GUIDE TO SEDIMENTATION FOR THE DRY TORTUGAS

compiled by
Robert B. Halley

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Figure 1. Location of field trip stops in the Dry Tortugas. Also see front and back inside covers.
INTRODUCTION

Robert B. Halley
Fisher Island Station
Miami Beach, Florida

The Dry Tortugas are a remote and exotic set of islands some 70 miles west of Key West, Florida. They form points of land in a tropical marine preserve which harbors areas of outstanding historical and biological interest. It is impossible to visit the Tortugas without being enraptured by the stark beauty of the islands and the thriving lushness of the surrounding reefs. Visitors are encouraged to pursue their particular interests beyond geology while in the Tortugas, although this guide emphasizes the sedimentology of the area.

The collections of papers in this volume are compiled to serve as a general introduction to sedimentation in the Dry Tortugas. Individual contributions touch on physical, chemical, biological and historical aspects of carbonate sedimentation in the area. The papers are not exhaustive studies, but rather they provide background on a broad front for the educated layman.

The Tortugas field trip consists of five stops located on Figure 1 and the front and back covers. The stops and the papers from this volume which apply to each stop are as follows:

STOP 1. East Key (Davis and O'Neill)
STOP 2. Garden Key (Meeder; G.E. Davis; Anonymous)
STOP 3. Southeast Reef (Meeder; G.E. Davis; Shinn and others)
STOP 4. Loggerhead Patch Reefs (Meeder; G.E. Davis)
STOP 5. Loggerhead Key (Ginsburg; Halley and Steinen)

Four of the included papers are new publications for this volume. Two are reproduced with the permission of the authors and respective publishers. They originally appeared as:


Stops 1, 3 and 4 and a portion of Stop 2 are snorkeling stops, and visitors are encouraged to review the articles pertaining to these stops before entering the water. Have fun!
Fort Jefferson National Monument, Florida

Fort Jefferson, largest of the 19th-century American coastal forts, is the central feature of the seven Dry Tortugas Islands and the surrounding shoals and waters of the Gulf of Mexico that make up Fort Jefferson National Monument. Though off the beaten track, the monument is famous for its bird and marine life, as well as for its legends of pirates and sunken gold.

Dry Tortugas

Like a strand of beads hanging from the tip of Florida, reef islands trail westward into the Gulf of Mexico. Almost 70 miles west of Key West, is a cluster of coral keys called Dry Tortugas. In 1513, Spanish explorer Ponce de Leon named them las Tortugas--the Turtles--because of "the great amount of turtles which there do breed." The later name, Dry Tortugas, warns the mariner that there is no fresh water here.

Past Tortugas sailed the treasure-laden ships of Spain, braving ship-wreck and corsairs. Not until Florida became part of the United States in 1821 were the pirates finally driven out. Then, for additional insurance to a growing United States commerce in the Gulf, a lighthouse was built at Tortugas, on Garden Key, in 1825. Thirty-one years later the present 150-foot light was erected on Loggerhead Key.

The strategic importance of the Tortugas was recognized early. In the words of the naval captain who surveyed the Keys in 1830, Tortugas could "control navigation of the Gulf." Commerce from the growing Mississippi Valley sailed the gulf to reach the Atlantic. Enemy seizure of the Tortugas would cut off this vital traffic, and a fleet operating from this strategic base could be effective against even a superior force.

There were still keen memories of Jackson's fight with the British at New Orleans, and England was currently developing her West Indies possessions. Trouble in Cuba was near. Texas, a new republic, seemed about to from an alliance with France or England, thus providing the Europeans with a foothold on the gulf coast. To guard against this possibility, Fort Jefferson was built on Garden Key.

Key to the Gulf of Mexico

During the first half of the 1800's the United States began a chain of seacoast defenses from Maine to Texas. Fort Jefferson, one-half mile in perimeter, was the largest link in the chain. From foundation to crown its 8-foot-thick walls stand 50 feet high. Its three gun tiers were designed for 450 guns, and it was large enough to garrison 1,500 men. Planned and supervised by the U.S. Army Corps of Engineers, the fort was started in 1846, and, although work went on for almost 30 years, it was never finished. Artisans imported from the North and slaves from Key West made up most of the labor force. After 1861 the slaves were partly replaced by military prisoners, but slave labor did not end completely until Lincoln freed the slaves in 1863.
Federal troops occupied the half-completed, unarmed Fort Jefferson on January 19, 1861, to keep it from falling into the hands of Florida secessionists, but aside from a few warning shots at Confederate privateers there was no action. The average garrison numbered 500 men, and building quarters for them accounted for most of the wartime construction.

Little important work was done after 1866, for the new rifled cannon had already made the fort obsolete. Further, the engineers found that the foundations rested not upon a solid coral reef, but upon sand and coral boulders washed up by the sea. The huge structure settled, and the walls began to crack.

For almost ten years after the war, Fort Jefferson remained a prison. Among the prisoners sent there in 1865 were several of the "Lincoln Conspirators"—Michael O'Loughlin, Samuel Arnold, Edward Spangler, and Dr. Samuel A. Mudd. Dr. Mudd, knowing nothing of President Lincoln's assassination, had set the broken leg of the fugitive assassin, John Wilkes Booth. The physician was convicted of conspiracy and sentenced to life imprisonment at hard labor.

Normally, the Tortugas was a healthful post, but in 1867 yellow fever came. From August 18 to November 14 the epidemic raged, striking 270 of the 300 men at the fort. Among the first of the 38 fatalities was the post surgeon, Maj. Joseph Sim Smith. Dr. Mudd, together with Dr. Daniel Whitehurst from Key West, worked day and night to fight the scourge. Two years later, Dr. Mudd was pardoned.

Because of hurricane damage and another fever outbreak, Fort Jefferson was abandoned in 1874. During the 1880's, however, the United States began a naval building program, and Navy men looked at this outpost as a possible naval base. From Tortugas Harbor the battleship Maine weighed anchor for Cuba, where she was blown up in Havana Harbor on February 15, 1898. Soon the Navy began a coaling station outside the fort walls, bringing the total cost of the fortification to some $3.5 million. The big sheds were hardly completed before a hurricane smashed the loading rigs.

One of the first naval wireless stations was built at the fort early in the 1900's, and, during World War I, Tortugas was equipped to serve as a seaplane base. But as the military moved out again, fire and storms and salvagers took their toll, leaving the "Gibraltar of the Gulf" a vast ruin.

Tortugas Birds

One of our great national wildlife spectacles occurs each year between April and September, when the sooty terns gather on Bush Key for their nesting season. The terns come by the thousands from the Caribbean Sea and west-central Atlantic Ocean. As early as mid-January, sooties begin conducting nocturnal maneuvers over the Tortugas, spending their days at sea. Presumably, mating occurs during this time, for when they land on Bush Key in March, egg-laying begins immediately. Their nests are no more than depressions in the warm sand. The parents take turns shading their single egg from the sun. When the young are strong enough for continuous flight, the colony disperses. Unless hurricanes carry them farther north, most adult sooties spend the winter in the Gulf and northwest Caribbean. Juvenile sooties, however, leave
their parents and follow an indirect, 9,000-mile route to West Africa and do not return to the Tortugas until at least their fourth summer.

The presence of these tropical oceanic birds at Tortugas was recorded by Ponce de Leon (1513), Capt. John Hawkins (1565), John James Audubon (1832), and Louis Agazzis (1858). Prior to the early 1900's commercial egg raiding reduced the colony to a mere 4,000 individual birds. From 1903 a resident warden effectively protected the birds during the nesting season, and today the rookery contains an estimated 100,000 breeding adults. A colony of brown noddies, interspersed among the sooties, comprises only about 2,500 birds, but the population is slowly increasing. The two species share the ability to capture fish and squid from the surface of the water while in flight, rather than diving into it as do most terns.

Large numbers of frigatebirds also congregate at the Dry Tortugas in summer. With a wingspan of almost 7 feet, the frigatebird is among the most graceful of soaring birds. Though it may occasionally indulge in aerial piracy, it usually captures its own fish from the water. A few blue-faced and brown boobies are observed occasionally. Roseate terns nest on Hospital, Bush, and Long Keys at the same time other terns are nesting. In season, a continuous procession of songbirds and other migrants fly over or rest at the islands, which lie across one of the principal flyways from the United States to Cuba and South America. Familiar gulls and terns of the North, as well as many migratory shore birds, spend the winter at Tortugas.

Marine Life

The warm, clear waters of the Gulf of Mexico and maximum available light combine to produce optimum conditions for the development of coral reefs. These formations are associated with the shallow waters on the outer edge of off-shore tropical islands. The true builders of coral reefs are small primitive animals called polyps. Over the centuries accumulations of living polyps have formed coral colonies of rigid structures.

The reef complex supports a myriad of marine life. Multicolored sea ferns sway in the gentle ocean currents, beckoning the viewer to take a closer look; sea anemones thrust their rose and lavender tentacles upward in search of food; a lobster's antennae wave frantically, trying to detect potential danger. Other strange animals, including several species of sponges of various sizes and colors, dot the sandy bottom. Large clusters of staghorn coral resemble an underwater forest.

Indiscriminate hunting has diminished the sea turtle population, but these large creatures are still observed in the Dry Tortugas area. Species seen recently include hawksbill, green and loggerhead turtles. Thousands of hatchling green turtles have been released on the beaches of Everglades National Park and Fort Jefferson National Monument in an effort to enlarge populations. Other such releases were made throughout the Caribbean area, and additional releases are planned for future years.

Although a diversity of lower animal forms inhabits the reef, the most dominant creatures are the scores of aggressive and colorful small fishes.
The varied hues serve the purposes of camouflage, recognition, warning, or as an aid to courtship. The small fish attract larger ones, including the amberjack, grouper, wahoo, and tarpon, which play an important ecological role by feeding on the smaller fish and keeping their numbers in check. All the residents of the coral reef must be constantly alert for the marauders of the sea—the ever-cruising shark and the swift-moving barracuda. Sitting atop the food chain, these predators are also essential in maintaining a natural balance in the marine habitat.

Plants

Fewer than 50 species of land plants are native to the Dry Tortugas, because the saline soil, long droughts, and frequent storms impose severe growing conditions. Many plants have been introduced, either accidentally or for ornamental purposes. On Garden and Loggerhead Keys, the latter group includes such conspicuous plants as coconut and date palms, tamarind, Australian pines, gumbo-limbo, and century plants.

The native flora is tropical, mainly mangrove (or buttonwood), bay cedar, sea-grape, sea-lavender, purslane, and seaoats—all typical of Florida's lower east coast.
Morphodynamics of East Key, 
Dry Tortugas, Florida

by

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East Key is located on a large crescent shaped bank which comprises essentially the eastern half of the Dry Tortugas complex. The island is slightly elongate in a north-south direction. Its present size of 262m by 120m is less than half of what it was about 60 years ago (Bowman, 1918) although East Key is still one of the largest of the seven islands in the Dry Tortugas group.

In addition to long term changes in shape, size and location, East Key also displays significant changes in morphology on a seasonal basis. These various changes have been documented through charts, aerial photographs and field surveys (O'Neill, 1976).

General Sedimentology

The most detailed recent studies of Dry Tortugas sediments in general (Jindrich, 1972) and East Key in particular (O'Neill, 1976) are unpublished theses. The sediment on East Key is generally coarse sand with a range in mean grain size from -0.75Ø to 1.80Ø and a grand mean of 0.90Ø. Sorting ranged from 0.80Ø to 0.35Ø with an average value of 0.57Ø. Virtually all samples from East Key are negatively skewed (coarse) with the mean value of -0.22 (O'Neill, 1976). There is a general tendency for sediments to coarsen both seaward and landward of the berm. Sorting is generally poor in the interior of the island and increases from the berm down to the foreshore slope.

Surveys conducted by the U.S. Army during the civil war indicated the presence of beachrock on East Key (Manucy, 1961) however none has been reported subsequently.

The most detailed analysis of sediment composition is that by O'Neill (1976) who point-counted 35 thin sections collected from three of the profiles surveyed. All sediment grains are biogenic with Halimeda being the most abundant constituent. Mean values of the 35 samples are:

<table>
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<tr>
<td>Halimeda</td>
<td>52%</td>
</tr>
<tr>
<td>Coral</td>
<td>35%</td>
</tr>
<tr>
<td>Mollusks</td>
<td>6%</td>
</tr>
<tr>
<td>Coralline algae</td>
<td>3%</td>
</tr>
<tr>
<td>Foraminifera</td>
<td>1%</td>
</tr>
<tr>
<td>Echinoids</td>
<td>1%</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>2%</td>
</tr>
</tbody>
</table>

1Present address: 7076 Maida Lane, Fort Meyers, Florida 33901
These values compare well with the single sample analyzed by Jindrich (1972) although he found about twice the percentage of mollusks.

Morphology

East Key rests on a shallow bank with depths from near 2 meters. The subtidal zone adjacent to the island is typically gently sloping except on the west side where the bottom is inclined at the angle of repose of the coarse biogenic sand. Grain flow has been observed along this area. This steep slope terminates abruptly at a depth of near 2 meters.

The island is slightly elongate with the long axis striking about NNE. Maximum elevation recorded by O'Neill (1976) was 2.1 meters above mean tide level. East Key is characterized by high storm beach-ridges on the east and west sides of the island with a low central area (Fig. 1). The central two-thirds of the island is relatively stable with significant changes occurring on both the north and south ends.

Historical Changes

Numerous changes in the size, shape, location and even the presence of islands in the Dry Tortugas are documented in the historical record (O'Neill, 1976). East Key is among the most dynamic of the group. The survey by Gauld (1973-75) shows it to be the second largest of the Tortugas Group. At that time East Key had a northwest-southwest orientation and a teardrop shape with the small end pointing to the southwest. A survey in 1829 (Robertson, 1964) indicated that East Key had an areal extent of 4.9 km² with an elevation of 1.2m. The Gerdes map of 1850-51 shows that East Key is smaller than North Key however this is probably in error. No other map shows such a size relationship and Blunt's map of 1858 agrees with the Gault map (1773) that East Key is next in size to Loggerhead Key.

A post-Civil War map of Platt (1867-68) shows the position of East Key but the condition of the map is such that the outline cannot be delineated. His subsequent survey (Platt, 1875) shows East Key to have a teardrop shape but with its orientation reversed from that shown on Gauld's map (1773); the small end points to the northwest (Fig. 2). East Key reached its maximum size during the latter part of the 19th century (Platt, 1875; Barnette, 1898) and its northwest-southeast orientation persisted (Fig. 2).

There has been significant decrease in the size of East Key since the turn of the century. Bowman (1918) gave a size of 533m by 267m, Davis (1942) measured it as 364m by 181m and O'Neill's (1976) surveys showed a decrease to 262m by 120m.

The above historical changes consider the size and shape of East Key. While these shape changes and size reductions were taking place the location of East Key was also shifting. The absolute position of East Key for the first century of its charted history appears to be at the same approximate location although detailed bathymetry makes relative positioning difficult. East Key appears to be at the same position relative to the bank edge in both the Gault map of 1773 and the Blunt map of 1858 (O'Neill, 1976). Although the northwestern tip of the island was close to the edge of the bank in 1875 (Fig. 2) the bulk of the island mass was shifted to the southeast.
Fig. 1 - Topography of East Key as of September 1, 1975. Datum is MLT. (After O'Neill, 1976).

Fig. 2 - Historical changes in size, shape and location of East Key. 1875 and 1893 data from maps; 1960 and 1974 data from aerial photographs. (After O'Neill, 1976).
During the past century there has been significant southeasterly migration of East Key. Using the edge of the shallow bank upon which the island rests it is possible to view this migration (Fig. 2). Between 1875 and 1898 there was little apparent change although there appears to have been a shift to the southwest of about 70-80 meters. Great movement of East Key occurred between 1898 and 1960 when it moved nearly 200 meters to the southeast (Fig. 2). Southeast-erly movement of the adjacent North Key and Northeast Key caused their disappearance because they moved from the bank edge into the deep lagoon (O'Neill, 1976).

Between 1960 and 1974 easterly movement of East Key was documented by aerial photographs (Figs. 2 and 3). In 1960 the stabilized or vegetated portion of East Key shows only a single beach ridge. The subsequent photo from 1974 shows several accretion ridges on the east side of the island in both the vegetated and unvegetated portion of the island (Fig. 3). The geomorphic pattern corroborates a recent easterly movement of East Key.

**Seasonal Changes**

One of the primary objectives of the recent study by O'Neill (1976) was to determine the nature and extent of seasonal changes in the configuration of East Key, if in fact such changes could be documented. The island was surveyed in detail in July, 1974, December, 1974, April, 1975 and September, 1975. Permanent survey stakes were implaced during the first survey and reoccupied during subsequent visits. Each topographic survey was related to mean low tide.

