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TOPOGRAPHIC CONTROL AND ACCUMULATION RATE OF SOME HOLOCENE CORAL REEFS: SOUTH FLORIDA AND DRY TORTUGAS

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ABSTRACT

Core drilling and examination of underwater excavations on 6 reef sites in south Florida and Dry Tortugas revealed that underlying topography is the major factor controlling reef morphology. Carbon-14 dating of coral recovered from cores enables calculation of accumulation rates. Accumulation rates were found to range from 0.38 m/1000 years in thin Holocene reefs to as much as 4.85 m/1000 years in thicker buildups. Cementation and alteration of corals were found to be more pronounced in areas of low buildup rates than in areas of rapid accumulation rates.

Acropora palmata, generally considered the major reef builder in Florida, was found to be absent in most reefs drilled. At Dry Tortugas, the more than 13-meter thick Holocene reef did not contain *A. palmata*. The principal reef builders in this outer reef are the same as those which built the Pleistocene Key Largo formation, long considered to be a fossilized patch reef complex.

KEY WORDS: Reefs, Topography, Accumulation Rate, Carbon-14, Cement, Dune, Core, Holocene, Pleistocene, Soilstone Crust

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Introduction

This paper briefly describes thickness, rate of accumulation, and documents the localizing effect of pre-Holocene topography on modern coral reefs in the Florida Keys and Dry Tortugas. Observations on thickness and conclusions regarding rate of accumulation and topographic control are based on coring and diver examination of underwater excavations.

Previous investigations in the Florida reef tract having geologic implications were directed toward 1) sediment composition and hermatypic fauna (1,2,3,4,5,6); 2) morphology of reefs, such as reef flats, terraces, spurs and grooves (4,6); and 3) sediment thickness, most extensively described by Enos (7). Enos combined shallow seismic profiling (sparker) and sediment push-coring to determine three dimensional aspects of Holocene sediment accumulations. Although these techniques are superior for back reef and fore reef sediments, their application is limited in coral reefs proper. Push coring is impossible in reefs and seismic signals are so scattered within these unbedded porous accumulations that records are practically useless.*

Rotary drilling devices operated by divers have recently been employed to determine the three dimensional anatomy of a more than 10-m thick Holocene reef in Panama by drilling a 13-hole transect across a relatively small reef (8) and to determine the thickness and lateral extent of coralline algal ridges in St. Croix (9).

In this study a miniaturized version of the drill pioneered by Macintyre (10) was used to drill transects of core holes across 1) Long Reef in Biscayne National Monument, 2) two parallel reefs near Marker G (off Big Pine Key in the lower Florida Keys), and 3) Southeast Reef at Dry Tortugas. Additional information was gained from two underwater dredge sites off Bal Harbor and Virginia Key, and a single core hole drilled at Carysfort Reef off Key Largo, Florida.

The sites are described in order of location from north to south (Fig. 1), followed by sites at Dry Tortugas, an atoll approximately 104 km west of Key West, Florida.

Bal Harbor

Absence of living *Acropora palmata* led Vaughan (1) to conclude that reefs north of Fowey Rock (see Fig. 1) are dead. He attributed lack of this coral to cold waters carried southward by the Florida counter-current. Parallel en echelon reef ridges composed of slow growing massive corals, such as *Montastrea annularis*, *Siderastrea*, *Diploria*, *Dichocoenia*, and *Porites asteroides*, do occur here, however, and extend northward at least as far as West Palm Beach. Scattered colonies of *Solenastrea* and *Siderastrea* occur as far north as the Carolinas (11). These low parallel ridges, often only 10 to 30 m wide and ranging in depth from 5 to 20 m, are separated by carbonate sand-filled swales 100 or more meters wide. All reefs described, except for Southeast Reef at Dry Tortugas, are discontinuous bank accumulations occurring either at the major break in slope on the platform or farther landward on the shelf. An almost continuous unnamed "fossil" reef occurs seaward below the major slope break at depths of 12 to 20 m. The outer reef, not investigated in this study, occurs through the area shown in Figure 1 and extends northward at least to West Palm Beach and probably farther. It is invariably separated from the "named reefs" by a 500- to 1000-m wide sand-filled trough 15 to 30 m deep. Unlike most of the reefs described in this study, the outer deeper reef is known to contain significant amounts of *Acropora palmata* (12).

