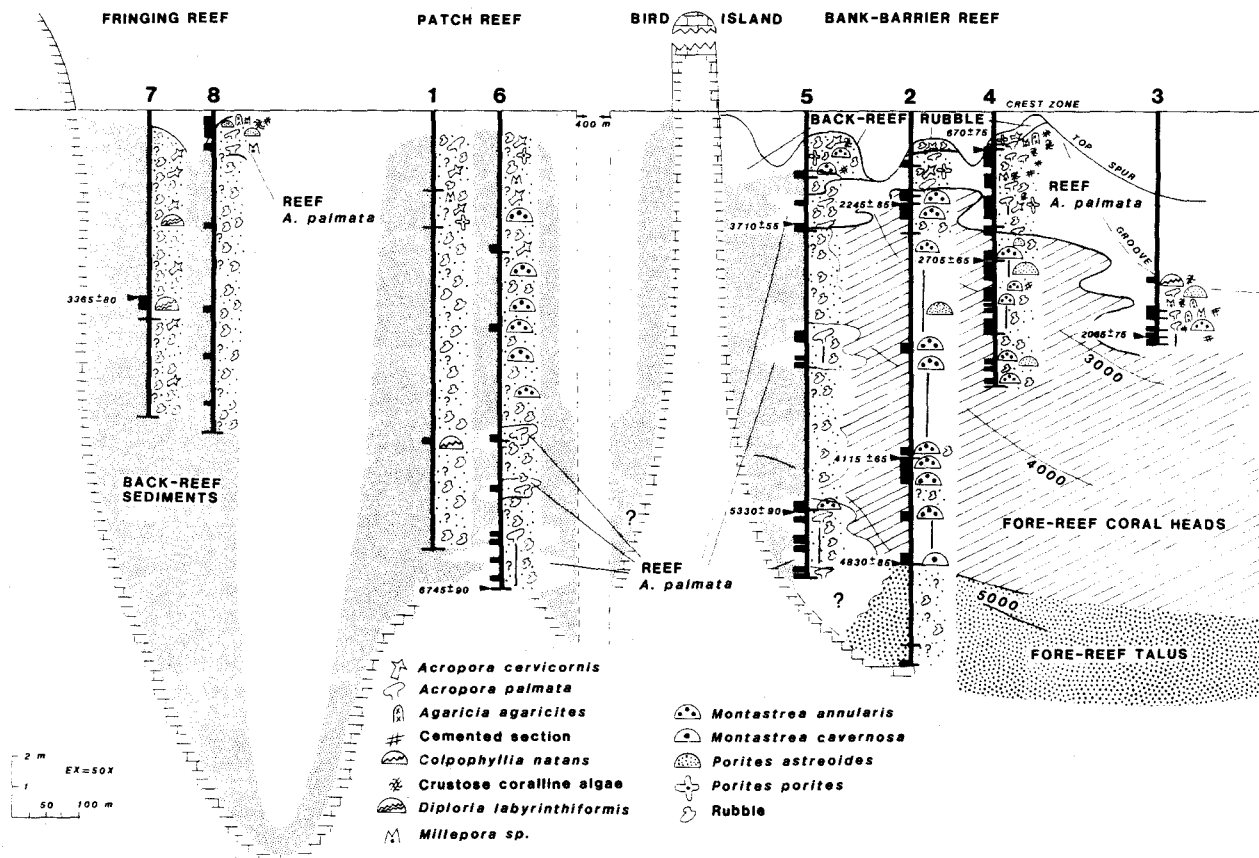


Figure 2: Cross section of Nonsuch Bay reef complex along the core-hole transect. Dominant reef components recovered, positions of five facies and the radiocarbon-dated samples are shown. Thin horizontal bars indicate core intervals and vertical black sections are cored intervals noted during the drilling.

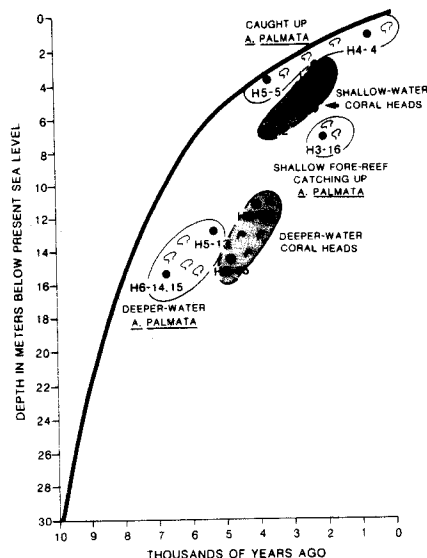


Figure 3: Plots of five coral-head and five *A. palmata* radiocarbon-dated cores on a minimum sea-level curve for the western Atlantic (Lighty et al., 1982.)

