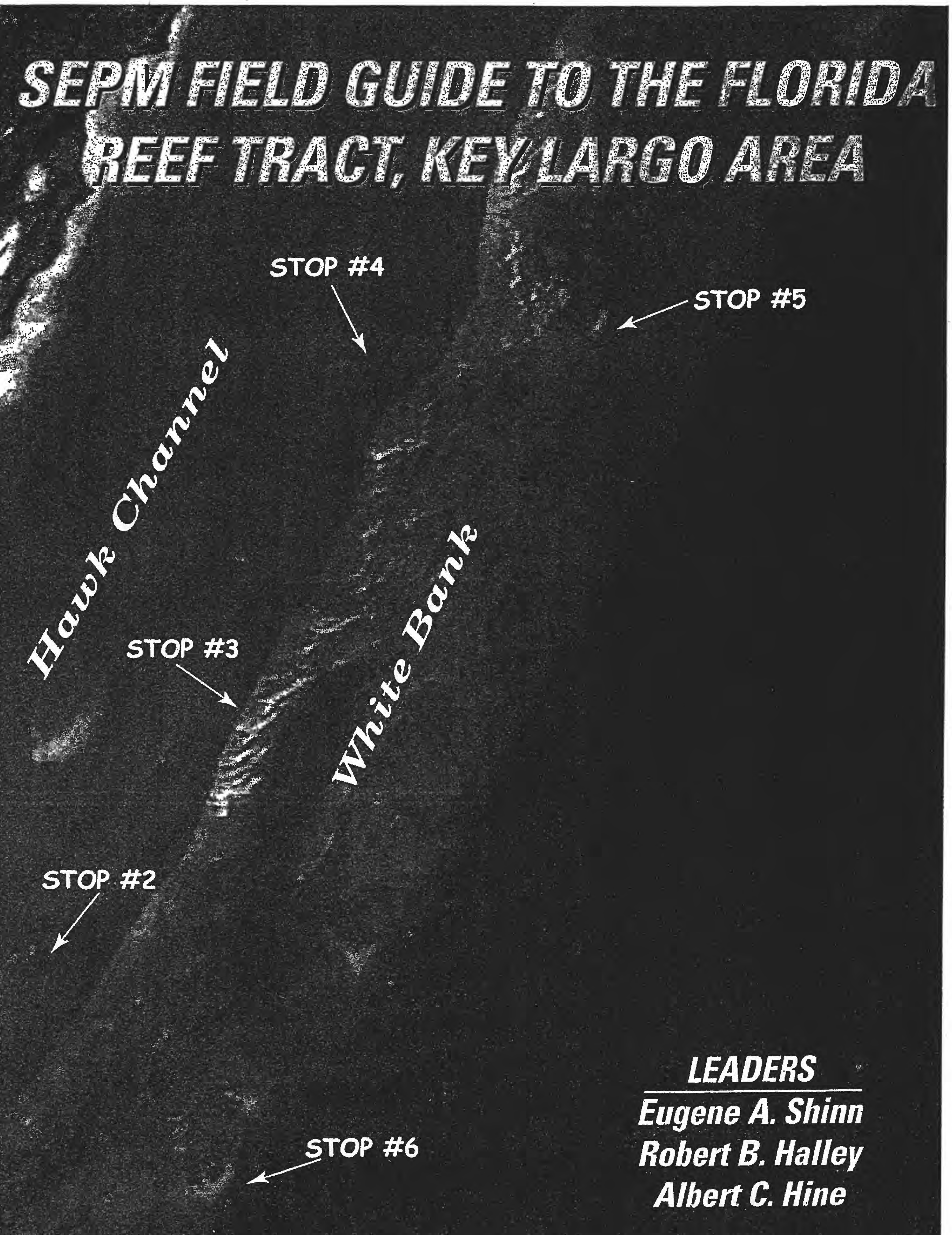
SEPM FIELD GUIDE TO THE FLORIDA REEF TRACT, KEY LARGO AREA



LEADERS

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Field Trip Leaders

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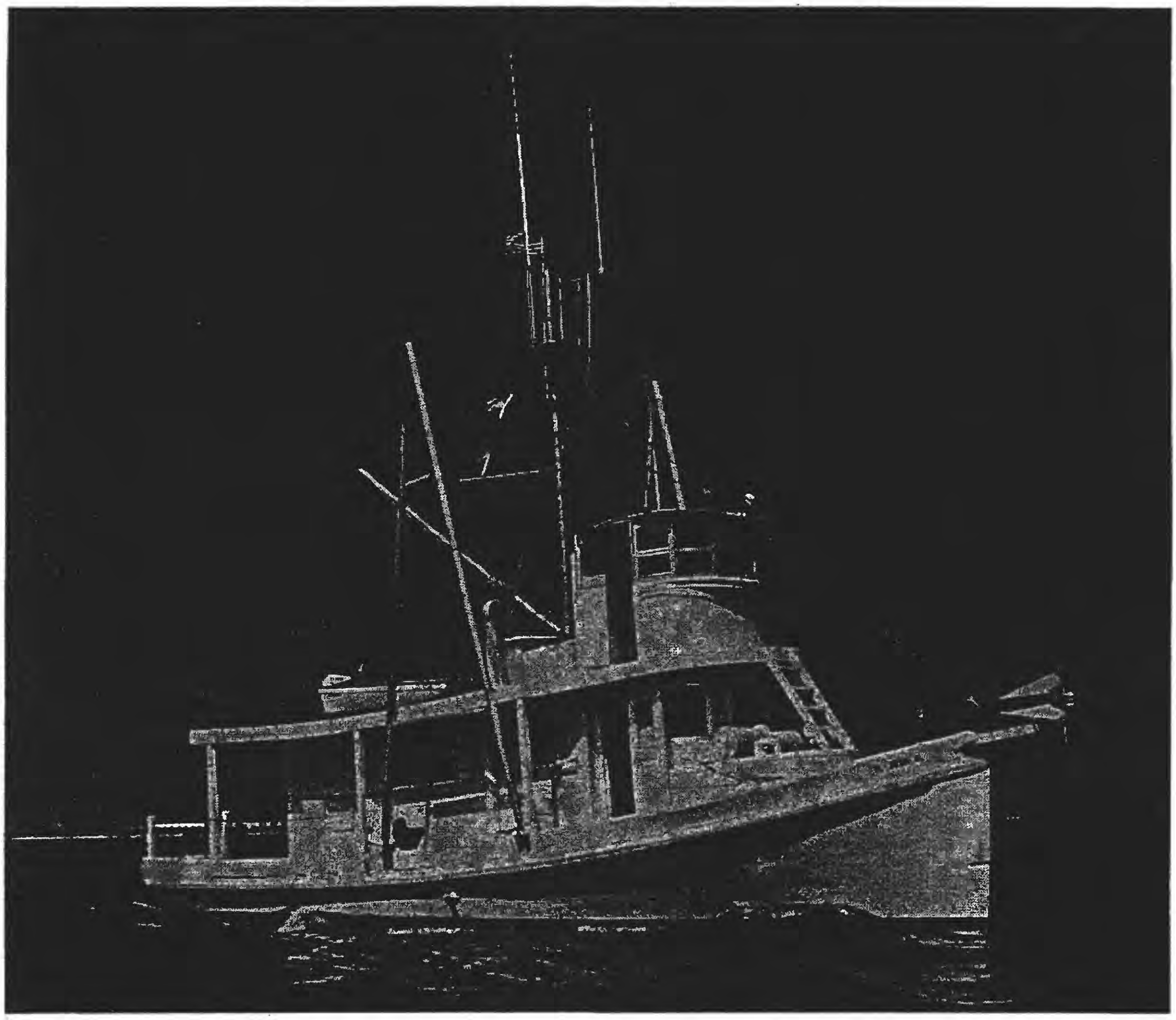