Maximum thickness of the Bal Harbor reef at the dredge site is 2.4 m. It consists principally of massive corals so altered by boring sponges (13) and infilling of fine-grained sediment as to be almost unrecognizable. Only the centers of some relatively large massive corals escaped profound alteration. These diagenetic processes have resulted in an extremely hard grey "reef rock."

The altered accumulation rests on a laminated soilstone crust (14), which in turn rests on lightly cemented cross-bedded quartz and carbonate sand. Patches of terrestrial plant root systems and occasional land snails of the genus *Cerion* were found in the upper portion of the sand accumulation (Fig. 2). These features are all suggestive of eolian origin, probably as parallel coastal dunes similar to those common to the coast today.

Interpreted Geologic History

The area was flooded between 6 and 7 thousand years ago (Table 1) and corals began to populate the cemented sand dune ridges, while sediments, which retard the settling and attachment of corals, began accumulating in interdune swales. Corals continued to grow but the accumulation was unable to keep pace with sea level in this transitional area, where southward extending cold waters during winter months prevent the existence of rapidly growing species. This interpretation suggests that linearity and distribution of these parallel reefs are controlled solely by underlying dune topography.

* Uniboom was employed in this study and sparker had been tried previously. Neither provided significant information within the reefs but worked well in fore and back reef deposits.

Accumulation Rate

A single unaltered coral, *Siderastrea* sp., attached to the laminated soilstone crust, was collected and dated by the C-14 method. As shown in Table 1, this coral has a radiocarbon age of 6300±120 yrs. Assuming continual buildup since that time and assuming the reef is still growing, the average accumulation rate is 0.38 m/1000 years.

Sewer Trench Exposure

Eighteen km to the south of Bal Harbor, a similar reef accumulation has been cut by a sewer line excavation (Fig. 1). The trench is approximately 6 m deep by 8 m wide and extends through several tens of meters of reef. A profile of samples similar to that at Bal Harbor was collected (Fig. 3).

Maximum thickness of Holocene reef accumulation examined was 3.7 m. The section differs from that at Bal Harbor in that corals are not unusually altered and the rock is predominantly light grey to pure white. Cementation was not evident. Large well preserved massive corals are readily apparent and the accumulation contains numerous interconnected passageways up to 30 cm across. The predominant coral species are the same as at Bal Harbor and *Acropora palmata* is absent.

A laminated soilstone crust underlies the reef and rests on semi-lithified quartz and carbonate sand (Fig. 3). Plant roots were visible in the underlying sand, but land snails and cross-bedding were not detected. Because the section examined was entirely within the reef, it was not possible to see changes where the trench cut through adjacent off-reef sands. A clear relationship with the underlying rock topography could not be determined. Nevertheless, the reefs in this area are parallel, as off Bal Harbor, and the geologic history is assumed to be similar. The shallower water and younger radiocarbon age