In the subsequent 2,000 years this reef underwent a rapid upward shoaling. A well-developed coral-head community (accumulation rates of up to 4.6 m/1000 years) flourished seaward of the *A. palmata* and back-reef sediments, which accumulated at a rate of about 5.6 m/1000 years. There is however, no evidence of continuous *A. palmata* framework sections. This could be explained either by frequent storm destruction of these coral communities or by the existence of extensive, but undocumented, *A. palmata* framework directly adjacent to Bird Island. In the last 3,000 years, the *A. palmata* facies has prograded seaward over the coral-head facies, forming the present-day bank-barrier reef with its emergent reef crest consisting of extensive fields of coral rubble. Active *A. palmata* framework construction now dominates the fore reef, and coral heads followed by fragile branching corals flourish on a coral-rubble substrate shoreward of the reef crest. Although this interpretation of the origin of the barrier reef is based only on data from a transect that passes through Bird Island, it would not be unreasonable to assume that this island may represent an exposed section of an Oligocene ridge that has controlled the development of this barrier-reef through an initial fringing-reef stage.

The limited accumulation of the shallow fore-reef *A. palmata* facies (0.9 m/1000 years) indicates that much of the coral formed in this area was probably transported shoreward. It should also be noted that the outermost core hole penetrated a fore-reef groove--an area of low reef-framework accumulation. Shoreward of the reef crest, the back-reef rubble facies has accumulated at a rather unimpressive rate of 0.7 m/1000 years owing to the vertical space limitation.

In the lagoon patch reef, growth was apparently initiated when a deeper-water *A. palmata* community was established on a Oligocene erosional high about 6,000 to 7,000 years ago.

This framework-forming community was eventually replaced by scattered *A. cervicornis* and coral-head communities that formed coral debris, which subsequently trapped large quantities of sediment in the back reef. The overall accumulation rate for this patch reef was 2.2 m/1000 years.

The fringing reef consists of similar sediment and coral debris that accumulated at a rate of 1.6 m/1000 years. The outer edge of this reef, however, is capped by a shallow-water *A. palmata* framework.

SUBMARINE LITHIFICATION

Submarine lithification is poorly developed in the Nonsuch Bay complex, in contrast to the lithification reported in Caribbean reef areas such as Jamaica (Land and Coreau 1970), Belize (James et al. 1976; Shinn et al. 1982; Macintyre 1984), and Panama (Macintyre 1977).

For the most part, the submarine cements in Nonsuch Bay appear to be associated with the fore-reef *A. palmata* facies, where they generally occur as crust and infilled rim deposits around the outer edges of coral skeletons (Fig. 4a). As in Galeta Reef, Panama, these rims show a distinct transition from dense sediment-rich submicrocrystalline (<4 μm) to microcrystalline (4-30 μm) magnesium calcite crusts to relatively clean magnesium calcite infill of skeletal cavities that exhibit a distinct peloidal (20-60 μm in diameter) texture (Fig. 4b). Below this area of dense magnesium calcite, the innermost penetration of cement is marked by the deposition of porous submicrocrystalline (<4 μm) magnesium calcite. At this inner limit of cement deposition, acicular aragonite rim cements (up to 100 μm) also occur on the walls of coral skeletal cavities. Cavities that contain both phases of cements generally indicate that the aragonite predates the magnesium calcite (Fig. 4c).

Submarine lithification in Nonsuch Bay also occurs in the multicyclic bored and cemented pavement limestone found in patches in the back-reef rubble facies (Fig. 4d). As in Panama (Macintyre 1977, 1983), these lithified sections consist of an agglomeration of skeletal components, much of which has been entirely replaced by sediment-rich magnesium calcite as a result of extensive boring and subsequent filling and coating of dense magnesium calcite.

Voids in the dense magnesium calcite deposits and peloid surfaces exhibit dentate or scalenohedral calcite crystals (Fig. 4e)--a characteristic feature of these submarine magnesium calcite deposits (for example, see Macintyre et al. 1968; Land Coreau 1970; Ginsburg et al. 1971; Schroeder 1972; Macintyre 1977).