Certain topographic elements of East Key were present during each of the four surveys and serve as excellent reference locations for changes in island configuration. They are: 1) a high ridge on the west-central island, 2) a low area just north of center, 3) a high ridge adjacent and east of the low area and 4) a high ridge on the southeast side (Fig. 4). These features characterize a central and static core of East Key with significant changes occurring at the north and south ends of the island.

During the July, 1974 survey, East Key displayed a sizeable platform, nearly a meter above MLT and extending about 50 meters to the north of the core area. Less than 6 months later and during the winter (December, 1974) there has been extreme change in East Key. The platform on the north end had been removed and a large extension had developed on the south end of the island (Fig. 4). This "tail" extended about 60 meters beyond the southern limit of the island during the July survey producing a total change of more than 100 meters although the actual size of the island remained essentially the same.

Between December, 1974 and April, 1975 the large "tail" on the south end of East Key was removed and a new northerly platform had developed, similar but smaller than the one present during the first survey (Fig. 4). The final survey in September, 1975 showed that there had been some additional accretion to the north in comparison to the previous survey.

Although only a little more than a year's time was included in this portion of the study, there seems to be a pattern to the changes in morphology of East Key and there is a reasonable explanation for these changes. A dominant wind component from the south in the spring and summer creates waves from the south resulting in erosion to the southern portion of the island and accretion on the
Fig. 3 - Aerial photographs of East Key in 1960 (Top) and 1974 (Bottom) showing movement as compared to a fixed point. (After O'Neill, 1976).
Fig. 4 - Seasonal changes in shape of East Key during 1974-75. Data taken from O'Neill, 1976.
north. During the winter northerly winds dominate and cause the opposite effect. Winter winds from the north are stronger and for a shorter duration than those with southerly components. Note that this process-response cycle does not include intense tropical storms.

Summary

East Key is comprised wholly of biogenic sand and fine gravel. It lacks any beachrock or bedrock which may act as a stabilizing agent such as on Loggerhead Key. During the past two centuries, maps and charts document the size, shape and location of East Key. The island moved in a generally southeasterly direction across the shallow carbonate bank. East Key was preserved, unlike some of the other islands, because of its easterly position with respect to the deep lagoon. Those islands west of the lagoon moved easterly and disappeared into the lagoon, (O'Neill, 1976).

East Key has decreased markedly in size during its southeasterly movement. In addition there appears to be a change in morphology which is related to seasonal changes in predominant wind direction.
References Cited


Maps

1773-75, George Gauld

1850-51, U. S. Coast Survey, (Gerdes survey) Reg. No. 33

1858, Edmund and William Blunt

1867-68, U. S. Coast Survey (Platt survey), Reg. No. 1271

1875, U. S. Coast Survey (H. G. Ogden), Reg. No. 1418

1897-98, U.S.G. & G.S. (Barnett), Reg. No. 2349

1922, U.S.G. & G.S., Chart 585
A Century of Natural Change in Coral Distribution
at the Dry Tortugas:
A Comparison of Reef Maps
from 1881 and 1976

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INTRODUCTION

Coral reef ecosystems are among the oldest and most complex on earth. Their persistence and significant accretion through geologic time attest to their stability. Precisely how this stability is achieved and whether it is a function of ecosystem complexity are questions presently receiving a great deal of attention (Connell 1978), yet detailed observations of long-term changes on coral reefs, short of geologic records, are rare. Nearly a century of change at the Dry Tortugas is now possible to study because of detailed mapping of the atoll-like reef system conducted in 1881 by A. Agassiz (1882) and again in 1976 by the author (Davis 1979).

The Dry Tortugas was named Las Tortugas over 465 years ago by the Spanish explorer Ponce de Leon, and there has been a great deal of interest in it ever since. Military strategists saw it as the key to the defenses of the Gulf of Mexico and hence the southern entrance to North America. British admiralty charts dating from 1773 provide detailed documentation of the general structure and appearance of the reef system (Robertson 1964).

Alexander Agassiz used a careful examination of Dry Tortugas reefs to elucidate the geologic structure of the Florida peninsula and dispute Charles Darwin's hypothesis of reef formation by subside (Agassiz 1888). From five weeks of observations conducted in 1881, Agassiz (1882) produced a detailed color map at a scale of 1:40,000 using nine mapping units, which showed the distribution of reef corals, octocorallia, and sediments at the Dry Tortugas (Fig. 1).

One of Agassiz's students, Alfred G. Mayor, established a tropical marine research station under the auspices of the Carnegie Institute at the Dry Tortugas in 1904. During the next forty years, many of the world's leading coral reef scientists studied at the Tortugas laboratory. Their work, constituting some of the most noteworthy on reef geology and biology, included classic studies of marine algae (Taylor 1928), sponges (deLaubenfels 1936), corals (Mayer 1914, Hoffmeister 1925, Wells 1932, Yonge 1935a and b, Cary 1914, 1918a, and 1918b), fishes (Longley and Hildebrand 1941), and reef development (Vaughn 1910, 1914).

In recognition of the significance of Dry Tortugas wildlife, a bird sanctuary was established there in 1918, and the area was proclaimed a national monument in 1935 to protect the historic and natural resources.

In 1976, the National Park Service initiated an interdisciplinary investigation of Dry Tortugas reefs called the Tortugas Reef Atoll Continuing Transect Studies (TRACTS). The objective of TRACTS was to develop a "bench-mark" description of marine resources at Fort Jefferson National Monument using modern technology for in situ observations and sampling in submarine habitats. This "bench-mark" may be used to define and evaluate long-term change, both from the past, based on the Carnegie Laboratory descriptions, and for the future. Scientists from universities and federal and state governmental agencies participated in the first year of TRACTS. One of the TRACTS projects developed a benthic community
Fig. 1 - Map of Dry Tortugas. (After Agassiz, 1882).
map showing the distribution of reef corals and sediments using mapping units similar to those used by A. Agassiz nearly a century before. That map was published by the U.S. Department of the Interior, Bureau of Land Management, Outer Continental Shelf Office (Davis 1979). The purpose of this paper is to describe the present distribution of reef corals and associated benthic communities and compare that distribution to the one presented by Agassiz (1882) for 1881 (Fig. 1).

MAPPING TECHNIQUES

The 1976 map of Dry Tortugas benthic communities was developed from color aerial photographs "ground truthed" by SCUBA equipped observers (Fig. 2).* National Ocean Survey Navigational Chart Number 11438 (C&GS 585) was used as a base map at a scale of 1:30,000. From 1971 through 1975, extensive SCUBA surveys of Dry Tortugas reefs were part of a spiny lobster study (Davis 1977a). During the actual field mapping in 1976, an additional 80 man-hours of observation were conducted in conjunction with modified plane table plotting of positions to supplement the previous 1,200 man-hours of survey observation. An uncontrolled photomosaic made from standard 22.8 cm x 22.8 cm (9 in x 9 in), vertical, natural color aerial photographs at a nominal scale of 1:30,000, was used to determine the distribution of benthic communities. The photographs were from series 74C(c) made in March 1974, by the Coastal Mapping Division of the National Ocean Survey, Rockville, Maryland. Discrimination among the eight mapping units was done visually by the author, and traced onto polyester drafting film. The mean of three counts using a 64 dot per square inch grid was used to determine areas occupied by various mapping units.

MAPPING UNITS

Agassiz (1882) used nine categories into which he divided the types of bottom at the Dry Tortugas, including the islands. His mapping units were: (1) land, (2) fine sand and ooze, (3) broken coral heads, (4) large heads of Aestrea (Montastrea annularis) and Maelhodina (Diploria) (5) Madrepora (Acropora) cervicornis, (6) coarse sand on flats above six fathom line, (7) Madrepora (Acropora) palmata, (8) gorgonias and broken ground, and (9) coarse sand and Porites. In the text (p. 124) Agassiz described "more or less extensive patches of marine lawns formed by a species of Thalassia, with occasional patches of Anadyomene," but did not include any vegetative mapping unit. A comparision with the eight mapping units used by Davis (1979) is shown in Table 1. Each of the mapping units used by Davis (1979) is described here in more detail.

Land:

The islands above sea level were mapped in this unit (Fig. 3).

Sea Grasses:

Turtle grass, Thalassia testudinum, dominated the sea grass community, particularly on the shallow flats less than 2 m in depth (Fig. 4). Frequently the deeper grass beds were mixed stands of Thalassia and Manatee grass.

*Figure 2 is folded in pocket in back of this volume.
Syringodium filiforme. In deeper parts of the lagoon southwest of Pulaski Shoal, Syringodium gradually replaced Thalassia, and in turn was replaced by Halophila spp. at T1-12 m.

The density of grasses varied considerably, from a few stems per square meter to over 5,000 stems/m² in the shallow Thalassia beds. Porites porites was common on the shallow grass beds.

Algae:

On coral rubble in relatively high wave energy zones the benthic community was dominated by fleshy algae, represented primarily by the genera Laurencia, Dictyota, Sargassum, Padina, and Zonaria (Fig. 5). Also included in this mapping unit were small patches of Halodule wrightii and calcareous green algae such as Halimeda, Avrainvillea, Penicillus, and Udotea. On the narrow intertidal ridge that extends south-southwest of Long Key, crustose coralline algae, Goniolithon spp., and microscopic forms, such as members of the Rivulariaceae, were also mapped in this unit.

Patch Reef:

Clumps of hermatypic corals ranging in diameter from five meters to over 100 meters were scattered across the tops of shoals, on the steepest sides of shoals, and occasionally on the sand plain outside the "atoll." The massive structure of these patches was generally formed by the common star corals, Montastrea annularis and Siderastrea siderea, but brain corals such as Diploria labyrinthiformis and Colpophyllia natans were also frequently conspicuous contributors to reef structures (Fig. 6). The colonial zooanthid Polythoa was also common. One of the distinguishing features of the patch reefs was their remarkable relief from the surrounding terrain. They invariably rose abruptly several meters above the adjacent substrate. The distinction between patch reef and bank barrier fringing reef was made primarily on the basis of physiography, not species composition or coral abundance. In several shoal fringe situations, the slope was so steep that the dense coral cover appeared to be a patch attached to it, accreting horizontally. They were quite different than a sparse fringe of individual corals attached to a cliff or a structured spur and groove reef system. Consequently, these situations were mapped as patch reefs.

Bank Barrier/Fringing Reef:

Except for the virtual absence of Acropora palmata, the Dry Tortugas bank barrier fringing reef would be a classic West Indian or Floridian Acropora reef with well-developed spur and groove systems and buttress zones as described by Goreau (1959) and discussed by Shinn (1963). The shallower portions of this reef type were dominated by Montastrea annularis and Siderastrea siderea, but Porites porites, P. asteroideas, Agaricia agaricites, Millepora alcicornis, Madracis decactis, Stephanocoenia michelini, Acropora cervicornis and Mycetophyllia ferox were also major community elements (Fig. 7). Montastrea cavernosa replaced M. annularis below about 16 m, and
the octocoral *Pseudopterogorgia bipinnata* was common on the deep reef. A species list of scleractinia observed on patch reefs and bank barrier fringing reefs at Dry Tortugas is presented in Table 2.

**Staghorn Reef:**

Extensive areas were covered with dense, virtually monospecific stands of *Acropora cervicornis* (Fig. 8). Northwest of Loggerhead Key the *A. cervicornis* reef was composed of east-west oriented ridges 2-3 m high and 7 to 18 m wide, separated by sand bottomed ravines 3 to 10 m wide. In other areas, *A. cervicornis* blanketed slopes on the edges of channels or occupied large patches of hard bottom. Occasionally, large individual heads of *Montastrea annularis*, *Diploria* or *Colpophyllia* occurred within the expanse of staghorn coral.

**Hard Bottom Dominated by Octocorallia:**

Where there was living cover on hard bottom shallower than 10 m, it was usually conspicuously dominated by a complex array of octocorals (Fig. 9). Some 30 species were present, but *Pseudopterogorgia americana*, *P. acerosa*, and *Plexaura flexuosa* were clearly the most common. Others commonly observed were members of the genera *Pseudoplexaura*, *Eunicea*, *Plexaurella*, *Muricea*, *Pterogorgia*, and *Gorgonia*. The frequently encrusting scleraxonian gorgonacean *Briareum asbestinum*, and low profile forms of *Diploria clivosa* were also common elements in this community.

**Bare Sand and Rubble:**

Included in this mapping unit were those areas where no significant macroscopic living cover was apparent (Fig. 10). The sediments ranged from coral rubble to fine calcareous mud, and from well-sorted to mixed size classes. The 1976 map (Davis, 1979) is somewhat misleading in that the entire area below 10 fathoms (18.3 m) is indicated as bare sand and rubble, whereas only the areas shallower than that were actually mapped. Patch reefs were not uncommon on the sand plains to the south and northwest of the Dry Tortugas to depths of 28 m, but they were not discernible on the aerial photographs and therefore could not be accurately mapped.

**CORAL DISTRIBUTION**

The Dry Tortugas reefs form an elliptical atoll-like structure about 27 km along the major, or southwest-northeast, axis and 12 km on the minor axis. The three major shoals, Pulaski (NE), Loggerhead (W), and Long Key (S) are separated by 10-20 m deep channels on the northwest, southwest, and southeast. They surround a 12-23 m deep lagoon. Mean water depth over these shoals is 2-3 m, while depths immediately outside of the shoals range from 11-29 m. In 1976, there were seven islands (keys) at the Dry Tortugas. From west to east, they were Loggerhead, Garden, Bush, Long, Hospital, Middle, and East Keys. Middle Key was frequently awash, and Hospital Key occasionally was submerged during spring tides during the 1970's, but the remainder of the keys were continually above sea level.
Living coral reefs occupied less than four percent of the bottom above the 10 fathom line at the Dry Tortugas in 1976. Table 3 shows the area that each reef type occupied. The most extensive reef type was staghorn coral, Acropora cervicornis. It covered a total of 478 hectares, and accounted for 55% of the scleractinian coral cover. Nearly half of the staghorn reef type was concentrated in a single 220 hectare reef on the northwest side of Loggerhead Shoal. This reef was at depths of 6-14 m in the area of strong tidal currents that ran on a northeast-southwest axis perpendicular to ridges of coral. This reef sustained significant anchor damage from commercial fishing boats seeking shelter from northeast winter storms in 1975 (Davis 1977b). Small patches of A. cervicornis were common on the octocoral dominated hard bottom of Pulaski Shoal, but it rarely occurred in large enough areas to be mapped at the 1:30,000 scale.

Patch reefs occupied a total of 251 hectares in 1976. While they occupied only 1.1% of the bottom, they provided shelter for spectacular concentrations of fishes, spiny lobsters, and echinoderms near seagrass and octocoral foraging areas which made them critical elements of the Dry Tortugas system. These daytime concentrations of reef animals and the shallowness of the water over them also made the patch reefs the most popular sites for reef viewing by glass bottom boat and recreational diving.

The structured bank barrier coral reef, with clear zonation and a well-developed spur and groove system, accounted for only 16% of the scleractinian dominated bottom, and only 0.6% of the entire Dry Tortugas system. This reef type was limited to a narrow band on the southeast edges of Long Key Shoal and Pulaski Shoal. These areas constitute the windward side of the Dry Tortugas during the spring, summer, and early fall, with relatively constant "trade winds" of 10-15 knots from the southeast. During the winter, strong weather fronts sweep down from the north across the Gulf of Mexico or from the North Atlantic, seasonally reversing the "windward" and "leeward" sides of the atoll. The shape of the shoals appears to result from a prevailing westward current from Key West (Vaughn 1914), whereas the form of the coral reefs was determined by the nature of seasonal weather patterns and the form of the resultant energy impinging upon them. Steady gentle winds produced a classic spur and groove reef, and the high energy of severe winter storms was reflected by massive coral buttresses, mapped as fringing patch reefs, which were particularly well-developed along the northeastern edge of Pulaski Shoal.

On the shallow flats between the outer reefs and the lagoonal grassbeds, a hard bottom community conspicuously dominated by octocorals occupied a total of 3,965 hectares. The numerous shallow patches within the lagoon were also topped by this octocoral community.

On the shallowest portions of the southeastern reef flats, a small algal community occupied a total of 114 hectares. Nearly all of this partially intertidal community was located in two areas at about the same position on both Long Key and Loggerhead Shoals. Southeast of East Key, on Pulaski Shoal, there was a very small patch of this algal community, on the reef top at the point of transition between the bank barrier and fringing patch reefs.
Sea grasses covered 6,904 hectares, primarily within the lagoon. The grass community ranged from barely subtidal on Long Key Shoal to 15 m depths in the northeastern portion of the lagoon. It covered sediments ranging from fine sands in the deeper areas of the lagoon to coarse sand and Porites rubble on the shallow flats. A usually conspicuous element of grass beds, the queen conch, *Strombus gigas*, was scarce during the early 1970's. After 1975, juvenile conchs became quite common, particularly on Long Key Shoal, but adults continued to be scarce. Residents of Fort Jefferson reported a drastic decline in the adult *S. gigas* population on the grass beds near the fort in 1970, and shells of recently dead adult *S. gigas* were exceptionally abundant on Long Key Shoal. No verifiable explanation was offered for what appeared to be the sudden death of most of the conch population, although the occurrence of "red tide" was noted in the vicinity and may be implicated.