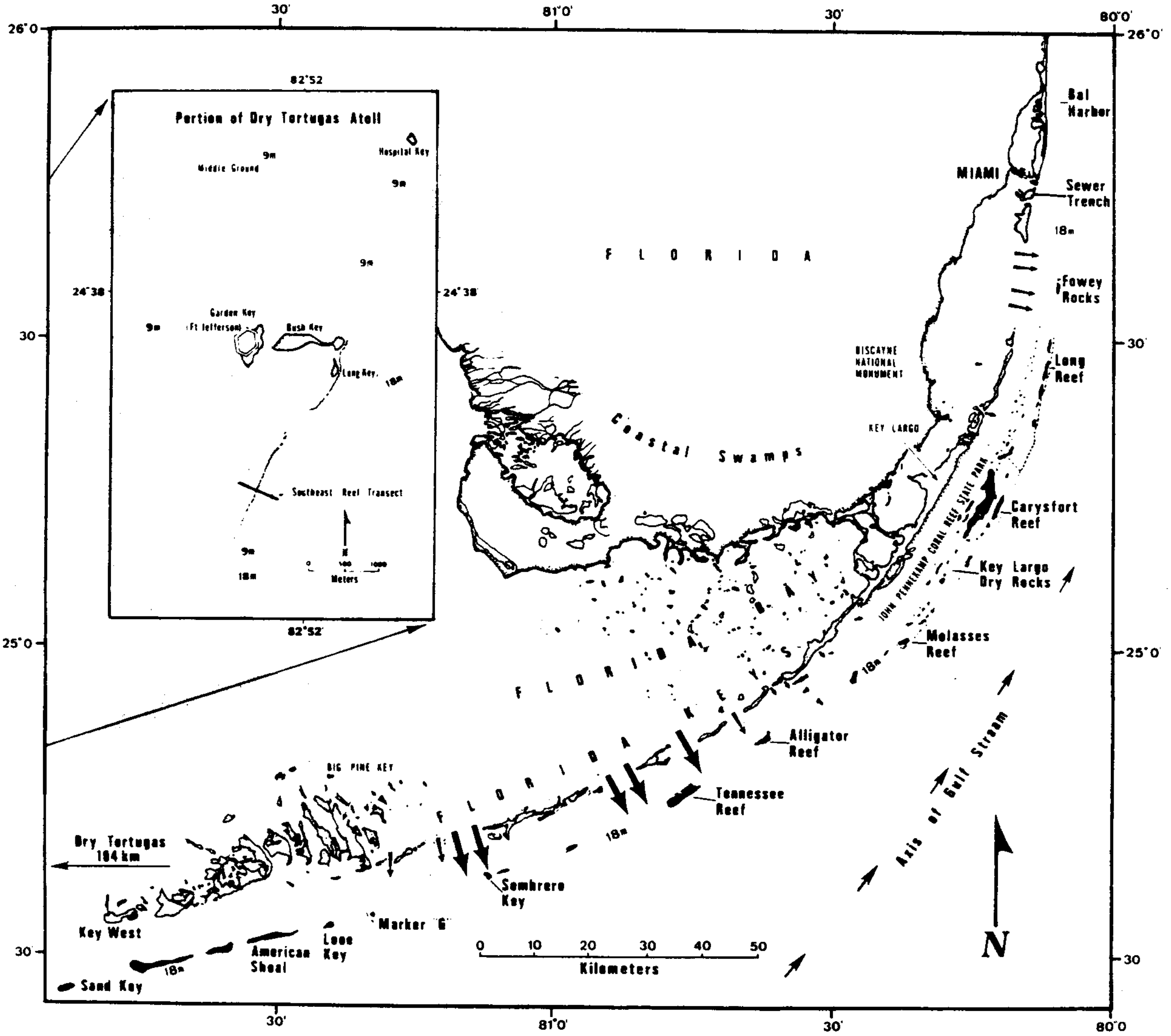

Fig. 1. Index map of study area. Pulaski Reef and Loggerhead Key at Dry Tortugas are not shown.

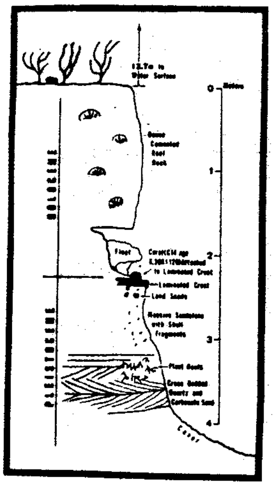

Fig. 2. Measured section in Bal Harbor excavation

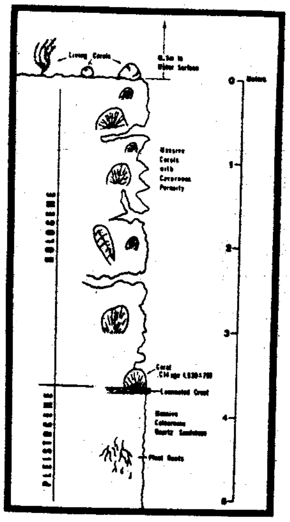

Fig. 3. Measured section in sewer trench.

(see Table 1), however, indicate the area was still dry land when the Bal Harbor reef started accumulating.

Accumulation Rate

A sample of *Montastrea cavernosa* at the base of the 3.7-m thick reef and attached to the soilstone crust gave a C-14 age of 4930±70 yrs. This age implies an average accumulation rate of 0.74 m/1000 years (Table 1).

Long Reef

Long Reef, the longest single shallow reef in the Florida Keys, lies east of Elliot Key within Biscayne National Monument. Approximately 4 km long and about 100 m wide above the 3-m contour, it is almost entirely an accumulation of coral rubble dotted sparsely with live massive corals, some *Acropora palmata*, and abundant encrustations of *Millepora* sp. To the west the coral rubble ridge merges with an extensive pasture of *Thalassia* at a depth of approximately 2.5 m and slopes westward down to a depth of about 8 m. To the east live coral growth, including scattered colonies of *Acropora palmata*, extends out to a depth of 8 to 10 m, where coral merges with carbonate sand. Another reef ridge composed of few live corals lies approximately ½ km to the east in 12 to 15 m of water near the edge of the deep Straits of Florida.