The shrimp trawler R/V *Sea Angel*

Dedication

This guide is dedicated to the memory of Captain Roy Gaensslen (1924-1997) without whom much of the work and ideas expressed here would not have happened. His work-horse boat ***Sea Angel*** and later ***Captain's Lady***, as well as his skills as captain, diver, mechanic, and general know-how, between 1975 and 1997 were invaluable to the USGS efforts to map and understand the Florida reef tract. In his memory, we have named a prominent, previously unnamed reef **Roy's Reef** (stop 2).

Stops on this field trip will include:

(See cover for locations)

1) Rodriguez Key, a nearshore sediment bank that supports a uniquely zoned coral-and coralline-algae-based ecosystem adapted to turbid water and extreme water temperature fluctuations.
2) Roy's Reef (in Hawk Channel), a large relatively flat-lying patch reef dominated by gorgonians and scattered massive coral heads.
3) White Bank, an 8-m-thick well-sorted carbonate sandbank with current- and wave-induced bedforms.
4) A coral patch called "Cannon Patch" consisting mainly of massive head corals rooted on the underlying Pleistocene limestone.
5) Grecian Rocks, shown on pre-1970s charts and described in earlier literature (i.e., Shinn, 1963 and 1967) as Key Largo Dry Rocks. (Chart makers reversed the names of these two adjacent reefs in the early 1970s.) Both reefs are part of a linear trend approximately 1 km landward of the platform margin.
6) Molasses Reef, a platform-margin reef with a well-developed spur and groove system.

Stop 1, Rodriguez Bank

Rodriguez bank, similar to nearby Tavernier bank, was first studied in detail in the late 1950s by geologists from a Shell Oil Company-sponsored laboratory in Coral Gables, Florida, directed by Dr. Robert N. Ginsburg. The results of the study were considered confidential and were not released for publication until the late 1970s (Turmel and Swanson, 1977). This bank and island complex remain a classic geological field trip stop visited by thousands of students over the years mainly because of its composition and well-defined zonation. The bank also provides us with an excellent opportunity to examine and classify the common sediment-producing plants and animals that will be seen later in the trip.

Rodriguez bank was first studied because it was considered a better analogue for ancient reefs than the true coral reefs offshore. The reason for study was the close association of corals and coralline algae with fine-grained sediment. Earlier research on ancient reefs suggested they generally lacked framework organisms. That is, the reef builders were actually floating in a lime-mud matrix. The assumption that Rodriquez is a better analogue to ancient reefs, however, is no longer valid. Numerous core borings not available in the past and man-made underwater outcrops of frame-built reefs generally show that the reefs contain an abundance of fine-grained carbonate sediment that filters into the coral framework interstices during and after reef development. Examination and comparison with some Cretaceous reefs (chiefly constructed by rudistids) showed that what was once considered a supporting lime-mud matrix is actually a secondary infill similar to that in modern coral reefs. The carbonate mud in some ancient reefs has been shown to post-date an initial phase of submarine cementation. There are, however, numerous older Paleozoic carbonate mounds that can be considered close analogues and were probably formed by depositional processes that we can observe at Rodriguez bank.

Zonation and Organisms

The maps in Figures 1 and 2, depicted in color on the USGS benthic habitat map (Lidz et al., 1997), show the major zones. A thicket of finger coral, *Porites furcata*, armors the seaward edge of this muddy bank. The *Porites* thicket ends at the toe of the bank slope where the bottom transitionally grades into a lime