Channel bottoms and aprons at the bases of outer reefs were composed of bare sand, without any conspicuous vegetation or coral growth. A linear feature of coarse sand and coral rubble separated the staghorn coral reef from the hard bottom octocoral community and patch reefs west of Loggerhead Key. It was apparently the result of occasional severe winter storm-generated surf breaking over the staghorn reef onto the octocoral-patch reef area. Large overturned coral heads of *Diploria* and *Siderastrea* were evidence of the extreme wave energy impinging on this area of usually quiet smooth waters. These bare sand and rubble areas occupied nearly half of the bottom above the outer 10 fathom isobath at the Dry Tortugas in 1976.

**DISCUSSION**

Several major changes in the coral reefs at the Dry Tortugas were apparent when the Agassiz and Davis maps were compared. Comparisons between the maps were limited to the area within the 10 fathom line. Improvements in technology created some minor differences. There was a 3.6% difference in the area encompassed by the 10 fathom (18.3 m) contour between the two maps. Agassiz (1882) showed Fort Jefferson about 900 m further west and 130 m closer to the Loggerhead Key light than the modern navigation chart upon which the 1976 map was based. As a result, there were some difficulties in making direct quantitative comparisons between the two maps, but a number of fundamental changes over the intervening century were clear.

The distribution of mapping units by area for the Agassiz map is presented in Table 4. Table 5 summarizes the differences between the two maps as percentages of the mapped areas. Since Agassiz did not specifically map the vegetative communities that he observed and that covered 30.8% of the mapped area in 1976, a precise comparison is not possible. However, Agassiz showed 32.1% (7,053 ha) as "coarse sand on flats above six fathoms" and "coarse sand and Porites." These two mapping units very closely describe the sediments, depths, and geographical distribution occupied by sea grasses in 1976. This suggested little change in the amount or distribution of grasses. In a similar manner, Agassiz's broken coral head mapping unit generally occupied areas mapped as algae on coral rubble in 1976. Again there was little difference in the area involved, 0.3% (114 ha) in 1881 and 0.5% (114 ha) in 1976.
In contrast to the apparent lack of change in the vegetative cover, coral distributions were markedly different. A band of elkhorn coral, Acropora palmata, covering 44 hectares, was alive and well at the crest of the Long Key Reef in 1881. All that remained of this prominent feature in 1976 were two small patches of A. palmata that occupied a total of less than 600 m², and a swatch of algal-covered A. palmata rubble on the reef crest. From cores through the entire holocene reef accretion taken during TRACTS in 1976, Shinn et al. (1977) concluded that A. palmata played no role in building Long Key Reef.

Another major change in coral distribution was the appearance of the extensive staghorn, A. cervicornis, reef on the northwest side of Loggerhead Shoal. Agassiz showed linear ridges of gorgoniae on broken ground alternating with bands of sand. A. cervicornis completely dominated the "broken ground" of these ridges in 1976 (Fig. 8).

Agassiz apparently mapped both patch reefs and bank barrier fringing reefs as large heads of Astrea and Maeandrina. The extent and distributions of these mapping units suggested that there was a significant increase in the amount of patch reef, or that Agassiz's techniques did not permit him to locate over half of the patch reefs. Patch reefs notably missing from the Agassiz map were those immediately west of the Loggerhead Key light, a series of parallel patches northwest of Loggerhead Key, and the extensive fringing patch reefs along the northeast edge of Palaski Shoal. These reefs are relatively easy to detect from the surface, so it does not seem reasonable to assume that Agassiz simply did not find them.

While there were several significant changes in coral distributions, the percentage of the total area covered by coral reefs only increased from 2.7% in 1881 to 3.8% in 1976 (Table 5). However, the extent of the octocoral dominated community appeared to increase from 4.8% to 17.4%, in spite of the shift of nearly 200 hectares (northwest of Loggerhead Shoal) from octocorals to staghorn reef. Part, if not all, of this apparent change may have resulted from differences in mapping techniques. Agassiz mapped octocorals and broken ground as numerous small discrete patches surrounded by sand. Davis mapped the somewhat patchy octocorals as continuous zones ignoring the small sand patches. When the octocoral mapping units were combined with the bare sand mapping units, the difference between 1881 and 1976 was quite small, 64.7% and 65.2%, respectively (Table 5).

Another interesting change was that even with the loss of Bird Key following hurricanes in 1910 and 1919, the proportion of land at the Dry Tortugas was the same in 1976 as it was in 1881, apparently accretion at Garden Key made up for losses. The names of the Keys have changed several times, sometimes confusingly swapping the names of Bush and Long Keys between the islands (Robertson 1964), but other than that there was little change in the islands.

The form and structure of Dry Tortugas reefs was apparently determined by prevailing physical environmental conditions. The shape of the major shoals which form the atoll-like structure was determined by prevailing westerly currents. The occurrence of spur and groove reefs on the southeastern, windward, side of the "atoll" reflects the moderate wave energy generated by mild summer "trade
winds," while the massive fringing patch reefs along the northeastern rim appear to be a result of regular high energy winter storms. This pattern of coral distribution and wave energy conforms with the observations presented by Adey (1978) in his discussion of the relative importance of changing sea level, growth potential of reef building organisms, and antecedent topography and geology in determining reef morphogenesis. However, the virtual elimination of A. palmata from present day Dry Tortugas reefs suggests that local, short-term, extreme climatic events, such as hurricanes (Stoddart 1963) or thermal shocks (Hudson, et al. 1976) may significantly alter large scale features of reefs. Appearance and development of the prominent A. cervicornis reef northwest of Loggerhead Key during the past century while no changes in the physical reef environment were apparent, further suggests short-term disturbances, or their absence, cause significant changes in coral distribution and reef morphogenesis. If coral reefs are indeed stable complex communities, the observed changes in Dry Tortugas reefs over the past 95 years show clearly that stability is maintained through major changes in structural elements related to short-term perturbations.

There is considerable concern over the impacts of coastal development, dredging activities, pollution, "over-fishing," and other human activities on coral reefs in Florida and elsewhere (Voss 1973, Dustan 1977, Johannes 1970). The observations at Dry Tortugas demonstrated major natural changes in reef structure that complicate establishment of cause and effect relationships between human activities and reef dynamics. The observed changes further demonstrated the necessity of establishing and maintaining ecosystem level sanctuaries in which natural phenomena can be documented and studied. Such sanctuaries can provide standards for comparison with other similar but human impacted systems and are essential for developing objective, quantitative information needed to make important socio-economic decisions regarding coral reef resources.

**SUMMARY**

The entire 23,000 hectare atoll-like coral reef system above the 10 fathom line at Dry Tortugas was mapped in detail twice, at an interval of approximately 100 years. The first map represented conditions in the early 1880's (Agassiz 1882), and the second represented conditions in the mid-1970's (Davis 1979). Comparisons were made for eight mapping units: (1) land, (2) bare sand and rubble, (3) algae, (4) sea grasses, (5) octocorals, (6) patch and bank barrier fringing coral reefs, (7) staghorn coral reefs, and (8) elkhorn coral reefs.

Tables 3 and 4 summarize quantitative descriptions of the reef system for the 1970's and the 1880's, respectively. Living coral reefs increased in area slightly from 2.7% in 1881 to 3.8% in 1976, but major changes in species distributions and reef types occurred. A 220 hectare Acropora cervicornis reef northwest of Loggerhead Key developed on what had been octocorals on broken ground in the 1880's. The only A. palmata at the Tortugas, a 44 hectare swath on the Long Key reef crest in 1881 was reduced to rubble with only two small patches totaling less than 600 m² of living A. palmata remaining in the 1970's.
One island disappeared following hurricanes, but accretion to other islands equaled the loss and the proportion of land in the Dry Tortugas was the same in 1976 as it was in 1881.

Difficulty in positively identifying 1880's mapping units made other comparisons difficult, but there appeared to be no significant changes in the extent or distribution of sea grasses, algal communities, or bare sand. Octocoral dominated areas showed an apparent increase from 4.8% to 17.4% of the mapped area during the 95 year interval between maps, but most of this increase was probably a result of different mapping techniques. The changes in coral distribution seen over the 95 year interval at the Dry Tortugas demonstrated the natural dynamic nature of coral reefs, and suggested that occasional short-term, extreme events, such as thermal shock or hurricanes, may play an important role in shaping coral reef structure and species distribution. These observations also demonstrated the value of an ecosystem level sanctuary that provides a standard for comparison with similar but exploited or otherwise human-influenced ecosystems, and permits study of natural phenomena beyond the overt influences of human activities.

ACKNOWLEDGEMENTS

I would like to thank Dr. R. N. Ginsburg for his encouragement to undertake the mapping effort and for making available a copy of Agassiz's original map, without either this endeavor could not have succeeded. I am also indebted to Dr. G. Y. Hendrix for his continual support and encouragement. Drs. P. Dustan, J. Porter, W. Jaap, and J. Wheaton-Smith provided valuable information from their investigations of reef community structure, sceleractinia and octocorallia during TRACTS and earlier cooperative studies. D. Robbin assisted in field mapping and drafting.
LITERATURE CITED


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<th>Title</th>
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<td>5.</td>
<td>An algal community dominated by <em>Padina</em> south of Loggerhead Key, Dry Tortugas.</td>
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<td>7.</td>
<td>A portion of the spur and groove bank barrier reef on the southeast side of Long Key Shoal, Dry Tortugas.</td>
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<td>A typical portion of the <em>Acropora cervicornis</em> reef west of Loggerhead Key, Dry Tortugas.</td>
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<td>A view of the octocoral dominated community southwest of Loggerhead Key, Dry Tortugas.</td>
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Table 1. A comparison of mapping units used by Agassiz (1882) and Davis (1979) for Dry Tortugas reefs.

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<td>staghorn reef <em>Acropora cervicornis</em></td>
<td>large heads of Astraea and Maeandrina</td>
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<td><em>Madrepora cervicornis</em></td>
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<td>gorgoniae and broken ground</td>
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Table 2. A list of Scleractina and Millipora observed on Dry Tortugas reefs, 1971-76.

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*Hydrozoan
Table 3. 1976 Dry Tortugas benthic community distribution within the outer 10 fm (18.3 m) isobath, from Davis (1979).

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<tr>
<td>Bank Barrier (137 ha)</td>
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<td>Patch (251 ha)</td>
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<td>Staghorn (478 ha)</td>
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<td>Hard Bottom (Octocorals)</td>
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<td>7,018</td>
<td>30.8</td>
</tr>
<tr>
<td>Algae (114 ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grasses (6,904 ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand/Rubble</td>
<td>10,892</td>
<td>47.8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>22,787</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Table 4. 1881 Dry Tortugas benthic community distribution within the outer 10 fm (18.3 m) isobath from Agassiz (1882)

<table>
<thead>
<tr>
<th>Bottom Type</th>
<th>hectares</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>44</td>
<td>0.2</td>
</tr>
<tr>
<td>Coral Reefs</td>
<td>615</td>
<td>2.7</td>
</tr>
<tr>
<td>Astrea and Maendrina</td>
<td>(154 ha)</td>
<td></td>
</tr>
<tr>
<td>Staghorn</td>
<td>(417 ha)</td>
<td></td>
</tr>
<tr>
<td>Elkhorn</td>
<td>(44 ha)</td>
<td></td>
</tr>
<tr>
<td>Broken Coral Heads</td>
<td>66</td>
<td>0.3</td>
</tr>
<tr>
<td>Hard Bottom (Octocorals)</td>
<td>1,055</td>
<td>4.8</td>
</tr>
<tr>
<td>Sediments</td>
<td>20,215</td>
<td>92.0</td>
</tr>
<tr>
<td>Coarse Sand and Porites</td>
<td>(2,812 ha)</td>
<td></td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>(4,241 ha)</td>
<td></td>
</tr>
<tr>
<td>Fine Sand and Ooze</td>
<td>(13,162 ha)</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>21,973</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Table 5. A summary of the comparison of the 1881 and 1976 maps of coral and sediment distributions at Dry Tortugas.

<table>
<thead>
<tr>
<th>Mapping Unit</th>
<th>1881</th>
<th>1976</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Bare sand and rubble</td>
<td>59.9</td>
<td>47.8</td>
</tr>
<tr>
<td>Algae</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Sea Grasses</td>
<td>32.1</td>
<td>30.3</td>
</tr>
<tr>
<td>Octocorals</td>
<td>4.89</td>
<td>17.4</td>
</tr>
<tr>
<td>Coral Reefs</td>
<td>2.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Patch</td>
<td>(0.7)</td>
<td>(1.1)</td>
</tr>
<tr>
<td>Bank barrier</td>
<td>(0.6)</td>
<td></td>
</tr>
<tr>
<td>Staghorn</td>
<td>(1.9)</td>
<td>(2.1)</td>
</tr>
<tr>
<td>Elkhorn</td>
<td>(0.9)</td>
<td>(0.0)</td>
</tr>
<tr>
<td>TOTAL AREA (ha)</td>
<td>21,973</td>
<td>22,787</td>
</tr>
</tbody>
</table>

1 Mapping units from Davis (1979) and equated with Agassiz (1882) according to Table 1.
Fig. 3 - An oblique aerial view of Long, Bush and Garden Keys, Dry Tortugas.
Fig. 4 - A shallow water sea grass bed dominated by *Thalassia testudinum* at Palaski Shoal, Dry Tortugas.
Fig. 5 - An algal community dominated by *Padina* south of Loggerhead Key, Dry Tortugas.
Fig. 6 - A Montastrea annularis patch reef at Paluski Shoal, Dry Tortugas.
Fig. 7 - A portion of the spur and groove bank barrier reef on the southeast side of Long Key Shoal.
Fig. 8 - A typical portion of the *Acropora cervicornis* reef west of Loggerhead Key, Dry Tortugas.
Fig. 9 - A view of the octocoral-dominated community southwest of Loggerhead Key, Dry Tortugas.
Fig. 10 - A view of the bare sand community at a depth of 9 m in the Southwest Channel, Dry Tortugas.
Corals and Coral Reefs of the Dry Tortugas, Florida

by

John F. Meeder
Rosenstiel School of Marine and Atmospheric Science
University of Miami
Miami, Florida

Two stops on this field trip allow close observations of corals. The first is a back-reef environment of a fringing reef along the Southeast Channel directly south of Carden Key. The second locality is a series of patch reefs off Loggerhead Key. The general setting, ecology, distribution, and types of corals are discussed for each stop.

Forty-two species of corals have been reported from the Dry Tortugas. Of these, forty-one species are covered in the key and later described in this paper. Descriptions are brief and include information on the depth range, environment, and geological role of each species in the key.

Introduction

Corals were considered members of the plant kingdom until Peyssonel (1753) demonstrated that corals from the western Atlantic were, in fact, animals. This discovery spurred an interest in corals reefs. Following their interests, naturalists, such as Darwin and Murray on board the ships "Beagle" and "Challenger," respectively, studied the reefs of the Pacific and speculated on their formation and development. Dana (1846) was the first American scientist to take serious interest in coral reefs. He also supported Darwin's subsidence theory which explains the formation of atolls and barrier reefs.

Louis Agassiz (1880) was the first scientist to investigate the Florida reef tract in detail. In the Agassiz report, L. F. Pourtales figured and identified twenty-nine species of stony corals from Florida. Agassiz did not accept Darwin's subsidence theory because he felt that the subsidence theory could not explain the Florida reefs. Agassiz (1888) further discussed Florida reefs and reviewed the works of Le Conte and E. B. Hunt (no references), who also disliked Darwin's subsidence theory. Agassiz thought that the southern extremity of Florida was of comparatively recent growth and that the processes of buildup are presently active, thereby eliminating the need of subsidence. He described the development of southern Florida thusly (p. 56):

"...Florida is built of concentric barrier reefs, which have been gradually cemented into a continuous sheet of land by the accumulation and consolidation of mud flats between them, a process which is now going on between the Florida keys and reefs from Cape Florida to the Tortugas, and must end in transforming them, in like manner, into a continuous tract, to be connected eventually with the mainland."

Agassiz noted that the Tortugas differed from the rest of the reef tract by its younger age, as evidenced by the lack of mud flats northward of the islands and the lack of mainland flora and fauna, which he thought represented a shorter
time for colonization. From this conclusion he suggested a model that explains the development of the Florida reef tract. Briefly, he concluded that the Gulf Stream currents carried materials to the Florida shelf margin where they were deposited, forming mounds. As the mounds build up close to sea level, they are colonized by corals which, after continued growth, form rounded reefs. As the reefs expand they grow together with tidal channels between them, which drain the developing mud flats behind and between them. These channels eventually fill up to form a continuous tract of land. This theory, however, does not explain the presence of the Florida platform. Agassiz circumvented this problem by suggesting that the Florida platform is "a fold of the earth's crust formed in an earlier geological period." This concept is no longer favored.