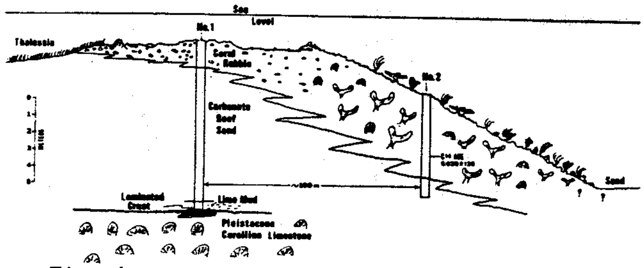

Fig. 4. Interpreted east-west cross section through Long Reef.

Two core holes were drilled at Long Reef, one in 2 m of water on the crest and one in 4.6 m about 100 m to the east (Fig. 4). In hole #1 only 1.5 m of coral was encountered, none of which is considered to be in situ. This coral rubble is underlain by approximately 8 m of uncemented carbonate sand, which rest on about 0.5 m of carbonate mud similar to that found nearshore and in Florida Bay. The carbonate mud lies directly on a laminated soilstone crust, which has developed over coralline limestone presumably equivalent to the Pleistocene Key Largo Formation. Hole #2 encountered mostly corals thought to be in situ. The most common coral was *A. palmata*, much of it lightly cemented. The hole did not reach bedrock because of drilling difficulties caused by loose carbonate sand encountered below 5 m.

Interpreted Geologic History

Though more core holes are needed to make the section complete, much can be deduced from the information already obtained. The data at hand suggest a paradox. How did carbonate mud and sand accumulate to form a "reef?" Clearly, Long Reef is not a reef in the classical sense, i.e., vertical buildup resulting from coral growth. Mud accumulating so near high energy conditions of the platform margin implies the presence of a seaward barrier to dampen ocean swells and seas. The authors think that, during a period of lowered sea level 4 to 6 thousand years ago, the more eastward reef grew to sea level and produced a quiet back reef area where mud could accumulate.

Accumulation Rate

Suitable material for dating was not obtainable from the sand encountered in core hole #1, but in situ coral was recovered from hole #2. *Montastrea annularis* from 3.7 m down gave a C-14 date of 5630±120 yrs which, assuming continual buildup, implies an accumulation rate of 0.65 m/1000 years (Table 1). Lack of prolific growth and present water depth suggest continuous growth rate cannot be assumed, although uninterrupted growth at fluctuating rates is likely.

SAMPLE SITE	LAT./LONG.	MATERIAL DATED	DEPTH IN SECTION (m)	INTERVAL BETWEEN SAMPLES	WATER DEPTH (m)	DEPTH FROM WATER SURFACE TO SAMPLE (m)	AGE DIFFERENCE BETWEEN SAMPLES	C^{14} AGE (yrs BP)	ACCUMULATION RATES (m/1000 yrs) FROM CORE TOP TO SAMPLE	INTERVALS BETWEEN SAMPLES
A	25°54'N/ 80°06'W	*Siderastrea*	2.4		13.7	16.1		6,380 ± 120	0.38	
B	25°44'N/ 80°07'W	*M. cavernosa*	3.7		6.1	9.8		4,930 ± 70	0.74	
C	25°27'N/ 80°07'W	*M. annularis*	3.7		4.6	8.2		5,630 ± 120	0.65	
D	25°13'N/ 80°12'W	*M. annularis*	4.0		1.8	5.8		4,570 ± 85	0.88	
				3.3			680			4.85
D		*M. annularis*	7.3		1.8	9.1		5,250 ± 95	1.38	
E	24°34'N/ 81°20'W	*M. annularis*	3.1		9.0	12.0		6,170 ± 80	0.40	
				1.5			990			1.51
E		*M. annularis*	4.6		9.0	13.4		7,160 ± 85	0.56	
E		————	8.2		9.0	17.1		37,480 ±1300	—	
F		*Colpophyllia*	3.1		8.0	10.7		4,735 ± 85	0.64	
G	24°37'N/ 82°52'20"W	*M. annularis*	4.9		0.3	5.2		3,593 ± 88	1.35	
				4.2			1,169			3.59
G		*M. annularis*	9.1		0.3	9.4		4,762 ± 85	1.91	
				4.0			1,121			3.56
G		*M. annularis*	13.1		0.3	13.4		5,883 ± 224	2.22	
				0.6			134			4.47
G		*M. annularis*	13.7		0.3	14.0		6,017 ± 90	2.28	
G		*M. annularis*	15.2		0.3	15.5		36,272 ±2146	—	
H	24°41'40"N/ 81°47'20"W	*M. annularis*	4.6		6.7	11.3		5,865 ± 90	0.77	
				2.1			730			1.36
H		*M. annularis*	6.7		6.7	13.4		6,595 ± 115	1.01	
				1.5			570			2.63
H		*Diploria*	8.2		6.7	14.9		7,165 ± 90	1.14	