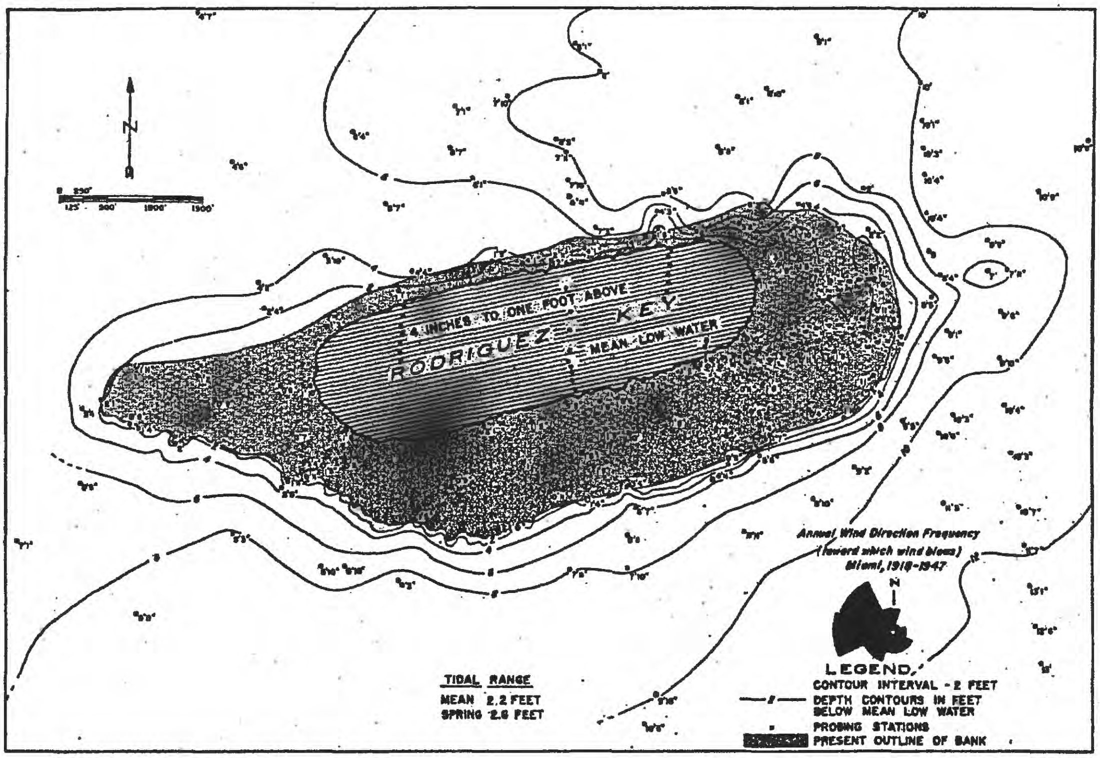

Figure 1. Bathymetry of Rodriguez bank (in feet) from Turmel and Swanson (1977).

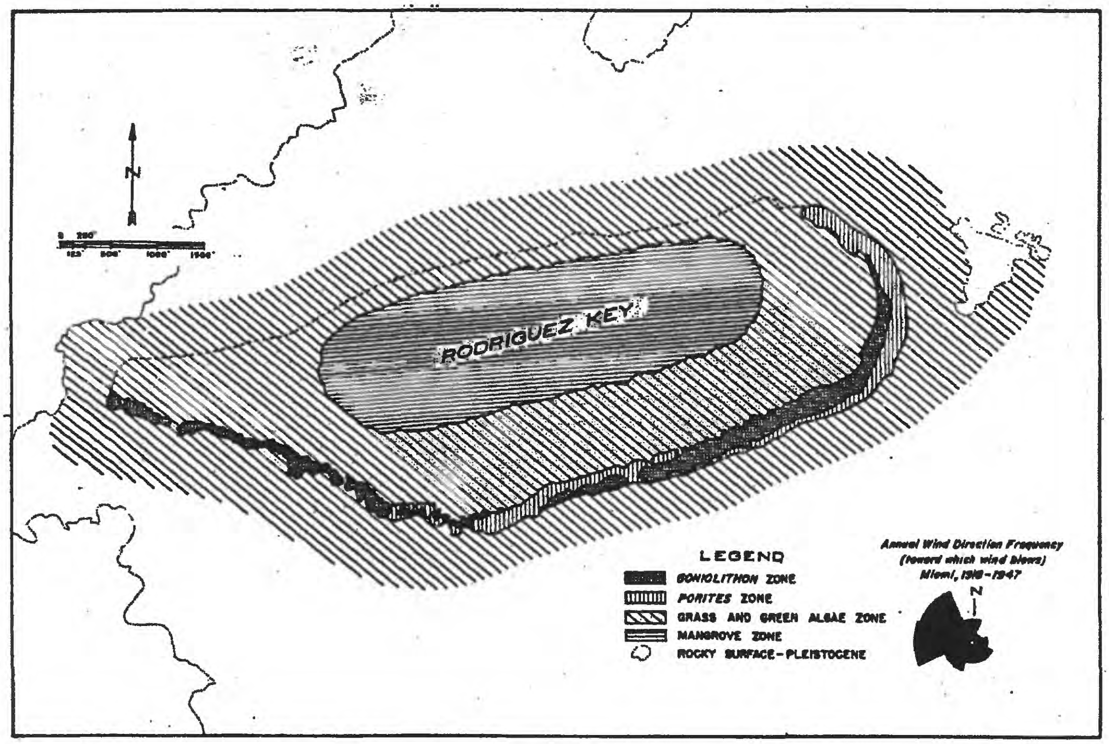

Figure 2. Benthic habitat zones from Turmel and Swanson (1977). The actual field research for this paper was conducted in 1958.

wackstone facies dominated by marine grasses. Scattered here and there are un-attached golf ball-size heads of the coral *Sideastrea radians* and two small branching corals, *Cladacora* sp. and *Oculina* sp. The *Porites* zone extends up the bank slope and merges with an intertidal-flat zone dominated by the branching calcified alga *Goniolithon*.

The *Gonilithon* flat forms a ridge frequently exposed during spring low tides. *Porites* corals do not tolerate prolonged exposure to air; thus, only transported dead or newly recruited live colonies can be found on the *Goniolithon* flat. The width of this zone varies from 15 to 30 m and it is widest at the northeast end of the bank. Variations in *Goniolithon* growth form can be readily observed. Near the bank margin where wave energy is most pronounced, the colonies are more massive and the stick-like branches are short. Farther bankward, especially just behind the *Goniolithon* zone where the water is slightly deeper, you will see scattered colonies of delicately branched *Goniolithon*. *Goniolithon* is important to geologists because it is composed of high-magnesium calcite and is thus less susceptible to alteration during fossilization. Coralline algae like *Goniolithon* have a characteristic internal screen wire-like architecture that is preservable and can be readily observed in ancient limestones when viewed in the petrographic microscope (Scholle, 1978). Other calcified algae such as the ubiquitous *Halimeda* sp. are composed of aragonite and quickly lose internal structure when exposed to diagenetic fluids.

There are a multitude of invertebrates, especially brittle stars, *Ascidians* (sea squirts), tunicates, sponges, sea cucumbers, and molluscs on the *Goniolithon* flat and elsewhere on the bank. The underlying matrix is a mixture of *Porites* coral and *Goniolithon* fragments. Coring shows (see Fig. 3) this coarse-grained matrix is more than 1 m thick (Turmel and Swanson, 1977). Although the *Porites* and *Goniolithon* zones are distinct, cores show they are not readily distinguishable in the subsurface.