Verril (1902a, b) made further investigations in Florida and the Dry Tortugas. The major step in knowledge of the Caribbean, especially of the Dry Tortugas, came with the creation of the Dry Tortugas Laboratory by the Carnegie Institute in 1904. Directed by A. G. Mayor, the Institute operated for nearly 20 years until Mayor's death in the early 1920's. The facility supported much of T. W. Vaughan's work (1911, 1912, 1913, 1914, 1915, 1916). Today, only a foundation and a plaque in Mayor's honor remain after destruction of the buildings in the hurricane of 1947. Vaughan was responsible for the recognition of roles of corals and other reef and lagoonal organisms in sedimentation. Vaughan (1919) reviewed his and other workers' summaries on the significance of strandline oscillation in Florida. Unlike Agassiz, he found that Darwin's subsidence theory applied to the Florida reef tract, especially when Daly's (1910) glacier control theory was incorporated. Vaughan and Shaw (1915) show that subsequent to the development of the Pleistocene barrier reef of Florida, the reef tract was elevated to 50 feet above its previous stand and that this elevation was followed by submergence of 30 feet.

Diversity

In 1943, Vaughan and Wells reported that the greatest number of coral species in the Caribbean was thirty-five species from the Bahamas, with twenty-five species occurring in the Dry Tortugas. Coreau and Wells (1967) reported sixty-two species of corals from Jamaica. At the time of their publication, the previously known coral faunas with the highest diversity were: Florida - forty-two species (Smith, 1948); Jamaica - forty-one species (Coreau, 1959); and Cuba - thirty-seven species (Duarte Bello, 1961). For the coral species of the Dry Tortugas, the most valuable references are Vaughan (1919), which covers fossil species from the Caribbean as well, Smith (1948), which covers many western Atlantic species, and Weisbord (1974), which covers the Late Cenozoic corals of Florida.

Coral Forms

A major problem with coral identification is that the morphology of the colony is highly variable depending upon environment. Wood-Jones (1918) studied the corals of Murray Islands and found that encrusting forms, massive, palmate, and short, thick-branching corals were indicative of rough water. Branched or thin, plate-like forms are generally found in shallow quiet waters, whereas columniform or spindly-branching forms are characteristic of deeper, quiet waters. Vaughan (1919) studied the growth forms in the Tortugas with similar results. Vaughan and Wells (1943) illustrated the variations in growth forms in Porites porites and Diploria clivosa and concluded that the variations are in relation to water movement (Fig. 1). More recent studies have shown that the availability of food and the ambient light intensity greatly affect skeletal growth in herma-
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Figure 1. Effects of water movements on growth form. (a,b) *Porites porites* (Pallas), Dry Tortugas, Florida; (a) form in quiet water; (b) form in shallow rough water; (c,d,e) *Diploria clivosa* (Ellis and Solander), Dry Tortugas, Florida; (c) form in quiet water; (d) form in rough water; (e) form in shallow, very rough water. From Vaughan and Wells (1943, p. 61, Fig. 24).

Figure 2. Locality map, Dry Tortugas.
typic corals (Barnes, 1973). Barnes found that colonies of *Montastrea annularis* vary from rounded to columnar-lobate colonies in shallow water, depending upon location, to irregular massive colonies exhibiting some peripheral growth at 13 m, to colonies with considerable peripheral growth at 25 m, to plate-like colonies at 35 m.

**Reef Types**

Darwin (1842) made the first distinction between fringing, barrier, and atoll reefs. Reefs are generally classified by their gross morphology, size, relationship to non-limestone rocks, and by depth of the surrounding waters (Stoddart, 1969). MacNeil (1954), as well as other workers, has recognized many other types of reefs which generally can be considered end members or intermediate stages of Darwin's simplistic classification. The definition of several major types are briefly reviewed:

Atoll—An atoll is an annular reef that develops at or near the surface of the sea, usually circular or subcircular in shape, often fringed by islands surrounding a central lagoon. Two basic types are: (1) deep-sea atolls, which are usually isolated, rise from the deep sea, and generally conform to Darwin's sub-sidence theory, and (2) shelf atolls or calm-water atolls, which are found rising from continental shelves, from banks within larger lagoons, or from slopes of larger islands. Davis (1928) termed reefs occurring behind the continental shelf bank reefs, bank barriers, or bank atolls, depending upon reef shape and the presence of islands.

Barrier reefs—Linear structures separated from land by a lagoon, barrier reefs are usually of a thicker and larger accumulation than fringing reefs.

Fringing reefs—Developing near shore where conditions for coral growth are favorable, fringing reefs' widths depend upon sea-floor slope and thicknesses are generally thin.

Bank reefs—Bank reefs are any reefs not found growing on the continental shelf edge.

Patch Reefs—These are small, near-sea-level reefs that rise from shelves or from lagoon bottoms.

The Florida reef tract has been called a fringing reef by many workers and a barrier reef by others. A lagoon, Hawk Channel, separates the reef from the mainland, but the offshore reef is relatively thin. The presence of Hawk Channel eliminates the typical fringing reef such as is found off portions of the Jamaican and St. Croix coasts. True barrier reefs, on the other hand, are often larger, much thicker accumulations along the shelf edge. The Great Barrier Reef of Australia and the Belize Barrier Reef serve as two examples. In many places the Florida reef tract does not rest on the shelf edge but is inshore; thus, the Florida reef tract should best be termed a bank reef, or more accurately a bank fringing reef, or bank barrier reef.

Agassiz (1880) noted that the Dry Tortugas differed from the rest of the Florida reef tract and thought that this difference was because of its younger age. Smith (1948) reports that the Dry Tortugas was first considered to be an atoll, but fails to cite the original reference. Most workers have not considered the Dry Tortugas an atoll, but rather a carbonate bank and island complex
surrounded by a fringing reef. Because the Dry Tortugas does not rest immediately on the shelf edge but on the Florida platform, the Dry Tortugas may best be termed a bank atoll, not to be confused with a true atoll.

Reef Zonation

Wells (1954) defines a zone as "an area where local ecological differences are reflected in the species association and signalized by one or more dominant species." Major differences in reef zonation occur in lee or windward reefs because of the differences in energy settings and gradients. Other differences occur because of the influences of depth, relief, and presence of tidal channels. Generally, three major reef zones can always be recognized: the fore reef, reef flat, and back-reef lagoon. Further zonation can usually be determined by more detailed study, and although more detailed generalized zonation (such as Goreau and Goreau, 1973 for Jamaican reefs) is useful, it must be understood that zonation varies considerably from one place to another along a reef tract because of the above mentioned reasons and because of orientation with respect to energy and other less understood factors.

Milliman (1973) summarizes Caribbean reef zonation:

Fore reef: shallower depths, Acropora palmata and A. cervicornis; deeper depths, Montastrea, Porites, and Siderastrea; growth forms range from massive in very shallow water, to hemispherical-to-ramose in mid-depths, to encrusting in deeper waters.

Reef flat: This zone varies considerably in the Florida reef tract. Millepora, Palythoa, Zoanthus, Acropora palmata, and Montastrea annularis are often dominant species in the outer reef flat, depending upon local setting. Halimeda, Siderastrea, Montastrea, Acropora cervicornis, and Diploria are common in the deeper, inner reef flat.

Lagoon: often filled with mud containing few coral species, extensive hardgrounds with diverse soft corals and isolated coral heads, or containing scattered patch reefs.

Within the Florida reef tract, many patch reefs vary considerably in coral species composition. In Biscayne National Monument several patch reefs are dominated by Porites porites. Inshore in Pennekamp Park Montastrea cavernosa appears to dominate the coral fauna. Dendogyra cylindrica, if not a dominant species in some patch reefs off Big Pine Key, surely characterizes these patch reefs (M. Noel, Personal communication). Most patch reefs are characterized by Montastrea annularis; Acropora cervicornis is also common in outer patch reefs along the Florida reef tract.

Goreau and Goreau (1973) summarized the zonation and distribution of coral species in Jamaica. This is the most complete study of any Caribbean reef to date, and information from their study is incorporated into the description section of this paper.

The Dry Tortugas

Corals are abundant in the lagoons, patch reefs, and fringing reefs of the Dry Tortugas. Two areas, Stop 2 and Stop 4 of this field trip, will be at a back-reef zone of a fringing reef along Southeast Channel and at a series of patch reefs off Loggerhead Key, respectively (Fig. 2). In addition to these scheduled stops, corals may be observed off the beach near the campsite at
Garden Key. Note: absolutely no collecting of corals or other animals or plants are allowed in the Dry Tortugas!

Because coral larvae generally must attach to hard substrates before growth will continue, corals are most abundant on hardgrounds or reefs. Many coral species can attach themselves to dead shells in lagoonal sediments. Those species that live in the lagoon are also usually well adapted for higher turbidities. *Manicina areolata*, *Cladocora arbuscula*, *Siderastrea radians*, *Porites divaricata*, *Favia fragum*, and *Millepora alcicornis* are commonly found in or near *Thalassia* beds. Along outer portions of Rodriguez Bank, just seaward of the calcareous algae-Gonio-lithon zone, these corals are abundant. All of these corals are common in the lagoons of the Dry Tortugas, except for *Cladocora arbuscula*, which is apparently not as abundant as farther north.

Stop 2. Southeast Channel--The transect in Figure 3 runs from the *Thalassia*-dominated lagoon to the top of the fringing reef offshore. Shinn et al. (1977) recovered a core from along the inner transect. The boat will anchor in or around zone 4 of the back-reef area. The reef crest at this locality is too deep for most skin divers and therefore the participants will pair up and swim towards the inner lagoon, zone 1. The reef itself is very diverse with respect to coral species and is dominated by *Acropora palmata*, *A. cervicornis*, *Montastrea annularis*, *M. cavernosa*, *Siderastrea siderea*, *Porites porites*, *P. astreoides*, *Colpophyllia* sp. and *Diploria* spp. *Millepora* and soft corals (sea whips and sea fans) are also very common.

As each team swims towards shore, the corals will become less abundant and less diverse. In zone 5, small isolated colonies of elk horn, *Acropora cervicornis*, occur, as well as individual large colonies of *Porites astreoides*, *Montastrea annularis*, *Diploria clivosa*, and *D. strigosa*. *Millepora* is also abundant. The hard bottom is of low relief and contains sandy patches. Water depth is between 3-7 m and a moderate current can be felt. Soft corals are very abundant. Notice that the soft corals and *Millepora* are orientated into the current.

The area included in zone 4 begins to shoal upwards (water depth 1-3 m). The bottom is rock with sandy patches. Coral colonies are small and usually encrusting or flattened in response to the high energies of storm surges. Soft corals are reduced in numbers. *Palythoa*, a non-stony anthozoan, characteristic of high energies, becomes common (Fig. 4B). *Diploria* sp., *Montastrea annularis*, *Porites astreoides*, and *Siderastrea radians* are the common corals.

The bottom of zone 3 is a sandy sheet with coral rubble and patches of hardgrounds exposed. The water depth ranges from 0.3-1 m and a moderate surge can generally be felt. Sparse *Thalassia* cover can be found but various green, brown, and red algae are more common. *Palythoa* is very common. *Manicina areolata*, *Porites divaricata*, *Siderastrea radians*, and *Favia fragum* are common corals.

Zone 2 is nearly shoaling and has a strong surge. The bottom is covered by coral and shell debris. Only a few *Palythoa* and a rare live coral colony can be found. Algae appears to dominate this zone.

The water depth of zone 1 deepens once the near-shoaling rubble zone is crossed. *Thalassia* and other marine plants cover the bottom. Corals, such as *Manicina areolata*, *Porites divaricata*, and *Siderastrea radians*, are uncommon in the grass beds (Fig. 4A). In some areas the grass cover is missing and the bottom is covered by sand or exposed rock. In the more stable pockets, which may be "blowouts" formed during storms, large colonies of *Montastrea annularis*, *Porites*
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</thead>
<tbody>
<tr>
<td>0-0.5m</td>
<td>sand</td>
<td>coral rubble</td>
<td>sand &amp; rubble</td>
<td>rock &amp; sand</td>
<td>rock &amp; sand</td>
<td>7-14m</td>
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<tr>
<td>0.6-2m</td>
<td>quiet</td>
<td>strong surge</td>
<td>mod. surge</td>
<td>mod. current</td>
<td>rock &amp; sand</td>
<td>3-7m</td>
</tr>
<tr>
<td>0.3-1m</td>
<td>sand</td>
<td>coral rubble</td>
<td>sand &amp; rubble</td>
<td>rock &amp; sand</td>
<td>rock &amp; sand</td>
<td>1-3m</td>
</tr>
<tr>
<td>0-0.5m</td>
<td>quiet</td>
<td>strong surge</td>
<td>mod. surge</td>
<td>mod. current</td>
<td>rock &amp; sand</td>
<td>3-7m</td>
</tr>
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<table>
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<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>very diverse</td>
<td>A. cervicornis</td>
<td>Diploria sp</td>
<td>Manicina</td>
<td>few Palythoa</td>
<td>M. areolata</td>
<td>S. radians</td>
</tr>
<tr>
<td>A. cervicornis</td>
<td>P. asteroides</td>
<td>M. annularis</td>
<td>areolata</td>
<td>P. divaricata</td>
<td>P. divaricata</td>
<td>P. annularis</td>
</tr>
<tr>
<td>A. palmata</td>
<td>Diploria sp</td>
<td>P. asteroides</td>
<td>Palythoa</td>
<td>P. divaricata</td>
<td>P. divaricata</td>
<td>P. asteroides</td>
</tr>
<tr>
<td>M. annularis</td>
<td>P. asteroides</td>
<td>Palythoa</td>
<td>P. divaricata</td>
<td>P. divaricata</td>
<td>P. divaricata</td>
<td>S. radians</td>
</tr>
<tr>
<td>Colpophyllia sp</td>
<td>Millepora</td>
<td>colonies small</td>
<td>S. radians</td>
<td>Favia fragum</td>
<td>various green</td>
<td>M. annularis</td>
</tr>
<tr>
<td>Diploria spp</td>
<td>abundant soft</td>
<td>flattened, or</td>
<td>Favia fragum</td>
<td>various green</td>
<td>red, and brown</td>
<td>P. asteroides</td>
</tr>
<tr>
<td>Porites asteroides</td>
<td>corals</td>
<td>encrusting</td>
<td>Favia fragum</td>
<td>various green</td>
<td>brown</td>
<td>S. siderea</td>
</tr>
<tr>
<td>P. porites</td>
<td>colonies large</td>
<td>few soft corals</td>
<td>various green</td>
<td>red, and brown</td>
<td>algae abundant</td>
<td>in deeper pockets</td>
</tr>
<tr>
<td>Siderastrea siderea</td>
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Figure 3. Transect across backreef area of fringing reef along Southeast Channel, Stop 2 (for exact location refer to Figure 2).
Figure 4. Photographs of characteristic coral zones. (A) Stop 2, zone 1: small Siderastrea radians colony in Thalassia- (turtle grass-)dominated community. (B) Stop 2, zones 4,5: Palythoa (1), Halimeda, a calcareous green algae (2), Porites astreoides (3) are common; Diadema, the dangerous sea urchin (4), is also abundant in many reef and lagoon environments. (C) Stop 4, zone 3: Acropora cervicornis (1) dominates this patch reef. Notice the dead corals (2) and the recent new growth (3). A few large massive colonies can be seen (4). (D) Stop 4, zone 4: typical view of Montastrea annularis patch reef exhibiting M. annularis (1), Millepora alcicornis, the stinging coral (2), Porites astreoides (3), and Porites porites (4).
*Astreoides*, and *Siderastrea siderea* can be found. These large coral heads are often the homes of many very large and delicious Florida lobsters; remember, these beasts are protected! Water conditions are generally quiet and water depth ranges from 0.6–2 m.

Distinct coral zonation along this transect is apparent from both growth forms and species composition. These changes are a reflection of the wave energy, which is directly related to water depth and substrate type. In zone 5 corals are dominantly large hemispherical forms, encrusting and flattened colonies. Small colonies become more abundant farther inshore. *Palythoa* is most tolerant to high energies and is common just offshore of the rubble zone, becoming less common towards the reef. The so-called reef-building coral species are always found on hard bottoms: *Acropora palmata*, *A. cervicornis*, *Montastrea annularis*, *Diploria* spp., and *Colpophyllia* sp. *Manicina arenolata, Siderastrea radians*, and *Porites divaricata* are generally associated with soft substrates.