Table 1. Sample sites: A-Bal Harbor 3-8-2; B-Sewer trench; C-Long Reef #2; D-Carysfort #1; E-Harbor C, Bahia Honda #1; F-Harbor C, Bahia Honda #2; G-Tortugas Southeast Reef #2; H-Pulaski Reef #1.

Carysfort Reef

A single core was drilled approximately 60 m seaward of Carysfort Reef lighthouse in 1.8 m of water. The site within Pennekamp Coral Reef Park off Key Largo is known for its luxuriant corals and abundance of *Acropora palmata*. Prolific coral growth in the park has been attributed to relative lack of tidal passes (15,16,17).

The cored section at Carysfort consisted of 13 m of Holocene coral containing abundant *A. palmata* resting on coralline Pleistocene limestone. Much of the coral material encountered appears to be in growth position.

No attempt is made to interpret the geologic history from only one core hole, other than to note that the seaward side of this reef appears to be the result of coral buildup rather than mechanical accumulation. The authors suspect, however, that sand underlies the prolific *A. palmata*-capped reef flat and the *Thalassia* beds immediately landward of the reef.

Accumulation Rate

A sample of *Montastrea annularis* from 4.0 m down hole gave a C-14 age of 4570±85 yrs, and a similar sample from 7.3 m gave an age of 5250±95 yrs (Table 1). The upper sample indicates an accumulation rate of 0.86 m/1000 years, whereas the lower sample indicates a rate of 1.39 m/1000 years. An accumulation rate of 4.85 m/1000 years is indicated for the interval between the two dated samples.

Marker G Reefs

Reefs in this area generally form parallel bands separated by carbonate sands, similar to the situation off Bal Harbor. Two such reefs and the sand area separating them were drilled near Marker G off Bahia Honda and Big Pine Keys, approximately 7 km northeast of Looe Key Reef.

The cross section in Figure 5 indicates that the Holocene reef accumulations mimicked the underlying Pleistocene reef both in topography and facies. However, whereas the Pleistocene is cemented, cement is absent in the Holocene. Not only is the Pleistocene basement composed of the same coral species, but also the bedrock underlying carbonate sand is composed of similar carbonate reef sand. A well developed soilstone crust caps the chalky cemented grainstone. The Holocene in this area appears to be a geologic "replay" of the Pleistocene.

Interpreted Geologic History

Although it is clear that Pleistocene topography at Marker G played the same role as at Bal Harbor, it is not known what caused the Pleistocene reefs to grow in parallel bands separated by carbonate sand. Possibly, sand dune topography in an earlier phase of Pleistocene reef growth controlled reef distribution in the same manner as during the Holocene at Bal Harbor. Only deeper drilling will determine if this hypothesis is correct.

Accumulation Rate

Material from two core holes were dated to determine approximate accumulation rates (Table 1). In BH #1 a *Montastrea annularis* sample from 3.1 m gave a C-14 age of 6170±80 yrs, indicating an accumulation rate of 0.49 m/1000 years, whereas a sample from 4.6 m dated at 7160±85 yrs gave a rate of 0.56 m/1000 years. A rate of 1.51 m/1000 years is calculated for the interval between 3.1 and 4.6 m. The sample from 8.2 m was 37,480±1300 yrs, confirming its Pleistocene age. Its true age is probably much older, but diagenetic calcite, resulting from pre-Holocene exposure to meteoric water, biased the counts toward a younger age. At 3.1 m down hole in BH #2, a species of *Colpophyllia* gave a C-14 age of 4735±85 yrs, indicating an accumulation rate of 0.64 m/1000 years.