Behind the *Porites* and *Goniolithon* zone lies the major part of the bank, which consists of soft wackstone sediment populated by marine grasses. One of the more conspicuous features of this zone is the white volcano-shape sediment

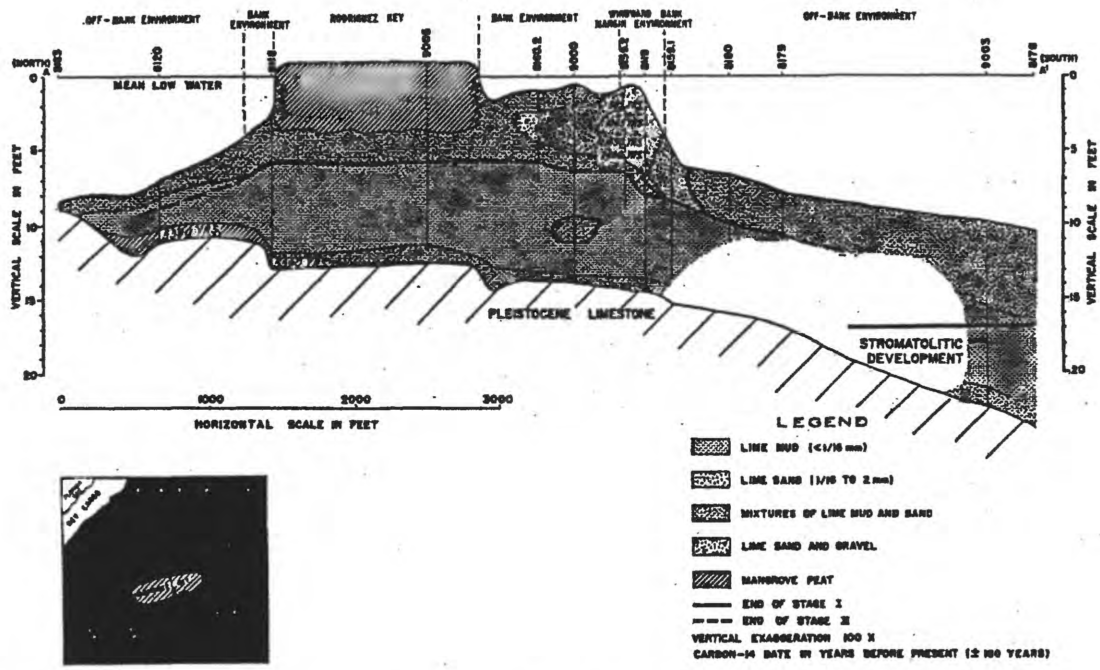

Figure 3. North-south cross section of Rodriguez bank based on cores.

mound constructed by the burrowing shrimp *Callianassa* sp. The upper few meters of sediment on the bank are extensively bioturbated by these crustaceans. Investigations using an underwater vacuum cleaner device called an airlift and plastic molds made by pouring polyester resin into the burrows show that individual burrow complexes penetrate more than 1 m below the surface. In addition to producing characteristic sedimentary structures and distinctive fecal pellets, these organisms play a major role in the alteration of sediment grain size (Shinn, 1968; Tedesco and Wanless, 1991). These authors point out that the sediment becomes coarser through time because the sediment they eject into the water column is winnowed by currents and the fine fraction transported elsewhere. In time, sediment reworked by *Callianassa* becomes coarser than that which originally accumulated. In addition, the sediment that fills inactive burrows is invariably more permeable than the matrix. Preservation of the coarser and more permeable fill can lead to preferential alteration (leaching, dolomitization, and silicification) and may explain why many burrows in outcrops of ancient limestones weather in relief.

The 1-cm-long rod-shape pellets of *Callianassa*, which are about the same diameter as the *Goniolithon* fragments, contain several longitudinal canals. The canals are produced during extrusion by finger-like processes in the animal's anus. Because of these internal canals, ancient *Callianassa* pellets were first misidentified as fossil algae and called *Favrina.* Abundant *Favrina* occur throughout Mesozoic and Cenozoic rocks, their occurrence is worldwide, and there are reports of oil reservoirs in Iran composed of *Favrina* sands. During construction, the organism lines the burrow with its sticky carbonate mud pellets. This stiff 1- to 2-mm-thick lining prevents burrow collapse and can easily be recognized in sediment cores and ancient limestones. In many areas on the Bahama Bank, the burrow lining has been preferentially cemented and in places is eroded from the sediment to form gravel composed of 6- to 10-cm-long tubes 1 to 1.5 cm in diameter. The grass-covered *Callianassa*-burrowed bank at Rodriguez gives way to a shallow (0.5- to 1-m-deep) grass-free moat along the seaward side of the mangrove island. A combination of shading by the mangrove tree canopy and frequent scouring during storms probably explains the absence of significant grass, which in turn enhances erodability.

The upper part of the island is composed mainly of mangrove peat. The mangrove peat is thickest at the northeastern end, and Figure 4 shows that some peat rests directly on the underlying limestone (Turmel and Swanson, 1977). Mangrove peat, which accumulates essentially at sea level, indicates that the first vegetation began to form when sea level was approximately 4 m below present. The peat, assumed to be mangrove, is overlain by lime sediment, which is in turn overlain by mangrove peat that forms the bulk of the island. Toward the southwest end of the island, the upper peat rises, becomes thinner, and overlies the lime mud that is contiguous with the rest of the bank. The overall morphology and the geologic cross sections (see Turmel and Swanson, 1977) show that the bank and island have been prograding to the southwest. Mangrove peat is exposed just beneath the turtle grass off the northeast end of the island. This

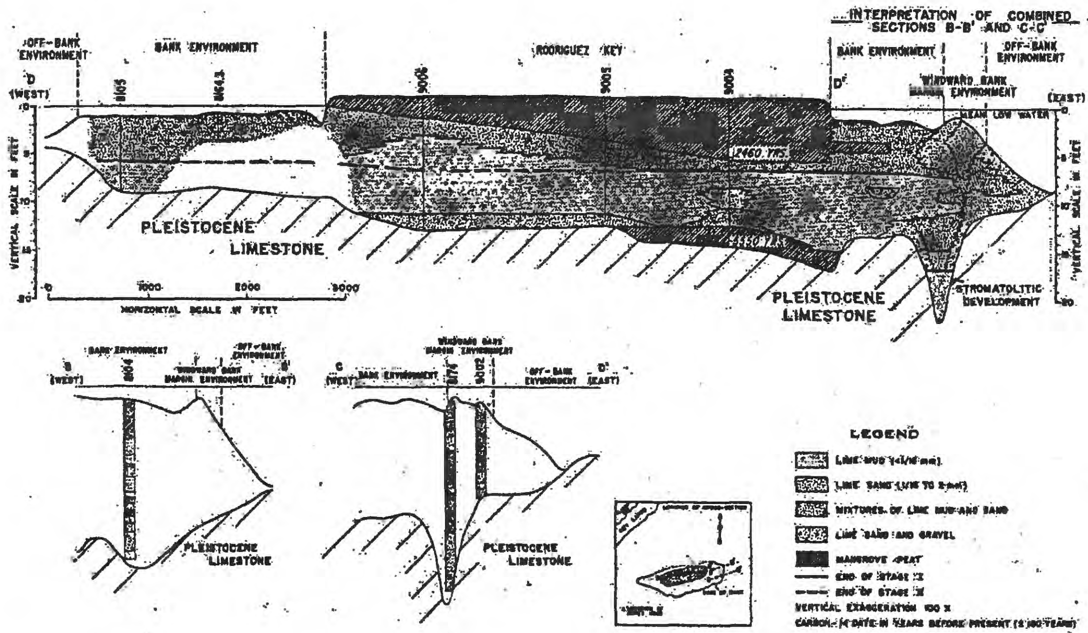

Figure 4. East-west cross section through Rodriguez Key from Turmel and Swanson (1977).