Electron microprobe analyses yielded mean values of 18.5 ± 1.0 to 15.1 ± 1.6 mole percent $MgCO_3$. These results are comparable to values obtained from submarine calcite cements from other reef areas in the Caribbean (see Macintyre 1984). The acicular aragonite rim cements yielded mean strontium values of $7,377 \pm 783$ to $7,549 \pm 973$ ppm, which are similar to values reported for acicular cements from Belize ($6,900 \pm 800$ ppm, Macintyre 1984) and Panama ($9,500 \pm 600$ ppm, Macintyre 1977).

The lagoon reef deposits of Nonsuch Bay show little or no submarine lithification, however, as is the case in the Belizean Barrier Reef (James et al. 1976). One notable exception is the small

section of the *A. palmata* facies that occurs in the top interval of the seaward core hole of the fringing reef. This section contains both cement crusts and patches of pavement limestone.

CARBONATE FOUNDATIONS

The substrate underlying the Holocene reef sections of Nonsuch Bay was penetrated in only two core holes. In Hole 2 of the bank-barrier reef, 16 cm of dense and mottled fine to coarse skeletal calcarenite was recovered. The skeletal grains consist mainly of molluscs, benthonic foraminifera, coralline algae, echinoids, and corals. A caliche cap consisting of a dense, finely banded submicrocrystalline crust that contains very fine (.125 to .063 mm) skeletal grains was found at the top of this limestone (Fig. 4f). The calcarenite grains have a submicrocrystalline coating, which in turn is covered by a blocky calcite cement (Fig. 4g). There is evidence of both leaching and micritization of skeletal grains.