Fort Jefferson National Monument
Dry Tortugas

Five core holes were drilled in a transect across Southeast Reef near Fort Jefferson (Fig. 1). As shown in cross section (Fig. 6), three cores reached and recovered Pleistocene bedrock. Other cores were drilled at Pulaski Reef, Loggerhead Key and at a site north of Fort Jefferson near the atoll center. Only the cores at Southeast Reef will be discussed here.

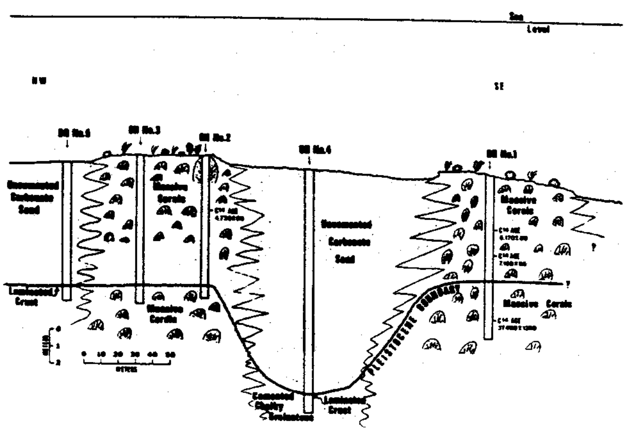

Fig. 5. Interpretive cross section through two parallel reefs at Marker G.

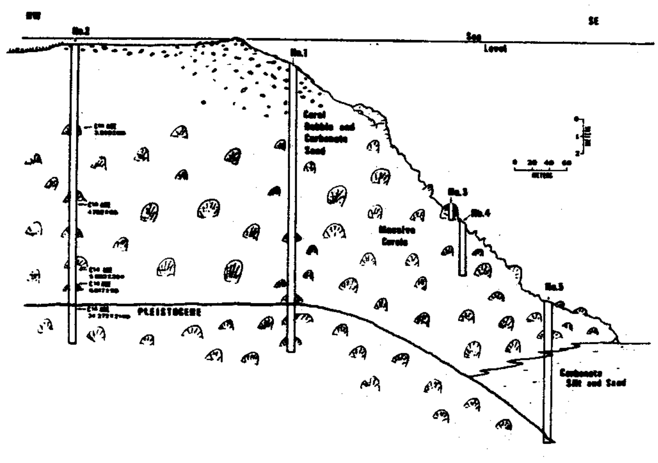

Fig. 6. Interpretive cross section through Southeast Reef.

The Southeast Reef drilling revealed the thickest Holocene reef section encountered. At hole #1, just seaward of the reef crest, and at hole #2 on the reef flat, the Holocene accumulattion is more than 13 m thick. In hole #5 in 24 m of water the section is reduced to 8 m. Pleistocene bedrock was difficult to identify in the field due to absence of laminated soilstone crusts and relative absence of leached porosity and calcite cement. Presence of black soil in tiny pockets beneath the unconformity and desiccation cracks in cemented internal sediment were the only identifying clues. The coral fauna was identical to that in the Holocene section above. Carbon-14 dating confirmed the Pleistocene interpretation (Table 1).

The most significant finding is the absence of *Acropora palmata*, long considered the major Holocene reef builder in the Caribbean. Although three small living colonies were discovered after extensive investigation, no *A. palmata* was found in cores or in the coral rubble comprising the reef crest and flat.

Interpreted Geologic History

The presence of identical coral fauna and intimation of a Pleistocene reef rim suggest that Dry Tortugas is built on a Pleistocene atoll. With the Holocene transgression, corals became established on and around the topographic rim and continued to keep pace with rising sea level. With progressive sea level rise, coral rubble and reef sand were thrown landward to produce a section similar to that at Long Reef. In Figure 6 note the abundance of carbonate sand in the first 5 m beneath the reef crest. The presence of this sand and rubble demonstrates, as it did at Long Reef, that the reef did not grow upward in the manner traditionally ascribed to reef growth, but rather as a mechanical accumulation. Perhaps physical accumulation, probably during hurricanes, is responsible for the reef's ability to keep pace with sea level rise. Below the sand, typical coral reef growth obtains.