peat (not seen by Turmel and Swanson, 1977) and the deeper depth of the moat at the northeast end clearly indicate erosion and retreat of the northeast end. There is no moat at the southwest end of the island. The southwest end appears to be prograding.

Observations following Hurricanes Donna in 1960 (Ball et al., 1967) and Betsy in 1965 (Perkins and Enos, 1968) and recent but less violent storms (personal observations) show storms have a negligible effect on the bank. Offshore frame-built reefs, however, are periodically decimated by the same storms. The reason the bank resists erosion is because the lime-mud matrix is cohesive and extremely difficult to scour, as Henry Flagler learned while building the overseas railway. During railway construction, a hurricane washed away riprap but did not affect compacted lime mud dredged from Florida Bay. Thereafter lime mud was used as fill, such as for the causeway connecting Upper and Lower Matecumbe Keys. In addition, hurricane surge that precedes the storm raises water level well above the bank, thus reducing the intensity of breaking waves.

During the past 40 years, one of us (Shinn) has noticed shallowing of the water just seaward of the bank. In the late 1950s and early 1960s, water depth 20 m seaward of the bank was 2 to 2.5 m deep. Today a person can walk in the same area. Because this is the inner margin of a navigable waterway called Hawk Channel (discussed later), it is likely that the entire waterway has also become slightly shallower. A few hundred years from now, Hawk Channel may no longer be navigable.

How the Bank was Built

Geologists originally studied Rodriguez bank to determine not only its structure but also why it formed in this particular location. Such information might aid in predicting the location of ancient analogue accumulations buried under hundreds of meters of overburden.

Mapping the underlying limestone surface using data obtained by probing with a metal rod (mean sea level was the datum used) revealed a shallow embayment in an underlying limestone terrace (see Fig. 5). The extent of the terrace beyond Rodriguez bank was not recognized during the initial study. Turmel and Swanson (1977) initially thought this embayment was crucial to bank formation because

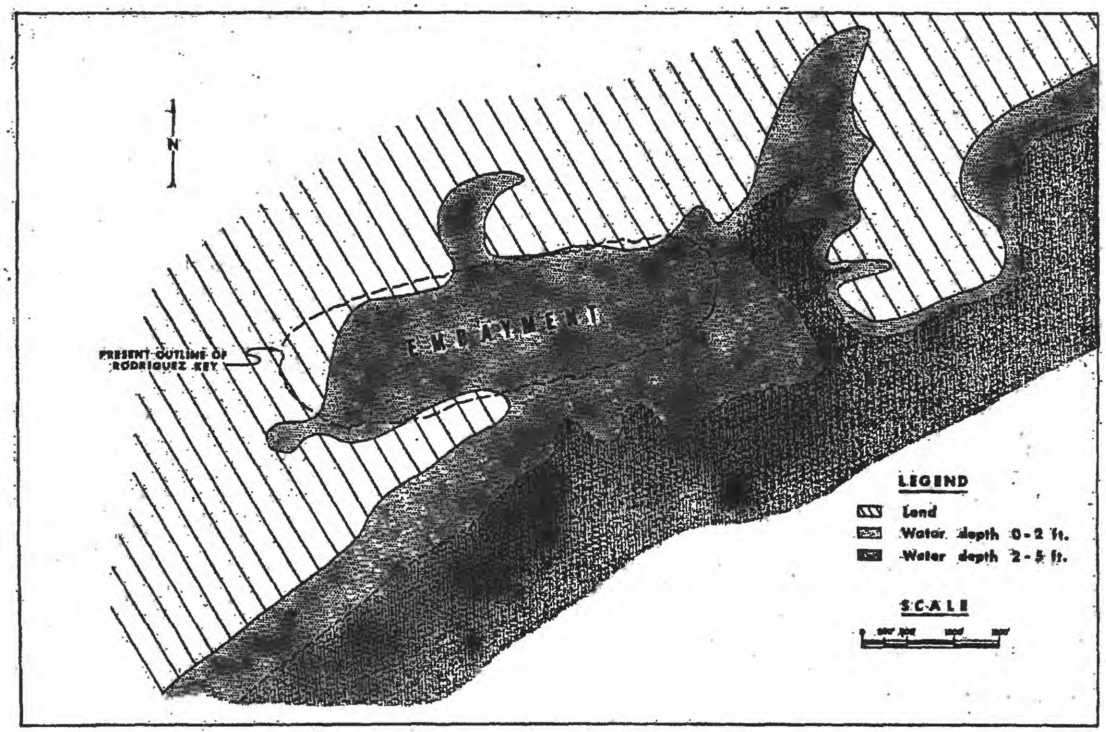

Figure 5. The -12 foot contour, part of a Keys-wide erosional terrace, defines the embayment in which the island and bank formed (Turmel and Swanson, 1977).

the bank and island formed over it. More recent observations show, however, that the embayment is part of a terrace that extends the entire length of the Keys. Although there have been no concerted research studies or publications devoted to this feature, we interpret it to represent an erosional shoreline. It is similar to the present rocky shoreline of the Florida Keys. The terrace is clearly visible in aerial photography and other embayments can be seen that lack a sediment buildup. You can find the terrace in the aerial photomosaic of Lidz et al. (1997). Nevertheless, the bedrock feature in combination with features farther offshore may have caused bank initiation. Whether this old shoreline (3-4 m below low tide) formed during a stillstand during the Holocene rise or during a fall in sea level during the Pleistocene is not known. Resolution of this question is important because we have observed that this erosional terrace is at least 1 m deeper in the lower Keys than in the upper Keys. Does this suggest differential subsidence of the Florida platform? If so, did it subside recently or during the Pleistocene, or is it gradually subsiding now??