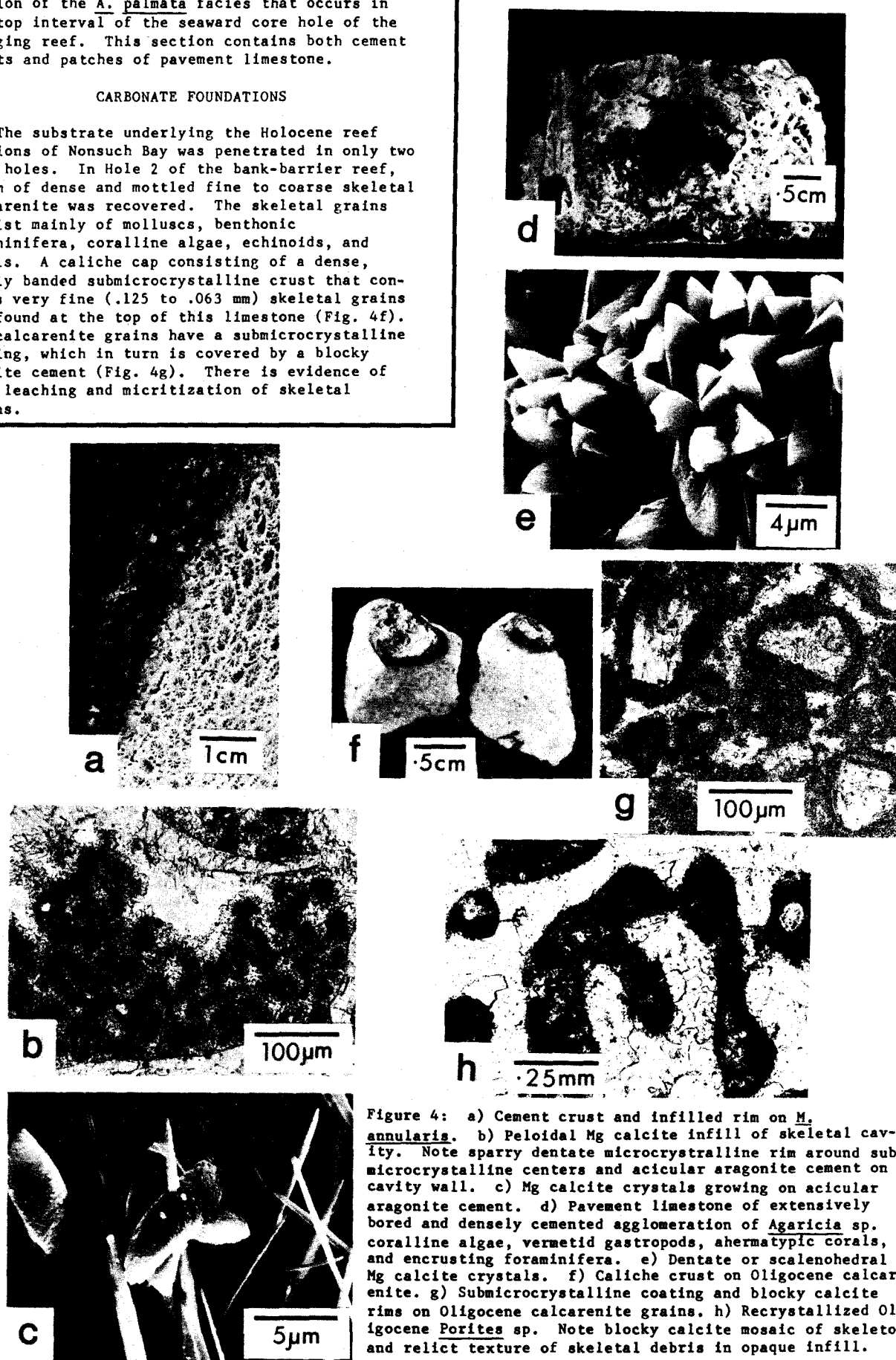


Figure 4: a) Cement crust and infilled rim on *M. annularis*. b) Peloidal Mg calcite infill of skeletal cavity. Note sparry dentate microcrystalline rim around submicrocrystalline centers and acicular aragonite cement on cavity wall. c) Mg calcite crystals growing on acicular aragonite cement. d) Pavement limestone of extensively bored and densely cemented agglomeration of *Agaricia* sp., coralline algae, vermetid gastropods, ahermatypic corals, and encrusting foraminifera. e) Dentate or scalenohedral Mg calcite crystals. f) Caliche crust on Oligocene calcarenite. g) Submicrocrystalline coating and blocky calcite rims on Oligocene calcarenite grains. h) Recrystallized Oligocene *Porites* sp. Note blocky calcite mosaic of skeleton and relict texture of skeletal debris in opaque infill.

By contrast, the substrate sample recovered from Hole 6 in the patch reef consists of a small fragment of recrystallized *Porites* sp. This coral has been altered to a blocky calcite mosaic and contains an opaque submicrocrystalline infill of original skeletal cavities (Fig. 4h). This infill commonly exhibits relict outlines of skeletal grains.

Electron microprobe analyses yielded mean values of 5.1 ± 0.5 to 1.8 ± 1.3 mole percent $MgCO_3$ for skeletal grains and their coatings and blocky calcite rims. The caliche crust, on the other hand, yielded values of 2.2 ± 0.5 to 2.7 ± 0.3 and the recrystallized *Porites* and its dense infill values of 0.4 ± 0.03 to 1.9 ± 0.6 mole percent $MgCO_3$. These values all indicate that these marine limestones have been altered to calcite under conditions of subaerial exposure.

Inasmuch as Oligocene limestones form the surrounding cliffs and the enclosed islands of Nonsuch Bay (Multer and Zankl, 1984), it is not illogical to assume that this altered limestone substrate is of Oligocene age.

CONCLUSIONS

The Holocene section of the Nonsuch Bay reef complex is at least 17 m thick. The reefs are established on a subaerially altered and eroded Oligocene limestone substrate, which largely controlled their distribution.

The maximum age for this reef complex is about 7,000 years B.P., which coincides with the flooding of this inshore area of the Antiguan insular shelf by the rising seas of the Holocene transgression.

The inner limit of the bank-barrier reef was established as a deeper-water *A. palmata* fringing reef that apparently flourished intermittently with the vigorous development of a fore-reef coral-head facies. During the last 3,000 years, the *A. palmata* facies after catching up with sea level, has prograded seaward over the coral-head facies, forming the present-day bank-barrier reef, which is dominated in the fore reef by *A. palmata*. Shoreward of its pronounced emergent reef crest is a back-reef coral rubble substrate.

Apart from short intervals of reef *A. palmata* facies, the lagoon reefs lack an internal rigid reef framework. For the most part, they consist of impressive accumulations of loose in situ coral debris and associated sediments.

Submarine lithification is not well developed in this windward reef complex--being restricted mainly to the reef *A. palmata* facies and the back-reef rubble facies of the bank-barrier reef. The dominantly magnesium calcite cement is similar to submarine cements reported in other reef settings and occurs as a coating on coral skeletons or as extensively bored and filled pavement limestones.

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