Stop 4. Loggerhead Key—This is a very interesting stop on patch reefs of different composition (Fig. 5). Two large patch reefs are within easy snorkeling depth; the inshore reef is dominated by *Acropora cervicornis* and the outer reef by *Montastrea annularis*. Generally, patch reefs dominated by *Acropora cervicornis* are found offshore, just behind fringing reefs in Florida. The presence of *A. cervicornis* here may be related to the orientation of Loggerhead Key with respect to the major current direction. The shore of Loggerhead Key is made of beachrock which is being undermined along the shoreface, causing collapsing of the beachrock and development of a very steep forebeach profile. The area just offshore of this beachrock is characterized by migrating sand waves and small exposed rock surfaces, suggesting a strong longshore current. Further evidence of this longshore current exists at both ends of Loggerhead Key: one end is erosional, the other depositional with bar and spit development. The current along the shore in this area may be stronger than the current farther offshore. This may be environmentally significant and may supply the energy required to transport *A. cervicornis* clumps. Most *A. cervicornis* patch reefs are found behind fringing reefs and may be the result of original recruitment aided by wave transportation.

Along the submerged beachrock, zone 1, young coral colonies of *Siderastrea radians* and *Favia fragum* were seen, also a few soft corals. The gradient here is steep, dropping from near sea level to nearly 2 m below it within a few meters.

Zone 2 is dominated by migrating sands with occasional rock outcrops. Small clumps of *Acropora cervicornis* are found in the sand, some of which have been stabilized by *Thalassia*. Occasional colonies of *Diploria* spp., *Montastrea, Siderastrea*, and *Porites* are present on exposed rock surfaces.

The *Acropora cervicornis* patch reef is placed in zone 3. The water depths around the patch reef vary from 2–4 m. *Thalassia*-stabilized sand flats with some very large blowouts exposing coral rubble or shell beds are found around the peripheral margins of both the *Acropora* and *Montastrea* patch reefs. *Acropora cervicornis* is the dominant species in zone 3 and forms nearly a monospecific thicket (Fig. 4C). Notice the truncated older coral branches and the thinner, newer branches which are nearly all the same length. This new growth has occurred since the winter freeze of 1975 (Shinn, Personal communication).

*Montastrea annularis* dominates the patch reef of zone 4. Other dominant species are *M. cavernosa*, *Favia fragum*, *Mellepora alcicornis*, *Diploria* spp., *Siderastrea siderea*, and *Porites astreoides* (Fig. 4D). There are also many less conspicuous species of hard corals and many soft corals.
<table>
<thead>
<tr>
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<tr>
<td>0-1.5m</td>
<td>1.5-2.5m</td>
<td>2-4m</td>
<td>3-7m</td>
</tr>
<tr>
<td>Blocks of beach rock</td>
<td>Sand waves and rock</td>
<td>Thalassia stabilized sands peripheral to patches</td>
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**Common Corals**

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<tr>
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<tbody>
<tr>
<td>Siderastrea radians</td>
<td>Favia fragum</td>
<td>Acropora cervicornis</td>
<td>Montastrea annularis</td>
</tr>
<tr>
<td>Diploria spp</td>
<td></td>
<td>Notice: truncated surface of coral colonies caused by freeze and subsequent growth Nearly monospecific thicket</td>
<td></td>
</tr>
<tr>
<td>Montastrea annularis</td>
<td>M. cavernosa</td>
<td>Millepora alcicornis</td>
<td>Porites asteroids</td>
</tr>
<tr>
<td>Siderastrea siderea</td>
<td>Diploria spp</td>
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**Figure 5.** Transect across patch reefs offshore of Loggerhead Key, Stop 4.

(for exact location refer to Figure 2).
Summary—The Dry Tortugas is a carbonate band which is bordered by a series of fringing reefs. The inner area between the fringing reefs is filled with coral and other carbonate rubble and sand. Much of the sand is derived from organisms that live on or near the reef.

Corals are very common in most environments in the Dry Tortugas and make up a significant amount of the living biomass. Three primary coral environments have been the objects of our visits: the back-reef zone of a fringing reef, patch reefs, and lagoons.

Introduction to Coral Key and Descriptions

The key presented here is developed and borrows heavily from the keys presented by Smith (1948) and Bayer and Cairns (handout, RSMAS, University of Miami). This key differs, however, in only including species that have been reported from the Dry Tortugas. A brief review of coral terminology with illustrations copied from Wells (1956) is presented to introduce and clarify all terms used in the key and subsequent descriptions.

Coral descriptions are not listed systematically but in the order in which they appear in the key. The number of each species description corresponds to the number in parenthesis following the species name in the key. The descriptions are based on the original author's description, those from Smith (1948), Roos (1964, 1971), Weisbord (1974), Vaughan (1919), and from personal observations.

Included with the coral descriptions is information on depth distribution, environmental distribution, and geological role. Information on the depth distribution is based mainly upon work by Goreau and Wells (1967) in Jamaica and by Roos (1964, 1971) in the Antilles. Figure 6 illustrates the ecological zonation of reefs in Jamaica. Goreau and Goreau (1973) divided the reef into three main areas: the back reef, reef crest, and fore reef areas, which were subsequently subdivided into 11 zones. Goreau and Goreau's system of numbering and estimating relative abundance is followed for the presence of corals on reefs. Additional information from Vaughan (1919) and Roos (1964, 1971) is also incorporated. The geological role of the individual coral species is taken from Goreau and Goreau (1973).

The purpose of these descriptions is not to add additional information but to collect significant information to aid the non-coral specialists with the use of the key for relatively easy and accurate coral identification. Good illustrations of most corals can be found in the following references: Vaughan (1916, 1919), Smith (1948), Roos (1964, 1971), and Weisbord (1974).

Reef Zones: Back reef/Reef crest /Seaward slope

Figure 6. Ecological zonation of reefs in Jamaica. Compiled from Goreau and Goreau (1973, pp. 432 and 448).
OUTLINE OF CORAL TERMS WITH BRIEF DESCRIPTIONS AND SKETCHES

Corals begin their lives as planula larvae which remain planktonic until they find a suitable substrate upon which to settle. Shortly after the larva attaches to the substrate, a basal disc is deposited firmly on the substrate. As a polyp grows upward from the basal disc, the margins of the disc turn upward forming a cup, which is called the epitheca or cup wall. The septa are the first skeletal structures to appear after deposition of the base plate.

As the coral grows, secondary thickening of the epitheca and sometimes the septa occurs. As the coral polyp matures, additional cycles of septa may develop. The first cycle is always complete and consists of six septa which are usually the largest ("1" in Figure below). Additional cycles of septa are added between the previously existing septa. The second cycle has a total of six septa ("2") and the third cycle twelve, if complete. The majority of reef corals exhibit three or four cycles of septa, often the third and forth cycles will be incomplete.
A portion of the polyp overhangs the top of the epitheca and is call the edge zone. This is the area responsible for the addition of carbonate material between and within corallites as growth continues in colonial corals. Only endotheca is present in solitary corals.

A great deal of variation occurs in the shape and development of the septa and columella. Septa consist of trabeculae, which are spines or rods formed by the sclerodermites in the polyp. Sclerodermites are the centers of calcification. Basically, there are two types: simple trabeculae composed of series of simple sclerodermites, and compound trabeculae which are composed of bundles of single sclerodermites.

Associated with the septa are pali and paliform lobes. A palus is a vertical lamella or pillar-like structure developed along the inner edge of certain entosepta, comprising the remnant part of a pair of exosepta joined at their inner margins. They are structurally identical with the septa and secondary to them. Entosepta are septa developed within the space between a pair of mesenteries. The second cycle of septa are generally developed within exocoels if they form after full development of the primaries. If they form at the same time, both primaries and secondaries are entoseptal. Paliform lobes are structures resembling the palus but formed by detached trabeculae offset
from the inner edge of the septa, appearing in vertical succession and differing from pali in not being formed as a result of substitution. Paliform lobes of primary and secondary septa may mingle axially to form a *columella*.

The *columella* is a solid or non-solid calcareous axial structure formed by various modifications of inner edges of septa, often projecting into the calice in the form of sharp-pointed protuberances in the central part of the calice in some corallites. There are three common types: laminar, spongy or trabecular, and styloform. *Trabecular columella* are spongy axial structures formed of trabeculae loosely joined with paliform lobes. *Styloform columella* are solidly fused and longitudinally projecting axial structures with entosepta fused to them by secondary dense calcareous skeletal deposit, generally covering or thickening various parts of the corallite (stereome). *Lamellar columella* are plate-like axial structures orientated parallel with the long axis of the calice.
Corallum or colony growth morphology is dependent upon environmental factors and coral type. Common coral morphologies are: (1) ramose or branching; (2) hemispherical or massive; (3) plate-like; (4) encrusting; (5) frond or lace-like; (6) solitary.

In addition to variations in growth morphology, great variation exists in colony formation or the distribution pattern of individual polyps in a colony.
KEY
TO THE STONY CORALS OF THE DRY TORTUGAS, FLORIDA

1. Skeleton surface characterized by radiating patterns of septa or sinuous grooves and ridges................................................................. 2
   Skeleton surface smooth, characterized by barely visible pores.....
   Millepora alcicornis Linnaeus (1)

2. Coral consists of a single cup or calice......................................... 3
   Coral forms colonies with many cups, may be branched, massive or encrusting
   ......................................................................................... 5

3. Cup with diameter up to 6 cm, numerous radiating septa with well developed teeth..... Scolymia lacera (Pallas) (2)
   Cups less than 10 mm in diameter, may occur in groups, growing on shells
   or other hard substrates............................................................... 4

4. Cup with diameter of 10 mm, poorly developed columella..... Phyllangia americana Edwards and Haime (3)
   Cups with diameter of 5 mm or less, distinct columella..... Astrangia solitaria (leSueur) (4)

5. Coral skeleton branched..................................................................... 6
   Coral skeleton not branched, may have lobes................................. 17

6. Branches broadly flattened..... Acropora palmata (Lamarck) (5)
   Branches cylindrical or slightly flattened....................................... 7

7. Cups distributed along entire length of branch................................. 8
   Branches with terminal cups only.................................................. 15

8. Skeleton porous.................................................................................. 9
   Exotheca between calices, solid, forming nonporous skeleton........... 12

9. Corallites in close contact, walls not projecting above surface of branch............................................................... 10
   Corallites separated, walls project above surface of branch.....
   Acropora cervicornis (Lamarck) (6)

10. Branches less than 6 mm in diameter, bifurcating to form clumps....
    Porites divaricata (leSueur) (7)
    Branches between 15-30 mm in diameter........................................ 11

11. Branches taper, often bifurcate near ends..... Porites furcata Lamarck (8)
    Branches with swollen or clubbed ends..... Porites porites (Pallas) (9)
12. Septa 10 or fewer......................................................... 13
   Septa 12 or more...................................................... 14

13. Corallum clavate or nodular.... *Madracis decactis* (Lyman) (10)
   Corallum ramose, branches 6-10 mm thick.... *Madracis mirabilis* (Duchassaing and Michelotti) (11)

14. Colonies of few, long, tapered, ascending branches; calices usually on
   prominent conical projections..... *Oculina varicosa* leSueur (12)
   Colonies bushy and profusely branched; calices never on prominent conical
   verrucae..... *Oculina diffusa* (Lamarck) (13)

15. Corallite circular, usually less than 4 mm in diameter, paliform lobe indistinct
   ..... *Cladocora arbuscula* leSueur (14)
   Corallites oblong, usually larger than 8 mm in width.......... 16

16. Corallites up to 35 mm long, 8-17 mm wide, septa smooth..... *Eusmilia
   fastigiata* (Pallas) (15)
   Corallites up to 12 cm long and 4.5 cm wide; septa with strong teeth.....
   *Musa angulosa* (Pallas) (16)

17. Coral leafy or cup-shaped, upright from substrate, or spreading and plate-
   like, free edge, columella present........................................ 18
   Coral massive, rounded, or hemispherical, often with projections, or thick
   encrustations over substrate........................................... 19

18. Valleys continuous, corallum unifacial..... *Agaricia fragilis* Dana (17)
   Valleys discontinuous or reticulate, corallum unifacial or secondarily
   bifacial..... *Agaricia agaricites* (Linnaeus) (18)

19. Coral usually firmly attached to solid bottom......................... 20
   Coral lies unattached on sea floor.................................... 25

20. Surface marked with pattern of sinuous grooves and ridges........... 21
   Surface marked with pattern of star-like calices, usually with only one
   center (sometimes two or three)...................................... 31

21. Septa distinctly toothed or serrated throughout.................... 22
   Uppermost edge of septa minutely dentate, septa smooth near columella
   ............................................................................... 26

22. Teeth coarse and irregular, large ones spine-like.................... 23
   Teeth fine and regular.................................................... 27

23. Floor of valleys with several parallel septal plates connecting calicinal
centers, weak columella.... *Mycetophyllia lamarckiana* (Edwards and Haime) (19)

Floor of valleys without parallel lamellae connecting centers............. 24

24. Columella well developed, colony 30 cm in diameter, valleys 20–25 mm in width, depta 7–9/cm..... *Isophyllia sinuosa* (Ellis and Solander) (20)

Columella weak, colony 10–13 cm in diameter, valleys 12–25 mm wide..... *Isophyllia multiflora* Verrill (21)

25. Edges of septa distinctly serrated, columella of flattened, twisted trabeculae .... *Manicina areolata* (Linnaeus) (22)

Edges of septa smooth, near columella, finely denticulated on upper surface, lamellar columella..... *Manicina mayorii* Wells (23)

26. Valleys without a lamellar columella, colonies large ascending pillars..... *Dendrogyra cylindrus* Ehrenberg (24)

Valleys with lamellar columella at bottom of valleys..... *Meandrina meandrites* (Linnaeus) (25)

27. Valleys with spongy or trabecular columella, continuous along bottom... 28

Bottom of valleys without spongy or trabecular columella, double wall conspicuous along top of collines................................................. 30

28. Valleys separated by collines furrowed on top "forming ambulacra," ambulacra may be deeper than valley..... *Diploria labirynthiformis* (Linnaeus) (26)

Valleys separated by collines ridged or rounded on top, sometimes with narrow, shallow, but never wide ambulacra............................................. 29

29. Valleys are wider than 6 mm, usually 3.5–4.0 mm, narrow sharply ridged collines ..... *Diploria clivosa* (Ellis and Solander) (27)

Valleys between 6–9 mm in width; septa 15–20/cm, very few do not meet the columella..... *Diploria strigosa* (Dana) (28)

30. Colonies massive, hemispherical boulders; valleys sinuous, usually continuous, 10–12 mm wide, 8–9 septa/cm..... *Colpophyllia natans* (Houttuyn) (29)

Colonies smaller, turbinate, with central attachment, valley discontinuous, 15–20 mm in width, 10–12 septa/cm..... *Colpophyllia amaranthus* (Houttuyn) (30)

31. Calices large, 5 mm in diameter or larger................................. 32

Calices small, 5 mm in diameter or smaller................................. 33

32. Calices 5–8 mm in diameter, calices monocentric, septa with fine teeth, columella large and distinct..... *Montastrea cavernosa* (Linnaeus) (31)

Calices 10 mm in diameter or larger, septa with coarse teeth..... *Isophyllastrea rigida* (Dana) (32)

33. Skeleton very porous, calices in close contact, with common porous walls 34
Skeleton dense, calices distinctly separated by solid skeletal material. 36

34. Calices 2.5-5.0 mm in diameter, distinctly polygonal, 36 or more septa of laminar nature but perforated; beaded or dentate margin................. 35

Calices less than 2 mm in diameter, indistinctly polygonal, 12 septa consisting of 1-4 united spire-like projections..... *Porites astreoides* Lamarck (33)

35. Septa numerous (up to 64), gently sloping into calicular pit, calices 4-5 mm in diameter..... *Siderastrea siderea* (Ellis and Solander) (34)

Septa up to 40, steeply sloping into calicular pit, which is deep and narrow, calices 2-4 mm wide..... *Siderastrea radians* (Pallas) (35)

36. Septa not more than 24 in fully developed calices......................... 37

Largest calices have more than 24 septa........................................ 40

37. Center of calices with solid, conical or columnar columella, standing up at point where septa converge..... *Stephanocoenia michelinia* (Edwards and Haime) (36)

Center of calices with group of small papillae at point where septa converge 38

38. Thin, sharp costae corresponding with septa extend out of calices onto peritheca, columella distinct..... *Montastrea annularis* (Ellis and Solander) (37)

Costae absent or reduced; broad ridge on peritheca around calices, columella inconspicuous................................................................. 39

39. 24 septa, third cycle septa bend toward and join those of second cycle before reaching columella, paliform lobes indistinct..... *Solenastrea hyades* (Dana) (38)

24 septa, third cycle septa short and free along inner edges, not joining septa of second cycle, 12 distinct paliform lobes..... *Solenastrea bournoni* Edwards and Haime (39)

40. Edges of septa finely granulated, wavy in projecting upper part, sides with fine sharp beads arranged in radiating rows; calices ovate to very elongate (up to 28 mm long but only 3-5 mm wide)..... *Dichocoenia stokesii* Edwards and Haime (40)

Edges of septa distinctly toothed, sides spinulose; calices round, ovate, or bluntly polygonal..... *Favia fragum* (Esper) (41)
BRIEF DESCRIPTIONS
OF THE STONY CORALS OF THE DRY TORTUGAS, FLORIDA

1. **Millepora alcicornis** Linnaeus

   Light orange-yellow to dark brown with whitish rims; encrusting, branching, and flattened forms, lattermost frond-like, often referred to as *M. com-planata*; entire surface covered with minute holes, arranged in patterns of five smaller ones around a central larger one; not a true coral but a hydroid.