A frequently asked question is which came first, the bank or the island? There is no clear answer; however, some mangrove peat formed directly on the underlying rock at the northeast end of the island, suggesting that a small island may have begun growing before the bank. If the island formed first, it could have played a role in bank formation. Or, the island and bank may have formed simultaneously. There are more clues to formation hidden within the bank (see Figs. 3 and 4).

Cores reveal depth-related facies changes. When the bank first began forming, its composition was principally fine-grained lime mud like that presently forming mud banks in Florida Bay. Some cores show that at least a portion of the first sediment to accumulate was laminated. Turmel and Swanson (1977) called the layers "stromatolitic," implying supratidal conditions. Sediment in a deeper bedrock trough off the northeast end of the island is identical to algal-laminated sediments forming on Florida Bay mud islands. The other examples of laminated lime mud (Turmel and Swanson, 1977) are simply non-bioturbated lime muds that can be found forming in 1 m of water on many Florida Bay mud banks. These laminations simply indicate that deposition was rapid and burrowing organisms could not keep up with sedimentation.

Cores show that *Porites* and *Goniolithon* did not arrive on the bank until about 2,500 C^{14} years ago. The *Porites/Goniolithon* zone is limited to the upper 2 m of bank deposition and occurs only along the seaward side of the bank (see Fig. 3).

Lack of corals and presence of fine-grained laminated sediment, mangrove peat, and sediment with supratidal algal mats indicate the island/bank began to form when sea level was at least 4 m lower than present. Corals began populating the bank during its upward accumulation. The lack of corals and the laminated fine-grained nature of the first sediments to be deposited indicate low-energy conditions similar to those in modern Florida Bay. There has been much speculation over the years as to whether there was an offshore barrier sufficient to create low-energy conditions in a manner similar to the way Key Largo provides a low-energy lee for Florida Bay. In the past, we have speculated that the offshore coral reefs at the platform margin had formed a living barrier as sea level rose. However, recent mapping (Lidz et al., 1997) using high-resolution seismic profiling, and verification of depths by core borings show a discontinuous Pleistocene rock ridge at the platform margin. In places, such as at Molasses and French Reefs directly offshore, the ridge is about 6 m below present sea level. This ridge would have formed discontinuous islands (like the Florida Keys) when sea level was more than 6 m lower than present. The island barrier and the reefs that began to grow on it would have created the low-energy conditions necessary for lime-mud accumulation behind it. As the offshore island chain and reefs became submerged by rising sea level, increasing water circulation would have allowed establishment of *Porites* and *Goniolithon*. Nevertheless, we still cannot say exactly why the bank was formed here. The bank may simply be an erosional remnant of a much more extensive area of mud deposition that existed when sea level was lower.

There are similar banks with *Porites* and *Goniolithon*, such as Caesars Creek bank north of Key Largo and tidal delta-like banks at Snake Creek and Whale Harbor to the south. Those banks are associated with tidal creeks, which serve to focus sedimentation. We can find no trace of former tidal passes on Key Largo near Rodriguez bank. Nearby Tavernier bank, however, may partially owe its origin to Tavernier Creek. Tavernier bank is the same thickness as Rodriguez bank and has the same zonation as Rodriguez but the island is different. A linear *Goniolithon* sand berm extends down the center of Tavernier Key. The sandy berm is thick enough to support a small freshwater lens that in the early days was exploited by sailors for drinking water (Romans, 1775). Rodriguez Key has no sand berm and the peat surface across the island floods during spring high tides. Although the precise origin of these banks is not resolved, many lessons in sedimentology can still be learned here.

Stop 2, Roy's Reef

Roy's Reef, named after the late Captain Roy Gaensslen, is a large relatively flat-lying patch reef that formed near the seaward end of a Pleistocene embayment. The embayment can be seen in the rock topography map of Lidz et al. (1997). The influence of this embayment on patch reef location is discussed later. Roy's patch reef is dominated by various species of gorgonian sea whips and the sea fan *Gorgonia ventalina*. This stop will allow you to become accustomed to more open circulation, coral and gorgonian development, and to examine the surrounding seagrass-covered sediments of Hawk Channel.

Hawk Channel

We have passed over Hawk Channel en route to Roy's Reef. Hawk Channel, which begins just seaward of Rodriguez bank, is a typical shelf lagoon. The Great Barrier Reef of Australia has a shelf lagoon many times larger and deeper.

Areally, Hawk Channel represents the largest single sediment facies and seagrass habitat on the Keys reef tract. A linear trough in the underlying Pleistocene limestone forms the channel. Depth of the limestone trough off Key Largo is 8 to 10 m and water depth is 5 to 8 m. The fine-grained, highly bioturbated marine-grass-covered sediment that has accumulated there ranges from 1 to about 4 m thick (Enos, 1977; Lidz et al., 1997). Patch reefs, such as Roy's Reef and those at near by Mosquito Bank, are both located in Hawk Channel. The underlying pre-Holocene rock topography map (see Lidz et al., 1997) shows that the major cluster of patch reefs at Mosquito Bank formed in a depression. Roy's Reef is situated toward the seaward part of this depression. During the Holocene sea-level rise, this depression contained sea water and was open to circulation from the east. This area was submerged longer than surrounding areas, thus allowing more time for coral recruitment and growth. Individual coral patches in this embayment most likely formed on localized highs, probably Pleistocene patch reefs (Shinn et al., 1977; Shinn et al., 1989) or on highs created by old lime-mud banks (Enos, 1977). Small topographic highs generally cannot be resolved with seismic-reflection techniques. Core drilling is required to confirm depth to the limestone underlying patch reefs. Regardless of what formed the individual highs, the clusters of coral patches here probably owe their origin to the pre-existing underlying rock topography (embayment) that allowed earlier flooding during the Holocene sea-level rise.

The origin of sediment in Hawk Channel can be attributed to *in-situ* sediment-producing organisms that live in the grass beds, plus large amounts are transported and deposited there during and after major storms. The lime-mud-laden water that pours through tidal passes from Florida Bay following major storms must pass over Hawk Channel to reach the deeper waters beyond the platform margin. Even minor storms and prop wash from boats resuspend sediment in Hawk Channel, reducing water visibility to a few centimeters. You will have another opportunity to examine these sediments adjacent to a much shallower coral patch at stop 4.