Accumulation Rate

Carbon-14 dating of coral samples from hole #2 (Fig. 6 and Table 1) shows that Southeast Reef accumulated at a rate greater than most other reefs in south Florida. Coral from 9.1 m dated at 4762±85 yrs, indicating an accumulation rate of 1.91 m/1000 years, whereas a sample from 13.1 m dated at 5883±224 yrs, a rate of 2.22 m/1000 years. Another sample from 13.7 m, dated at 6017 ±90 yrs, gave a calculated accumulation rate of 2.28 m/1000 years. Calculated rates for the intervals between dated samples gave uniform accumulation rates of 3.59 to 4.47 m/1000 years. A sample from 15.2 m, dated at 34,272±2146 yrs, confirmed that the bedrock is of Pleistocene age.

Discussion

Topographic Control

Examinations of underwater outcrops indicate that, for the most part, reefs accumulated over pre-existing highs, such as dune topography at Bal Harbor and reef topography at Marker G. Other reefs, such as Long Reef and Southeast Reef, are clearly located at a major break in slope, probably formed by reef growth during Pleistocene time. Similar topographic control for patch reefs behind the Belize barrier reef has been reported (18).

Accumulation Rates and Sea Level Rise

A clear relationship exists bewween radiocarbon age and relative thickness of accumulation. The bedrock upon which the sewer trench reef commenced growth is only 9.8 m below sea level compared to 16.1 m at Bal Harbor. The C-14 dates indicate that the Bal Harbor reef had been growing for a little over 1000 years when reef growth began at the sewer trench. Because of its shallower depth, the sewer trench site was probably dry land when reef growth started at Bal Harbor. In both areas rise in sea level eventually outpaced the reefs' ability to grow. In areas of thicker accumulation, rates of buildup were faster.

Two kinds of accumulation rates have been calculated (see Table 1) by 1) dividing the interval between dated samples and the top of core or section (i.e., the sea floor) by the C-14 age of the sample, and 2) dividing the interval between two dated samples within the section by the difference in C-14 age of the two samples. The latter method is considered the most reliable estimate of accumulation rate. Rates determined this way range from 4.85 to 1.36 m/1000 years. Rates derived by method #1 above are less reliable in that they assume the reef is still growing, whereas erosion may, in fact, have been exceeding accumulation for the past 1000 years or more.

Where reefs have reached the surface, such as at Tortugas Southeast Reef, accumulation must necessarily cease, because the rate of relative sea level rise has been greatly reduced during the past 3 to 4 thousand years (19, 20, 21).

Significance of *Acropora palmata*

The lack of *Acropora palmata* in the Southeast Reef and at Marker G may have environmental implications for growth of the Pleistocene reef forming the Key Largo Formation. It has been suggested that the absence of *A. palmata* implies a patch reef origin for the Key Largo Limestone (22) Patch reefs growing today do not contain *A. palmata*, and their coral fauna is identical with that in the Key Largo. Further credence for this hypothesis came from comparison of a linear chain of inshore patch reefs off Newfound Harbor in the lower Florida Keys with the Key Largo Formation (23).

Discovery that the reefs at Marker G and those at Dry Tortugas have the same coral fauna as the Key Largo Formation, but lack *A. palmata*, shows that it is no longer necessary to call on a patch reef origin. Reefs can form and keep pace with sea level at the platform margin, for reasons not understood, without the help of *A. palmata*.

Future work will be aimed at understanding why this coral is absent from Dry Tortugas.

Conclusions

1. Most linear coral reefs in south Florida and Dry Tortugas have been localized by pre-existing topography, some of which is formed by pre-existing coral reefs.
2. Rates of coral reef accumulation are greater in the area off Key Largo and at Dry Tortugas than anywhere else in the Florida reef tract.
3. Cementation is most widespread in the reefs where the accumulation rates are relatively slow. The observation that submarine cementation was generally restricted to those areas of relatively slow accumulation, i.e., Bal Harbor, is in keeping with the conclusions of Shinn (23) elsewhere. Rapid accumulation results in burial of sediments to depths below the reach of circulating sea water, the source of marine calcium carbonate precipitates.
4. *Acropora palmata* was never significant in the buildup of reefs at Dry Tortugas and Marker G.
5. The bulk of the shallow reef at Long Reef and the upper portion of the shallow reef at Dry Tortugas is not coral reef in the classical sense, but rather bioclastic accumulation of sand-size sediment veneered with coral rubble and scattered live colonies.
6. Rates of reef buildup were probably greater during the early history of reef growth than today.

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