   - **Depths:** maximum 50 m, optimum 1-10 m
   - **Environment:** lace-like form: common zones 3, 6; very common 5, 7, 8; branching form: common zones 6-10, very common 1-3
   - **Geological role:** frame-filler and sediment producer

2. **Scolymia lacera** (Pallas)

   Dull brown, green, or red with dark patches or concentric rings; large, circular solitary cups up to 6 cm in diameter, single center to the valley; not branched; radiating septa have large teeth and extend beyond wall of cup or corallite.

   - **Depths:** maximum 59 m, optimum 10-38 m
   - **Environment:** rare in zones 7-11; in lagoons up to 1 m, usually in deeper water
   - **Geological role:** frame-filler and sand producer

3. **Phyllopora americana** Edwards and Haine

   Encrusting, moderately large cups (10 mm in diameter), nearly circular and deep; septa usually prolonged beyond wall of cup.

   - **Depths:** maximum 17 m, optimum 3 m
   - **Environment:** not a true reef coral, attaches to hard surfaces
   - **Geological role:** sediment producer

4. **Astrangia solitaria** (Le Sueur)

   Cups single, growing attached to base of larger corals or rock, thin encrustations often connect several bases of cups; cups tabular, 6 mm tall, 4 mm in diameter; septa with toothed edges; septa prolonged as low ridge down side of cup.

   - **Depths:** maximum 43 m, optimum 1.5-5 m
   - **Environment:** not strictly a reef coral, corallites attached to rock or dead parts of other corals
   - **Geological role:** sediment producer

5. **Acropora palmata** (Lamarck)

   Brownish-yellow; ramose or branching; branches broadly flattened, resembling moose antlers; corallites project from surface; calices cover entire surface.

   - **Depths:** maximum 17 m, optimum 1-5 m
   - **Environment:** common zones 6, 8; very common 4, 5; commonly reach into surf, not usually in inner bays
   - **Geological role:** frame-builder and sediment producer

6. **Acropora cervicornis** (Lamarck)

   Brownish-yellow; ramose; branches cylindrical or nearly so; corallites protuberant, tubular or paliiform; calices along entire branch surface.

   - **Depths:** maximum 50 m, optimum 15-30 m
   - **Environment:** uncommon in zones 1-3, 6, 8; common in 7, 9; also found in quiet bays on sandy bottoms
   - **Geological role:** frame-filler and sediment producer
7. *Porites divaricata* leSueur
   Branches smaller than *P. furcata*, under 6 mm in diameter, no tapering or
dilation along length of branches; calices very shallow, 2 mm in diameter.
   Depths: maximum 47 m, optimum 1 m
   Environment: most common in zones 1 and 2
   Geological role: frame-fillers and sediment producers

8. *Porites furcata* Lamarck
   Branching colonies, average 10 mm in diameter without swollen ends of *P.
porites*; calices 1.5 mm in diameter; five pali usually present.
   Depths: maximum 50 m, optimum 1-20 m
   Environment: most abundant in reef zones 7-10
   Geological role: frame-builder, filler and sediment producer

9. *Porites porites* (Pallas)
   Yellowish-brown; branched with ends swollen and blunt (clubbed); calices
shallow, deeper on ends of branches, 2 mm in diameter; columella and six
pali usually present.
   Depths: maximum 25 m, optimum 2-3 m
   Environment: most common inshore and in lagoonal areas around reefs; also
   abundant on seaward side of reef crest
   Geological role: frame-builder, filler and sediment producer

10. *Madracis decactis* (Lyman)
    Polyps yellow to purple-brown with white tips; form thin small (under 15 cm)
encrustations, sometimes sparse branches or lobes; angular or circular cups –
do not touch; beaded boundaries 2 mm in diameter; septa usually 10, sometimes
8, smooth; columella styliform, well developed; peritheca extensive, non-
porous.
   Depths: maximum 70 m, optimum 5-40 m; usually below 20 m, most common below
   30 m
   Environment: rare in back-reef zones and seaward of reef crest
   Geological role: frame-builder and sediment producer

11. *Madracis mirabilis* (Duchassaing and Michelotti)
    Ten septa; intercalicular surface spinose to smooth; corallum ramose; branches
thick (6-10 mm), blunt, long, slender; differs from *M. decactis* in having
prickles or ridges between calices instead of rows of beads.
   Depths: maximum 60 m, optimum 3-40 m
   Environment: very common in reef zones 9-10
   Geological role: frame-builder and sediment producer

12. *Oculina varicosa* leSueur
    Colony up to 60 cm high; branches fewer and longer than *O. diffusa* and wider;
calices swollen at base.
   Depths: not well known
   Environment: rare on Florida reefs
   Geological role: probably frame-filler and sediment producer

13. *Oculina diffusa* (Lamarck)
    Colonies bushy and profusely branched, forming dense rounded clumps; calices
with low walls projecting only slightly above surface of branch, never on
prominent conical verrucae; branches less than 10 mm thick; 24 septa; columella
well developed.
   Depths: maximum 15 m
   Environment: uncommon in reef zones 1-3, 7 and 9
   Geological role: frame-filler and sediment producer
14. **Cladocora arbuscula** leSueur

Small, densely branching colonies; branch terminates as a calice; calices 3.5 mm in diameter; branches with fine longitudinal ridges continuous with septa.

**Depths:** maximum 15 m, optimum 2-4 m

**Environment:** patchy in back-reef zones, rare in reef zones 7 and 8

**Geological role:** frame-filler and sediment producer

15. **Eusmilia fastigiata** (Pallas)

Deep brown with greenish cup ringed with whitish tentacles; branched with cups at ends of branches, oval, valleys up to 35 mm long, 8-13 mm wide with sharp rim; no teeth on septa; 15-18 septa/cm, 7-9 principals.

**Depths:** maximum 65 m, optimum 3-30 m

**Environment:** uncommon in reef zones 8-9, on mangrove roots, in exposed places, leeside reefs

**Geological role:** frame-filler and sediment producer

16. **Mussa anguicosa** (Pallas)

Pink, purple, or brown, living colony completely covered by flesh of polyps; heavy, short branches ending in cups up to 12 cm long and 4.5 cm wide; walls 6-8 mm thick; septa with strong teeth point obliquely upward.

**Depths:** maximum 59 m, common between 10-25 m

**Environment:** common in reef zones 8-9, rare off Florida

**Geological role:** frame-filler and sand producer

17. **Agaricia fragilis** Dana

Light brown; coral usually cup-shaped or saucer-shaped fronds, thin, delicate, up to 15 cm across; cups on upper surface only, 2 mm across; ridges between cups long and low.

**Depths:** maximum 80 m, optimum 7-30 m

**Environment:** common in reef zone 9

**Geological role:** frame-filler and sediment producer

18. **Agaricia agaricites** (Linnaeus)

Chocolate to purple-brown, short white tentacles; coral usually foliaceous or frondous, massive, or encrusting; fronds usually bifacial, irregular, 5-20 mm thick; calices arranged in groups more or less parallel, small and shallow, 2-3 mm; septa low, up to 36 in number, finely serrulate; var. **Chlorella** Verrill - massive, slightly lobed form; var. **purpurea** Lesson - cups restricted to one face.

**Depths:** maximum 60 m, optimum 10-40 m

**Environment:** common in reef zones 5 and 7; very common in 8-9; also in inner bays, sometimes on mangrove roots

**Geological role:** frame-filler and sediment producer

19. **Myctophyllia lamarckiana** (Edwards and Haime)

Chocolate color but often with bright green, blue or purplish in older colonies; flat growths either stalked or completely encrusting; valleys interconnected, walls tend to disappear on older corals; septa 8-10/cm, 4-5 extending farther into valleys, toothed.

**Depths:** maximum 75 m, optimum 5-40 m

**Environment:** common in reef zones 7-9

**Geological role:** frame-filler and sediment producer

20. **Isophyllia sinuosa** (Ellis and Solander)

Color variegated with patches of lavender, bright green and white; medium size, massive with short stalk; valleys continuous, lobes radiating from center,
average width 22 mm widening toward rim to 35 mm, depth 8-10 mm, older colonies lose radial arrangement and valleys become discontinuous; 7-9 septa/cm, 6-10 slender coarse teeth, sides spinulose.
Depth: maximum 10 m, optimum 2 m
Environment: rare in reef zones 6-9
Geological role: frame-filler and sediment producer

21. *Isophyllia multiflora* Verrill
Greener in color than *I. sinuosa*; smaller colonies, more singular cups, fewer and narrower valleys, walls thinner, and septa more crowded, thinner and less protruding than in *I. sinuosa*.
Depth: below 3 m
Environment: uncommon on reefs
Geological role: frame-filler and sediment producer

22. *Manicina areolata* (Linnaeus)
Yellow to brown with greenish valley, tentacles transparent with white tentacles; oval shape with flat upper surface, narrow ends, short basal stock; 15 cm in length; valley branches out into side arms, up to 2.5 cm wide; septa thinner than in *M. mayori* Wells.
Depth: maximum 43 m, optimum 2-25 m
Environment: flat, shallow muddy bottoms
Geological role: sediment producer

23. *Manicina mayori* Wells
Yellow to brown with greenish valleys; larger and not narrow at ends as in *M. areolata*; no central stalk; valley not completely interconnected, long and winding; wall thinner, septa thicker, about 12/cm without holes or pores as in *M. areolata*.
Depth: maximum 65 m, optimum 7-28 m
Environment: back-reef lagoon
Geological role: sediment producer

24. *Dendrogyra cylindrus* Ehrenberg
Brownish-yellow, extended tentacles give colony a hairy appearance; heavy pillars up to 60 cm wide at base; winding, narrow valleys, not all interconnected; thick septa without teeth; narrow walls between valleys; sometimes reduced columella and septa meet across valley.
Depth: maximum 20 m, optimum 3-8 m
Environment: rare in reef zones 1-4 and 6; common in 7
Geological role: frame-builder and sediment producer

25. *Meandrina meandrites* (Linnaeus)
Yellow or brown, white tentacles; large boulders, flat or rounded, 30 cm plus in diameter; valleys long and twisting but not all interconnected, 10 mm wide, 8 mm deep; septa of adjacent valleys usually meet in sharp zigzag line on top of separating wall; 7 septa/cm, over 1 mm thick, no teeth on margins.
Depth: maximum 70 m, optimum 8-30 m
Environment: rare in reef zones 1, 2, 6, 11; common in 7-10
Geological role: frame-builder, frame-filler and sediment producer

26. *Diploria labyrinthiformis* (Linnaeus)
Orange-yellow to brownish-yellow; large rounded boulders; valleys twisting, narrower and deeper than *D. strigosa* (Dana), nearly all connected; walls thick with distinct groove; septa thicker, not as close as in *D. strigosa*.
Depth: maximum 43 m, optimum 2-15 m
Environment: not found in inner bays, somewhat deeper than other Diploria spp.; uncommon in reef zones 3, 6 and 9; common in 7 and 8
Geological role: frame-builder and sediment producer

27. Diploria clivosa (Ellis and Solander)
Greenish-brown in grooves, chocolate over walls, tentacles bright green with white tips; large, low growth with irregular knobs over surface; valleys not all connected together, shallow and narrow, very winding except near edge; walls never grooved; septa thin and close together.
Depths: common to depths of 25 m, optimum 1-3 m
Environment: mostly on bare rock, common in reef zones 3 and 7; uncommon in 1 and 2
Geological role: frame-builder and frame-filler, sediment producer

28. Diploria strigosa (Dana)
Dull yellow to greenish-brown; dome-shaped masses; valleys twisting, not all interconnecting, wider and deeper than D. clivosa; walls between valleys wider than D. clivosa but rarely grooved, if grooved, small and narrow; septa continue over walls.
Depths: maximum 40 m, optimum 3-10 m
Environment: common in reef zones 3-8
Geological role: frame-builder and sediment producer

29. Colpophyllia natans (Houttuyn)
Valleys green, walls brown; large, light, convex mass; valleys more or less interconnected and winding, shallower than C. amaranthus (Houttuyn); wall grooved.
Depths: maximum 55 m, optimum 2-20 m
Environment: common in reef zones 3, 7 and 8
Geological role: frame-builder and sediment producer

30. Colpophyllia amaranthus (Houttuyn)
Valleys green, walls brown; small, light, slightly convex mass with short stock at base; valleys short, straight, not interconnected, grooved above with thin boundary ridges.
Depths: maximum 15 m
Environment: uncommon
Geological role: frame-builder and sediment producer

31. Montastrea cavernosa (Linnaeus)
Brown, olive, green-purplish or blue; boulders 150 cm across; calices average 8 mm in diameter, usually projected above surface; septa prolonged into space between calices.
Depths: maximum 95 m, optimum 10-60 m
Environment: common in reef zones 9-11; uncommon in 1-4 and 6-8
Geological role: frame-builder and sediment producer

32. Isophyllastrea rigida (Dana)
Pink or purple with white oral discs; small boulders; calices polygonal and irregular in shape, 10 mm across; septa with 6-8 large teeth on edge, extend over walls; wall 3 mm thick; 25-30 septa in single corallite, 5-8 meeting the columella.
Depths: maximum 20 m, optimum 3 m
Environment: rare, most common in reef zone 7, also found in 1-3 and 6-9
Geological role: frame-filler and sediment producer
33. *Porites astreoides* Lamarck
Yellowish-brown; rounded, irregular masses, up to 50 cm in diameter; calices 1.25-1.5 mm in diameter; 12 septa, porous, small rough teeth.
**Depth:** maximum 70 m, optimum 5-20 m
**Environment:** muddy inner bays, mangrove roots, common in reef zones 1-3, 7 and 10; uncommon in 4-6, 8 and 9
**Geological role:** frame-builder and sediment producer

34. *Siderastrea siderea* (Ellis and Solander)
Light reddish-brown; hemispherical masses up to 50-75 cm in diameter; calices 4-5, sometimes 6 mm in diameter, wall raised; septa 50-60, five cycles, last incomplete.
**Depth:** maximum 70 m, optimum 3-20 m
**Environment:** NOT on muddy bottoms, common in reef zones 7 and 8; uncommon in 1-3, 6, 9 and 10
**Geological role:** frame-builder and sediment producer

35. *Siderastrea radians* (Pallas)
Grayish to brown; corals rounded, 30 cm or more in diameter, young colonies often encrusting; calices small (3 mm in diameter), angular, cavity of cup deep and narrow; septa 36-40, four unequal cycles; distinguishable from *S. siderea* (Ellis and Solander) by smaller, deeper, and narrower cup.
**Depth:** near surface to 33 m, optimum 2 m
**Environment:** muddy inner bays, common in reef zones 1-2; uncommon in 3-7
**Geological role:** frame-filler and sediment producer

36. *Stephanocenia michelini* (Edwards and Haime)
Polyps brown; forms rounded boulders under 30 cm in diameter; calices 213 mm in diameter, close together but not always touching; distinguished from *S. radians* (Pallas) by presence of lobes or pali at inner edges of septa; three cycles of septa, primaries and secondaries with well developed pali, tertiarys thin and shorter, margin entirely or finely dentate.
**Depth:** maximum 95 m plus, optimum 3-50 m
**Environment:** common in reef zones 8-10, rare in zones 1, 2, 7 and 11
**Geological role:** frame-builder, frame-filler, and sediment producer

37. *Montastrea annularis* (Ellis and Solander)
Yellow-brown; large boulders 150 cm, often encrusting or irregular in shape; calices circular, 2.0-2.5 mm wide, average 1 mm apart; rims of calice slightly projecting; septa prolonged across space between cups.
**Depth:** maximum 80 m, optimum 3-45 m
**Environment:** absent in landlocked bays, abundant in reef zones 7, 8 and 10; common in 3 and 9; uncommon in 1, 2, 4 and 11
**Geological role:** principal reef-builder in Caribbean, also sediment producer

38. *Solenastrea hyades* (Dana)
Yellow-brown; lobed masses or irregular encrustations; calices 3 mm in diameter, rims slightly raised above surface; calices almost touching or 3 mm apart; septa do not extend across spaces between calices; 12-24 septa, 12 extend to columella; small paliform lobes.
**Depth:** maximum 23 m, optimum 5-10 m
**Environment:** very little information
**Geological role:** frame-filler and sediment producer

39. *Solenastrea bourbonii* Edwards and Haime
Light brown; domes or rounded masses, 30 cm in diameter, often with irregular
bumps or projections on surface; calices smaller than S. hyades (Dana) (2 mm in diameter), separated by 1 mm; low ridges extend from septa part way across space between calices which are somewhat blistered.