Stop 3, White Bank Sand Accumulation

White Bank is a major sediment accumulation, intimately associated with offshore coral reefs. The linear bank forms the seaward boundary of Hawk Channel. Depth on the bank can be as little as 2 m at low tide and is less than 0.5 m a few kilometers north of our study area. This 2-mile-wide and more than 20-mile-long coarse-grained sediment accumulation is accreting westward over the muddy sediments of Hawk Channel. Major accretion along the relatively steep western slope of White Bank was observed after Hurricane Donna (Ball et al., 1967) and was also seen in sediment cores (Enos, 1977). Cores reveal that the Hawk Channel facies underlie the coarse sands of White Bank (Fig. 6).

Linear reefs occur along the seaward side of White Bank, such as Grecian and Key Largo Dry Rocks, and there are a number of sub-circular patch reefs,

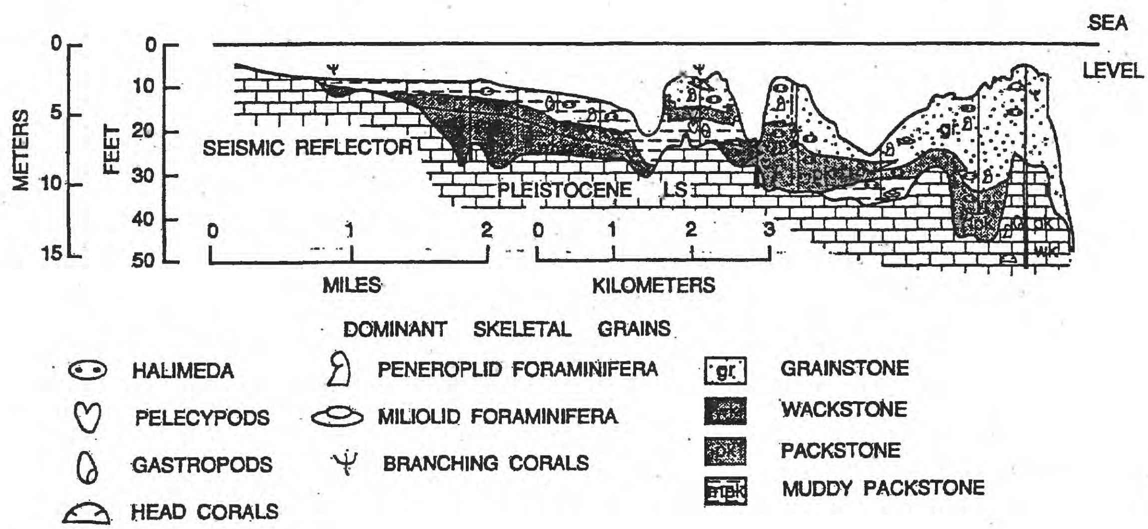

Figure 6. One of the sediment facies cross sections based on "sparker" profiling and sediment cores. Notice that the first sediment to accumulate on the underlying Pleistocene limestone was finer grained than that at the present surface. From Enos (1977).

with corals reaching the surface at low tide along the western portion of the bank. The shallowest water occurs near the western side of the bank close to the steep (approximately 15°) slope into Hawk Channel.

The western part of the bank is ornamented with broad curvilinear grass-free sand shoals that rise about 30 cm above the surrounding grass-covered sands (see image on cover). This is where we will be snorkeling and observing the bottom. If there are waves, you will see that the sands in these shoals are in nearly constant motion and form low ripples whose orientation changes with changing wind and wave directions. Box cores takes by Enos (1977) show ripple laminations and cross bedding. The grains, principally *Halimeda*, are highly polished, superficially coated, and look like ooids. Close examination, however, shows they are not true ooids. For reasons not understood, there are no ooids presently forming in Florida, whereas they are rapidly forming, and commercially exploited, on the nearby Bahama Bank. Ooids did form in Florida during the Pleistocene, creating the foundation for the cities of Miami, Key West, and those on all of the lower Florida Keys.

Here and there the grains have become cemented to form intraclasts. The cementation process usually starts around a burrow. Occasionally slabs up to 30 cm across can be found on the sand shoals. The cement is acicular aragonite and the process of cementation is apparently ongoing.

The size and shape of White Bank combined with its high porosity would make it a potential commercial reservoir if encountered in the subsurface.

Stop 4, Cannon Patch

Cannon Patch is so named for the presence of two cannons (see if you can find them). This patch reef is a spectacular example of a shelf-lagoon coral patch reef. Cannon Patch is shallower than most, allowing easy observation using only snorkel gear. At spring low tide, the surfaces of the corals are awash, so be careful and do not stand on the corals.

The principal builders are *Montastrea annularis* and *M. faveola*, previously thought to be two separate growth forms of *M. annularis*, and several brain corals such as *Diploria strigosa*, *D. labyrinthiformis* and *Colpophyllia natans*. You will see abundant gorgonian sea whips and the common sea fan *Gorgonia ventalina.*

Branching acroporid corals such as those that form the outer reefs are extremely rare on patch reefs in Hawk Channel. After examining the corals, you may swim off the side of the patch and explore the surrounding grass-covered sediments of Hawk Channel. Although shallower than most of the channel, this site will provide a good approximation of the facies accumulating in the Hawk Channel depression.

You may note that a very straight channel transects this patch reef. The warning marker sits in the center of this channel. Unconfirmed reports suggest that the channel was cut at night by a tug pulling a large barge in the early 1970s. Linear features such as this channel are rare in nature and lend credence to the barge hypothesis. Boats frequently strike this patch because of its shallow depth.

Stop 5, Grecian Rocks, a Linear *Acropora* Reef

Grecian Rocks is fairly typical of linear *Acropora palmata* reefs. Most *Acropora* reefs occur at the platform margin farther seaward. This reef, however, is situated about 1 km landward of the margin in a place where the margin is relatively deep and does not support reef growth. The bedrock topography in Lidz et al. (1997) shows that Grecian Rocks lies directly behind a depression in the 6-m-deep Pleistocene ridge. The break in the ridge is as much as 10 m below sea level. Because of the ridge break, waves and swells that reach here are sufficient for vigorous *Acropora palmata* growth. This species is generally associated with surf-zone conditions and thus is a relatively reliable indicator of sea level.