**Depth: more common below 10 m, below 20 m more or less replaces Montastrea annularis**

**Environment:** very rare in reef zones 1-3, 9-10

**Geological role:** frame-filler and sediment producer

40. *Dichocoenia stokesii* Edwards and Haime

Yellow or brown with yellow polyps; heavy round colonies up to 30 cm in diameter; short valleys, separate from each other, walls projecting from general surface; septa thick, without teeth.

**Depth:** maximum 40 m plus, optimum 3-20 m

**Environment:** mangrove-lined bays, rare in reef zones 1-4 and very rare in 6, 8-10

**Geological role:** frame-builder, frame-filler and sediment producer

41. *Favia fragum* (Esper)

Light yellow to brown; form small crusts on rocks; calices angular, circular, under 6.5 mm across; septa with irregular teeth on margins; 36-40 septa, 3-4 nearly complete cycles.

**Depth:** maximum 30 m, optimum 2-8 m

**Environment:** sometimes on mangrove roots, uncommon in reef zones 1-4 and 7

**Geological role:** frame-filler and sediment producer
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Beach rock in South Florida

by

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Abstract

The rapid intertidal lithification of beach deposits in the coral seas has received the attention of numerous investigators. Study of beach-rock from the Dry Tortugas, Florida, shows that the aragonite cement is precipitated from the sea water remaining in the beach sands at low tide. High temperatures, rate of beach drainage, and the permanence of the beach, control the localization of beachrock. The recognition of beachrock in the fossil record is briefly discussed.

Introduction

Beachrock or beach sandstone consists of calcareous skeletal debris cemented by calcium carbonate to form a friable to well-cemented rock; where mineral grains and rock fragments are common in the beach deposits they also occur in the beachrock. The particles are mostly sand-sized with beds composed of reef shingle or conglomerate, and intraformational breccia (Kuenen, 1933, p. 87) is less abundant. Recent beachrock occurs discontinuously in the intertidal zone, on islands with sand beaches, as a series of thin beds which dip seaward at less than 15° and whose strike is parallel to, or at slight angles with, the trend of the present beach. Exposed beachrock is usually broken into rough rectangular blocks by joints parallel and perpendicular to its strike, and in some areas these blocks lie below low tide with a steeper than ordinary dip. The maximum thickness of recent beachrock is probably not more than the order of the eight feet reported by Vaughan (1914, p. 63). Kuenen (1933, p. 87) calls attention to the "... very abrupt, flat junction between the beachrock and the substratum."

The formation of marine beachrock is limited to the latitudes of coral growth. Kuenen (1933, pp. 86-87) refers to descriptions of beachrock from the East Indies and adjacent regions. Other observations and descriptions may be found in Gardiner (1902, 1906, 1930), Branner (1904), Sewell (1935, 1936), Steers (1940), and Fairbridge (1948, 1950). The most detailed account of beachrock is that of Branner (1904) who studied it along the north-east coast of Brazil where it occurs intermittently for a distance of some 1,000 miles. Daly (1924, p. 139), Kuenen (1950, p. 434), Fairbridge (1948, p. 74), and others have called attention to the rapidity of beachrock formation.

The purpose of this paper is to describe the only occurrence of marine beachrock easily accessible from continental United States, and to discuss the formation and distribution of this rock.
The generous assistance of Commander Henthorne of the U.S. Coast Guard and the personnel of the Dry Tortugas Light Station made possible the author's work in the Dry Tortugas. The writer is indebted to K.O. Emery and Rhodes W. Fairbridge for criticism of the manuscript.

Beachrock in Florida

Typical beachrock has been found in Southeast Florida only in the Dry Tortugas. Vaughan (1914, p. 63) and Field (1919, p. 198) mention its occurrence around Loggerhead Key. It is found on both sides of the narrow island as shown in figure 1. The strike is generally parallel to that of the present beach though differences as large as 15° have been observed. The dips do not exceed 10°. As shown in figure 2, the truncated ends of the thin beds form a series of small cuesta-like ridges. Vaughan (1914) reported eight feet or more of beachrock at this locality.

Some exposures have smooth, nearly planed surfaces, often with small circular pits which are similar to the "stonelace" described by Emery (1946, p. 227). More typically the rock has a pitted, fissured, and honey-combed appearance, figure 3, which is characteristic of shore-exposed calcareous rocks in the coral seas. Here the rock is very brittle and its surface is discolored by algae.

Petrography

The beachrock is a thin-bedded, well sorted calcarenite with some beds of coral conglomerate. In hand specimen the grain size distribution within each bed appears uniform, but differences between adjacent beds produce distinct textures and fabrics. Variations in grain size on a finer scale are found within the beds of sand size debris giving laminae of the order of a centimeter in thickness, as shown in figure 4, and as described by Emery (1950).

The grains are fragments of algae, coral, molluscs, foraminifera, bryozoans, etc. Some of this skeletal debris in the beachrock still retains its original tint, and X-ray spectrographic analyses made through the courtesy of H.A. Lowenstam show that the content of aragonite is 90 and 92.4 per cent, respectively, for two samples as compared with 87.5 and 90 per cent for two samples of beach sand from the same locality. The unaltered character of the skeletal debris is confirmed by thin-section examination; grains of Halimeda, coral, molluscs, and incrusting algae showed no recrystallization or selective solution.

Considerable variation in the degree of cementation can be seen even in hand specimens. Some of the beds of medium to coarse sand-sized debris are so poorly cemented that they can be reduced to their component grains by rubbing with the fingers: other beds, generally but not always, those of finer grain size, are well cemented though still porous (see fig. 4). Some idea of the cementation can be gained by comparing the porosity of the beachrock with that of beach sands. The porosity of four samples of beachrock, whose cementation can be described as ranging from fair to moderate, varied from 30 to 38 per cent, with an average value of 34 per cent. Daly (1924, p. 136) gave values of 14.7, 14.8, and 16.5 per cent for the "...more thoroughly indurated beachrock..." from the east side of Loggerhead Key. He indicated that the porosity of average beachrock was higher than these values, and that
recently formed beachrock had a porosity of the order of 35 per cent. Beach sand from the present beach on Loggerhead Key had a porosity of 42 per cent when compacted to minimum volume by tamping. In situ porosity of a beach sand, similar to that of Loggerhead Key, collected on the lower Florida Keys, was 55 per cent for two samples.

The nature of the cementation is clearly shown in thin-section; around almost every grain is a fringe of acicular crystals of calcium carbonate, whose long axes are perpendicular to the grain border (see fig. 5). These crystals are from 0.005 mm. to 0.04 mm. in length and are stained lilac by cobalt nitrate, identifying them as aragonite. The borders of the detrital grains are usually brownish though the grain is clear, and the fringes of aragonite are also a dusty brown, suggesting iron oxides.

Origin of Beachrock

The two main hypotheses of beachrock formation—the action of fresh ground water, and that of sea water—have been discussed by Branner (1904, p. 196), Daly (1924, p. 135), Kuenen (1933, p. 87) and others. Solution of calcium carbonate from the island sands by ground water, followed by precipitation as this water seeps out through the beach at low tide was suggested by Field (1919, p. 198). Daly (1924, p. 138) has objected to this view because it fails to explain the sporadic occurrence of beachrock, and the cementation of deposits low in detrital calcium carbonate. Daly (1924, p. 139) believes that rapidly deposited sands, as from a storm, are required for beachrock formation. Bacterial decomposition of an assumed higher than usual content of organic matter in these deposits is thought to produce the precipitation of an initial aragonite cement which fixes the sand. Inorganic precipitation from sea water then accomplishes the major cementation.

Gardiner, Kuenen, Daly, and others interpret the localization of beachrock in the intertidal zone as evidence that the cementation is due to the precipitation of calcium carbonate from sea water, primarily as a result of heating and evaporation. The nature of the cementation supports this interpretation.

Recent investigations of the apparent solubility product of calcium carbonate in sea water, by Wattenberg and Timmerman (1936), Smith (1941), and Hindman (1943), indicate that normal surface sea water is supersaturated with respect to this component, though there is some difference in the results regarding the extent of supersaturation. These workers suggested that the absence of nuclei is an important factor in the maintenance of this apparently anomalous supersaturation.

Beach sands provide abundant nuclei for the precipitation of calcium carbonate from water contained within them. Moreover, the following factors, which are important in the intertidal zone of beaches, will aid the precipitation of calcium carbonate: (1) Increased temperatures within beach sands promote precipitation because the apparent solubility product decreases with increasing temperature, and because of an increase in the partial pressure of carbon dioxide. Longley (1917, p. 185) found the temperature of the beach surface at low tide on Loggerhead Key to be 39° at 1445 hrs., August 10, 1917. (2) The water remaining in the beach at low tide after drainage is in the form of intergranular films. This condition allows more complete exchange of carbon dioxide between atmosphere and solution, making possible more
rapid equilibration; i.e., precipitation from supersaturated solution.  
(3) Interstitial precipitation may be aided by evaporation of the residual films of water at low tide.

Discussion

The absence of any grain solution within the beachrock indicates that the aragonite cement has not been derived by internal solution and reprecipitation. Additional evidence that the cement is precipitated from sea water is beachrock which contains little or no detrital calcium carbonate (Branner, 1904, Daly, 1924).

On the view that normal surface sea water is just saturated with respect to calcium carbonate, concentration by evaporation is necessary for precipitation. Emery and Foster (1948) found that evaporation from the intertidal beach in Southern California is confined to the upper 30 cm. of the beach. The depth of evaporation is probably greater in tropical beaches. However, the formation of beachrock below a dry sand cover as thick as 100 cm. (Daly, 1924, p. 139), would require considerably deeper evaporation than is likely.

On the other hand, if one agrees to the supersaturation of normal sea water, one might wonder why cementation is restricted to the intertidal zone and does not take place wherever water is in contact with nuclei; as for example, below the low tide mark. This perhaps can be understood in terms of the sluggishness of the equilibration between solid and dissolved calcium carbonate, and the inhibition of this equilibration by organic matter. Miller (1952, p. 171) gives six to eight hours as the time required for equilibration in a small, pure, laboratory system. Hindman (1943) has shown that organic matter inhibits equilibration. Taking Hindman's (1943) value of the apparent solubility product of calcium carbonate in sea water, normal surface water in the tropics is several hundred per cent supersaturated. It is possible that even with such supersaturation precipitation on nuclei does not take place. Only in certain beaches and shallow water areas under the effects of high temperature and the film condition of the residual water can it occur at a significant rate.

The acicular form of the aragonite probably is related to several factors. K. Schultze (quoted by, Kubiena, 1938, pp. 182-3) found that the acicular form of crystals precipitated on and in gels is related to rate of evaporation and alkalinity. Descriptions of beachrock and the author's observations in the Tortugas, indicate that it occurs on beaches normally protected, but which receive storm wave action. The outbuilding of such beaches during storms produces a deposit which is not disturbed by normal wave action—a necessary condition for lithification.

Even on individual beaches, beachrock is not continuous. This distribution may be explained as a result of the rate at which a portion of the beach drains at low tide. Following Emery and Foster (1948) the rate of beach drainage is proportional to beach slope and permeability. Because storm-built beaches probably have a steeper slope and generally coarser grain size than normal beaches they might be expected to drain more rapidly. Such rapid drainage would allow more time for precipitation of calcium carbonate interstitially. It seems likely that storm-built beaches have pronounced variations in thickness, texture, and structure along their trends. This condition, and the connection between the storm-built beach and the normal beach will affect the rate of drainage at low tide, and thus localize beachrock.
The absence of beachrock on the few beaches of the Florida Keys is due to the thinness of the beach deposits. Pleistocene rock is within a few feet of sea level over most of the area and thus the beachesands are only a veneer.

The restriction of marine beachrock to the coral seas indicates that temperature is probably the most important factor in its formation. However, high temperatures and evaporation alone are not sufficient for beachrock formation. Emery and Foster (1948, p. 653) reported the common occurrence of a salt crust on Southern California beaches at low tide. As calcium carbonate is an early precipitate from evaporating sea water one would expect beachrock formation in these beaches. Its absence is probably related to restriction of precipitation to the exposed surface which is reworked by wave action at high tide.

As the tidal range at Loggerhead Key is less than a few feet the presence of eight feet of beachrock there (Vaughan, 1914) requires a relative drop of sea level of the order of five feet. A eustatic change of this magnitude is recognized throughout the coral seas.

Fossil Beachrock

The writer has found no report of pre-Tertiary beachrock in the literature. The recognition of numerous organic reefs in the geologic record suggests that an associated deposit such as beachrock is to be expected. However, there may be some question as to its preservation. As soon as it is exposed on the shore beachrock is very rapidly attacked by inter-tidal erosion. This erosion is so rapid and thorough that unless new rock is continually formed there would be very little of it on modern shores. Despite this continual destruction it seems likely that under conditions of rapid burial beachrock could be preserved.

The texture, structure, and composition of beachrock offer no obvious criteria for differentiating it from normal beach, bar, or nearshore deposits. The recognition of a brackish or intermittently-exposed facies might be supporting evidence for supposed beachrock.

The most significant criteria are those of calcareous shorelines in the tropics. The appearance of a buried surface such as that shown in figure 3 in an ancient limestone would suggest the term "solution unconformity." A local unconformity of this type with associated slabs or boulders of beach arenite would suggest beachrock. The presence of attached or boring organisms on or below this type of surface might further suggest its formation in the intertidal zone.

Conclusions

Marine beachrock is produced by an intertidal precipitation of interstitial aragonite under the influence of increased temperatures and the rate and degree of beach drainage. The restriction of beachrock to the coral seas is due to its temperature dependence and the localization of this rock is related to beach stability and structure.
References


Fig. 1.—Chart showing location of the Dry Tortugas and Loggerhead Key. Insert is an outline map of Loggerhead Key after Vaughan (1914) on which the distribution of beachrock is shown by the heavy dashed lines.
Fig. 2.—Beachrock on the northwest side of Loggerhead Key showing the seaward-dipping thin beds.

Fig. 3.—Intertidal erosion of beachrock northwest side of Loggerhead Key. Approx. 1/20 X.

Fig. 4.—Vertical section of beachrock X2. The two laminae of finer grain size show better cementation than the adjacent coarser laminae.

Fig. 5.—Thin section of beachrock, polarized light, X47. The white pore linings and grain borders are fringes of acicular aragonite.
GROUND WATER OBSERVATIONS ON SMALL CARBONATE ISLANDS
OF SOUTHERN FLORIDA

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The last stop of the Tortugas field trip will be on Loggerhead Key, a typical sand key relatively undisturbed by man. In this area we will observe patch reefs just to the north of the island (Meeder and Davis, this volume), beach rock along the northeastern shore, and will consider the unusual hydrology of small islands such as this one.

Introduction

Islands act as sinks or traps for ground water that may significantly differ from the sea water that surrounds them. Accumulation of ground water is controlled by a number of parameters, including porosity and permeability of the island sediments, varying density and salinity of ground water relative to sea water, climate, vegetation, and island size and topography. Just as these controls may vary widely, the ground waters beneath islands vary widely in their origin and composition. Here, we report briefly on observations of ground water from Loggerhead Key, a sandy key in the Dry Tortugas. For comparison, we include similar observations from Cluett Key, a mud key in Florida Bay (Fig. 1).

Loggerhead Key

Loggerhead Key is the westernmost permanent key in the Dry Tortugas. The island is approximately 1300 m long and 200 m wide. Its highest point of land is about 3 m above sea level on the northeast tip of the island. The island is composed predominantly of coarse and medium size carbonate sand, but beachrock occurs significantly along both sides of the island (Ginsburg, 1953, and this volume) and may extend for an unknown area beneath the island. Island sand is composed of fragments of the aragonitic green algae, Halimeda sp., coral, molluscs, and calcitic red algae. The sand is entirely calcium carbonate and is 80 to 90 percent aragonite and 10 to 20 percent calcite.

Climate of the Tortugas is assumed to be similar to that of Key West, which is approximately 110 km east and where weather records have been kept for over 100 years. Temperature is fairly constant in the Tortugas with winter temperatures between 60°F and 75°F and summer temperatures between 75°F and 90°F. Temperatures as low as 41°F and as high as 100°F have been recorded in Key West. Prevailing winds are easterly, usually of low velocity, but winds associated with winter frontal systems and occasional hurricanes are variable in direction and strength. Rainfall recorded at Key West averages about 100 cm a year and has been assumed to be similar to that of the Tortugas (Thomas, 1970). A gradient
Figure 1. Mean annual rainfall for southern Florida (after Thomas, 1970).
of increasing aridity to the west occurs throughout the Florida Keys and probably continues westward to the Tortugas. Rainfall on Loggerhead Key may be as low as 65 to 75 cm a year and is probably highly variable from year to year. Both in Key West and the Tortugas, rainfall is seasonal, most coming during summer thunderstorms. A significant fraction is also associated with winter frontal systems, which move through the area between November and April. The relatively low rainfall and high rate of evaporation limit the types of plants that can grow on the islands to those which are salt-tolerant and capable of withstanding a semi-arid climate.

During August 26-29, 1976, eight pits were dug to the top of the water table on Loggerhead Key. Polyvinylchloride pipes were seated at the water table in each pit and the pits refilled with sand. Twenty-four hours later, a water sample was taken through each pipe. Total dissolved solids in the water sample were measured immediately with a temperature-compensated refractometer (accuracy ±1 parts per thousand). Samples of ground water collected in this manner ranged in salinity from 3 to 32 parts per thousand. Sea water 100 yards northwest of the island contained 35 parts per thousand on August 28, 1976. These data are used to construct a salinity map (Fig. 2) at the top of the water table during this time period. Considerable artistic license is required to contour salinity based on eight data points, but the authors believe the general trends to be real.

Two observations can be drawn from the data presented in Figure 2. First, ground water with salinity about one-tenth that of sea water occurs beneath Loggerhead Key. Second, low salinity ground water occupies a central position beneath the island and becomes increasingly saline toward the edge of the island. The trends of ground water distribution on Loggerhead are characteristic of that beneath small islands (Todd, 1959, p. 290-293).

By most standards, none of the ground water recovered is potable. In fact, the lowest salinity water recovered is six times as salty as recommended drinking water. Nevertheless, it could sustain life for an indefinite period. The lack of potable water reflects the relatively low rainfall and high evaporation rate of the Tortugas area. Little fresh water appears to be flowing from the island to the surrounding sea. This is indicated by the near normal marine salinity along the island edge.

A dramatic change in vegetation has occurred on Loggerhead since the turn of the century because of the introduction of exotic plants to the island. Bowman (1916) reported the island to be dominated by bay cedar in its natural state and noted that the Director of the Tortugas Laboratory planted a number of exotic plants, including the Australian pine (Casuarina sp.). It is evident from photographs published by Davis (1942) that by 1941 Australian pine had spread at the northern end of the island. Today, the pines are widespread over all but cleared portions of Loggerhead Key. It is not known what effect this vegetation change has had on island hydrology; however, one might guess that the presence of this more extensive vegetative cover has significantly increased evapotranspiration.

Marine carbonate sediments are unstable in fresh water and can dissolve or recrystallize in short periods of time (geologically speaking) if immersed in ground waters that differ in chemical composition from sea water. Normal sea water contains about 35 parts per thousand dissolved solids and the ratios between these dissolved elements are very constant. A water sample from the center of the island was analyzed for calcium (Ca), magnesium (Mg), strontium (Sr), sodium (Na), and chlorine (Cl). The concentration of these ions is compared in Table 1 with those in sea water and with a mixture of 11 percent sea water and
Figure 2. Salinity at the water table of Loggerhead Key.
89 percent fresh water. The difference between the concentration of ions in Loggerhead ground water and in the 11 percent solution of sea and fresh water is listed in Table 1, both as parts per million (ppm) and as a percentage of the concentration in the 11 percent solution.

<table>
<thead>
<tr>
<th></th>
<th>Sea Water</th>
<th>Loggerhead Ground Water</th>
<th>11% Sea Water</th>
<th>Difference (% of 11% Sea Water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>400</td>
<td>55</td>
<td>44</td>
<td>+11 (20%)</td>
</tr>
<tr>
<td>Mg</td>
<td>1,300</td>
<td>220</td>
<td>143</td>
<td>+78 (55%)</td>
</tr>
<tr>
<td>Sr</td>
<td>8.1</td>
<td>3.0</td>
<td>0.89</td>
<td>+2.1 (70%)</td>
</tr>
<tr>
<td>Na</td>
<td>10,780</td>
<td>1,580</td>
<td>1,186</td>
<td>+394 (33%)</td>
</tr>
<tr>
<td>Cl</td>
<td>19,000</td>
<td>2,070</td>
<td>2,090</td>
<td>-20 (-1%)</td>
</tr>
</tbody>
</table>

Table 1. Concentration of major dissolved cations (in parts per million) in sea water, a sample of Loggerhead ground water, and an 11% sea-water/fresh-water solution. The differences between Loggerhead water and the 11% sea-water solution are listed at the right as ppm and as percent of the concentration in an 11% sea-water solution.

Note that the ground water sampled is not simply sea water diluted with fresh water. Based only on the chlorine concentration, ground water contains about 11 percent sea water, but this amount of sea water does not account for the dissolved ion concentration found in the ground water sample. Excessive amounts of Na, Mg, Ca, and Sr are not explained by simple sea water dilution.

The chemical data suggest that the sands beneath Loggerhead are reacting with ground water to provide the excess ions. Unstable minerals (aragonite and magnesium-rich calcites) are probably dissolving to enrich the ground water. Such processes are known to occur on other islands in the Bahamas and Caribbean (Harris and Matthews, 1968; Halley and Harris, 1979). It is possible that calcite and dolomite are precipitated from Loggerhead ground water, but more detailed geochemical and geologic information must be gained before these processes can be detected.

Cluett Key

Cluett Key, a site of modern dolomite formation (Steinen and others, 1978), lies about 200 km east-northeast of Loggerhead in western Florida Bay. The climate at Cluett Key is similar to that at Loggerhead Key, with the exception that Cluett receives 100 to 120 cm of rain each year (Fig. 1). The island is low, its highest point being about 1/2 m above sea level. The center of the island is occupied by an ephemeral pond, which has a maximum depth of approximately 30 cm. The island is fringed by red and black mangroves. The higher portions of the island support grasses and some hardwoods.

Cluett Key is a carbonate mud island. The sediment beneath it is similar to that in the surrounding bay, except that it may contain appreciable amounts of dolomite. A typical composition is 60 percent aragonite, 20 percent high-magnesium calcite, 10 percent low-magnesium calcite, and 10 percent dolomite. The sediment consists of scattered mollusc fragments floating in a pelleted lime mud matrix. Porosity of these sediments is high, between 60 and 80 percent. Because of the fine grain size of these sediments, permeability is very low, on the order of five millidarcies or about three orders of magnitude less permeable than the sand beneath Loggerhead Key.

After heavy rains, water ponds in the central low of the island and in crab
burrows and root holes beneath higher ground. After particularly hard rainfalls, fresh water is found in some crab holes in high ground on the west side of the island. Salinity of the pond occupying the topographically low center of the island reaches a low of 20 parts per thousand. The last bit of water left in the pond before it evaporates to dryness has been measured at 136 parts per thousand.

Samples from shallow wells in the top of the ground water table have a salinity distribution shown in Figure 3. Notice that Cluett shows a gross pattern opposite to that of Loggerhead Key, i.e., ground water becomes more saline toward the interior of the island, and the pond is underlain by a brine two to three times as saline as sea water. This hypersaline ground water occurs despite the fact that Cluett receives more rainfall than Loggerhead Key.

The development of brine ground water beneath Cluett Key is not fully understood, but important factors are island topography and sediment composition. Brine forms in the central pond during evaporation and sinks into the underlying mud. During periods when the pond is dry, water may be raised from the water table by capillary action to continue evaporation and brine formation. Less saline water entering the pond during storms floats on this brine, incapable of displacing the more dense underlying liquid. Only when water in the pond becomes more dense than the underlying brine can significant water move into the island ground water from the island surface.

During periods of high evaporation, enough water may be removed from the island water table so that water enters the sediments beneath the island from the surrounding bay. This occurs when the island water table is lowered sufficiently below the bay level to start flow inland from the island edge. The sediments through which this water flows are of such low permeability that flow must be very slow.

The importance of low permeability and slow flow in maintaining hypersaline ground water is illustrated by a number of deeper wells installed on the island. These produced hypersaline water from the muddy sediments beneath the pond to a depth of 3 m. Below 4 m is Pleistocene limestone on which the island rests. A core boring was made 3 m into this bedrock through a casing cemented to the Pleistocene surface. Water drawn from the Pleistocene limestone (which has high permeability) was of normal Florida Bay salinity. There is evidently sufficient flow through Pleistocene limestone to dilute any brine that may sink into the bedrock beneath Cluett Key.

Summary

The ground water of Loggerhead and Cluett Keys differs significantly from surrounding sea water despite the relatively small size (a few hundred m) of these islands. Climate alone does not determine the character of these ground waters; for example, Loggerhead Key is underlain by less saline ground water than Cluett Key despite the fact that it receives less rainfall. Ground water under small islands such as these is formed from a complex variety of variables that affect the hydrology of the islands. These variables include topography, sediment character, vegetation, and many more parameters that are themselves interrelated. They conspire to form island ground water that not only differs from sea water but also can react with the island sediments to change the character of ground water. In this manner, island ground waters serve as geologic agents, hastening the alteration of marine carbonate sediments to limestone and dolomite.
Figure 3. Salinity at the water table of Cluett Key.
REFERENCES


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

Eugene A. Shinn, J. Harold Hudson, Robert B. Hailey and Barbara Lidz

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 have geologic implications were directed toward 1) sediment composition and hemispheric 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 Pigeon Rock (see Fig. 1) are dead. He attributed lack of this coral to cold waters carried southward by

* 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.

the Florida counter-current. Parallel en echelon reef ridges composed of slow growing massive corals, such as Montastrea annularis, Siderastrea, Diploria, Dicoccinea, and Porites astreoides, do occur here, however, and extend northward at least as far as West Palm Beach. Colonnies of Selenastrea 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 diageneric processes have resulted in an extremely hard grey "reef rock."

The altered accumulation rests on a laminated soil-t-zone crust (14), which in turn rests on light-colored cemented cross-beded quartz and carbonate sand. Patches of terrestrial plant root systems and occasional land snails of the genus Coton 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.
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.](image)
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 limestone crust gave a C-14 age of 4530±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 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 merge 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 0.3 m of carbonated mud similar to that found nearshore and in Florida Bay. The carbonate mud lies directly on a laminated soil limestone 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.

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 *Thecacera* 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.

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**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 accumulation 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 siltstone 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±226 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 13.2 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.

**Accumulation Rates and Sea Level Rise**

A clear relationship exists between 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.

**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. Actinaria saltans 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.

Acknowledgements

The authors thank the National Park Service for permits and logistical support to drill at Fort Jefferson National Monument, Dry Tortugas; for permits to drill Long Reef in Biscayne National Monument; and the Florida State Department of Natural Resources for permission for research in Pennekamp Coral Reef Park.

Appreciation is extended to Jerry J. Stipp of the University of Miami's Carbon-14 Dating Laboratory and Captain Roy Gaensslen of the R/V SEA ANGEL for their aid, and to Daniel Robbin for drafting the illustrations and for his assistance in drilling at Marker G.

References

ANNOUNCEMENT OF 1979 SEGS ANNUAL FIELD TRIP

WHERE: Dry Tortugas, Fort Jefferson National Monument
70 miles west of Key West, Florida

WHEN: Depart Key West Friday, August 24, at 8:00 AM
Return to Key West Sunday afternoon, August 26

LEADERS: Robert Halley, Richard Davis

ACCOMMODATIONS: Camping at Fort Jefferson

PURPOSE: To visit cultural, historical, biological and
geological points of interest including:

the Marquesas "atoll," the submarine sand dunes of the "quick sands," where
Mel Fisher has been salvaging gold from the Spanish wreck, Atocha, Rebecca
Shoal, and the coral reefs of the Tortugas atoll. We will walk on the shifting
sand island, East Key. At Loggerhead Key, we will examine the ruins of the
famous Carnegie Institute, where Mayor and Vaughan did coral research, and
see spectacular examples of beach rock, giant barracuda, and finally old
Fort Jefferson, the largest brick fort ever built by the United States. Fort
Jefferson is best known as the prison where Samuel Mudd served his time for
setting the leg of President Abraham Lincoln's assassin, John Wilkes Booth.

REQUIRED EQUIPMENT FOR THE TRIP: (asterisked items optional)

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<tr>
<td>mattress</td>
<td>Bathing suit</td>
</tr>
<tr>
<td>Long pants</td>
<td>Charcoal</td>
</tr>
<tr>
<td>Trash bags</td>
<td>Off, 6-12, suntan lotion</td>
</tr>
<tr>
<td>Rain gear</td>
<td>Swim fins, snorkel and mask</td>
</tr>
<tr>
<td>*Liquid Joy</td>
<td>*Binoculars (this is a bird watcher's haven)</td>
</tr>
<tr>
<td>*Fishing rod</td>
<td>Food</td>
</tr>
<tr>
<td></td>
<td>Cooking and eating utensils</td>
</tr>
<tr>
<td></td>
<td>(stove)</td>
</tr>
<tr>
<td></td>
<td>2 gallons drinking water/person</td>
</tr>
<tr>
<td></td>
<td>Broad-brimmed hat</td>
</tr>
<tr>
<td></td>
<td>Flashlights or lanterns</td>
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</table>

NOTE: Each camper will be responsible for his own meals.

TRANSPORTATION: Via the SEA DWELLERS I, Captain T. J. Holub

We will meet the SEA DWELLERS I at the Key West Oceanside Marina (parking
available). To get there, turn left from US 1 on State Road 941 on Stock Island
just before you reach Key West. Drive to Oceanside Marina. If you cross Cow
Key Channel bridge, you have gone too far.

SCHEDULE: Depart Key West on board SEA DWELLERS I promptly at 6:00 AM, Friday,
August 24. Return to Key West late Sunday afternoon, August 26.

REGISTRATION: SEGS members, their families, and friends.
COST: $125 per person. Payment in full required by July 31.
Please complete registration form below and send with deposit or
payment in full to:

Phil Pontigo
Florida Bureau of Geology
903 W. Tennessee St.
Tallahassee, Florida 32304

ADDITIONAL IMPORTANT INFORMATION:

There are no fresh water showers, as there is no fresh water available.
one of our leaders recommends a "Joy bath" with liquid Joy and salt
water and says it really works. He knows from experience!

Everyone must be totally self-contained and be prepared to remove all
their own trash and garbage.

Groups efforts will reduce hauling around unnecessarily duplicated
equipment, i.e. stoves, lanterns, etc.

Be sure to ice down your coolers thoroughly. There will be 1500 lbs.
or ice on board the boat, but it melts - and must be stretched for
three days' time.

Bring your own beverages and food - ENOUGH FOR THREE DAYS. There
will be beer and soda on board and available for purchase from SEA
DWELLERS in case you run out, but there will NOT be any food available
for purchase.

We need 35 people to make this trip go. Our initial announcement
produced about 20 persons who said they were interested. So bring
a friend! In the happy event we have more people than we can handle
those first in with full payment will have preference.

In case the August field trip should be cancelled due to severe weather
conditions, alternate dates of September 7-9 is scheduled. Therefore,
it is important that you include your phone number on the information
form below.

If anyone has further questions regarding the field trip you may contact
Bob Halley at 305/672-1784; written responses to SEGS.

Detach and Return

Please enclose the following information with your filed trip payment:

Name ___________________________  # of people in party _____
Address __________________________  Tel. # ____________________
The following publications can be ordered from

Southeastern Geological Society
Post Office Box 1634
Tallahassee, Florida 32302

Add 50 cents per publication ordered to cover handling and mailing charges. Allow reasonable time for processing order. Please enclose payment with order.

<table>
<thead>
<tr>
<th>Guidebooks</th>
<th>Price</th>
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<tbody>
<tr>
<td>No. 7 - Geology of the Crystalline Rocks and of the Paleozoic Area of Northwest Georgia. 1951.</td>
<td>$3.00</td>
</tr>
<tr>
<td>No. 9 - Late Cenozoic Stratigraphy and Sedimentation of Central Florida. 1960.</td>
<td>3.00</td>
</tr>
<tr>
<td>No. 11 - Highlights of the Cretaceous and Crystalline Terrains of Georgia. 1965.</td>
<td>2.00</td>
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<tr>
<td>No. 12 - Miocene-Pliocene Series of the Georgia-Florida Area. 1965.</td>
<td>3.00</td>
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<tr>
<td>No. 13 - Miocene-Pliocene Problems of Peninsular Florida. 1967.</td>
<td>1.50</td>
</tr>
<tr>
<td>No. 14 - Geology and Geohydrology of the Cross-Florida Barge Canal Area. 1970.</td>
<td>3.00</td>
</tr>
<tr>
<td>No. 15 - Geologic Review of Some North Florida Mineral Resources. 1971.</td>
<td>3.00</td>
</tr>
<tr>
<td>No. 16 - Space Age Geology - Terrestrial Applications, Techniques and Training. 1972.</td>
<td>3.00</td>
</tr>
<tr>
<td>No. 17 - Hydrogeology of West-Central Florida. 1975.</td>
<td>5.00</td>
</tr>
<tr>
<td>No. 18 - Mid-Tertiary Carbonates, Citrus, Levy, and Marion Counties, West-Central Florida. 1976.</td>
<td>5.00</td>
</tr>
<tr>
<td>No. 19 - Environment of the Central Florida Phosphate District. 1977.</td>
<td>5.00</td>
</tr>
<tr>
<td>No. 20 - Hydrogeology of South-Central Florida. 1978.</td>
<td>5.00</td>
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</table>

Prices subject to change without notice.