Grecian Rocks Reef is one of the few coral accumulations on the reef tract that has kept pace with Holocene sea-level rise. Less than 1% of Florida's reefs have kept pace with sea-level rise during the past 6,000 years (Shinn, 1998). The geologic history of Grecian Rocks (formerly called Key Largo Dry Rocks) has been studied in considerable detail. The zonation (Fig. 7) and the internal

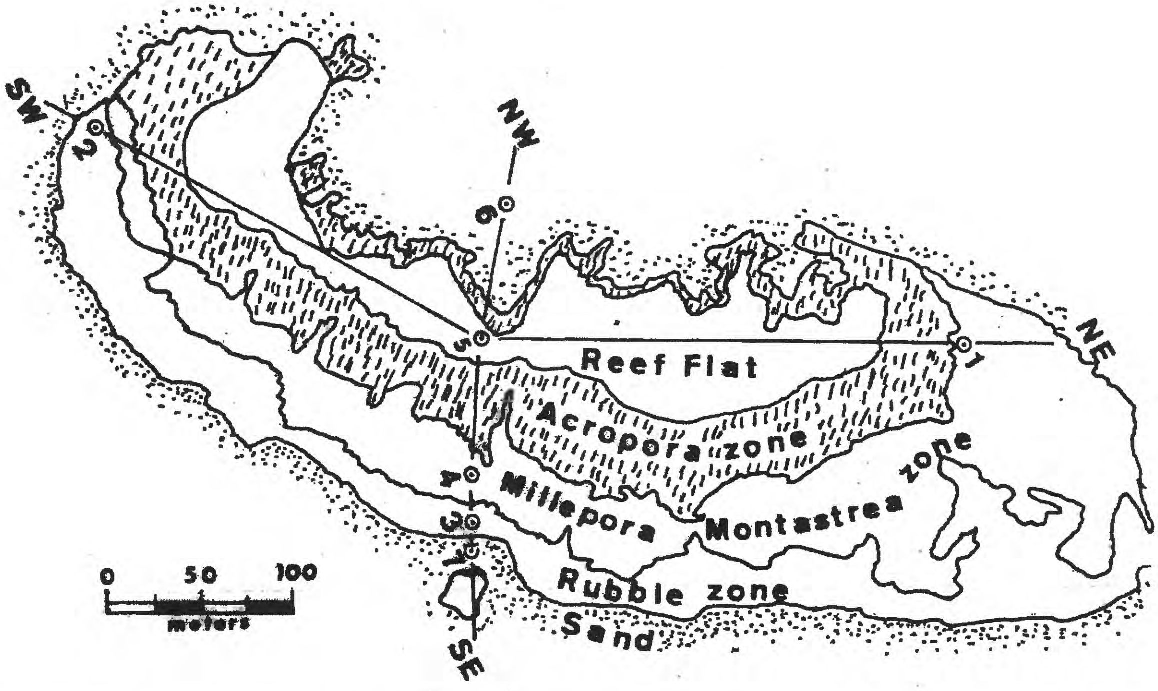

Figure 7. Coral zones at Grecian Rocks Reef. Northwest-southeast cross section based on cores is shown in Figure 9. From Shinn et al. (1980).

composition of the reef were examined using a variety of methods (Shinn, 1963; Shinn et al., 1980). The early study (Shinn, 1963) concluded that the orientation of *A. palmata* branches, typical of this species when growing in the surf zone, and not erosion, led to spur and groove formation. Observations made at Grecian Rocks on living spurs led to interpretation of the origin of the spurs at Molasses and other platform-margin reefs where *A. palmata* has been overgrown and obscured by *Millepora* and other encrusters.

Reef Flat and Zonation

The ecological zones at Grecian Rocks are shown in Figures 7 and 8. The most obvious zone is a reef flat that is exposed at low tide. It was formed by *A. palmata* that grew to the surface, became overcrowded, and was fossilized *in situ.* During an early study (Shinn, 1963), it was observed that the reef flat was enlarging in a landward direction by a fringe of rapidly growing *A. palmata*. The growing fringe produced an abrupt 1- to 2-m change in water depth on the leeward side of the reef flat. The calm deeper water in the lee of the reef flat supported a profusion of large massive corals, principally *Monstastrea* sp. and large colonies of *A. palmata* with unoriented branches. The corals in this relatively quiet area began life by settling on fragments of *A. palmata* and other corals transported from the front of the reef and from the reef flat during storms.

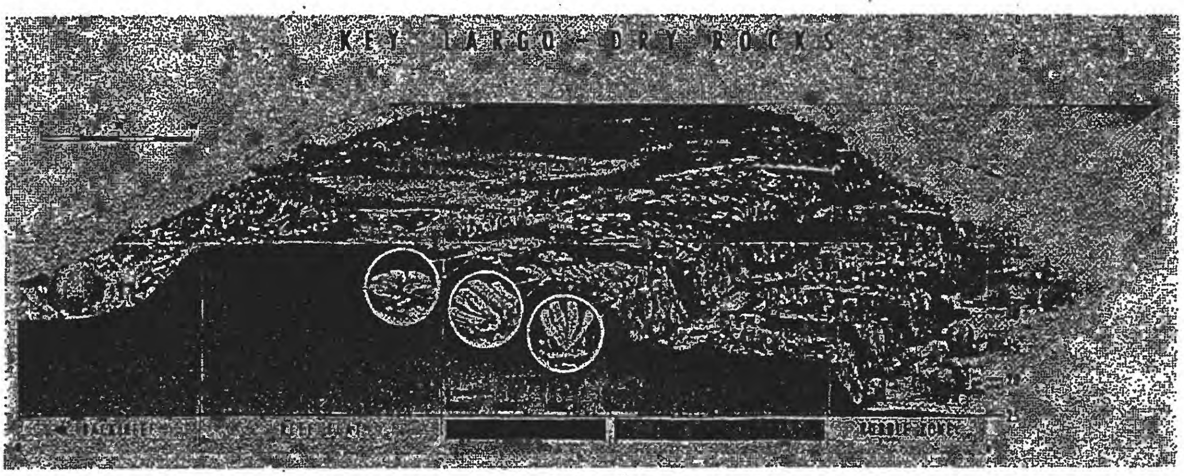

Figure 8. Block diagram of Grecian Rocks showing major zones and terraces. From Shinn (1963). This reef was called Key Largo Dry Rocks in 1963.

A few meters landward of this zone, corals disappear and the 10-m-thick accumulation of carbonate sand supports a lush carpet of sea grasses, principally turtle grass. Here and there are 30-cm-deep sand holes ('blowouts') in the grass carpet that have been shown by before-and-after aerial photographs to have formed during Hurricane Donna. Additional blowouts have been initiated by anchor scars and enlarged by more recent storms.

Core drilling (Fig. 9; Shinn et al., 1980) shows that most of the reef flat rests on carbonate sand and coral rubble. A small amount of peat overlying a calcrete crust was recovered from the bottom of one core, indicating a time when the

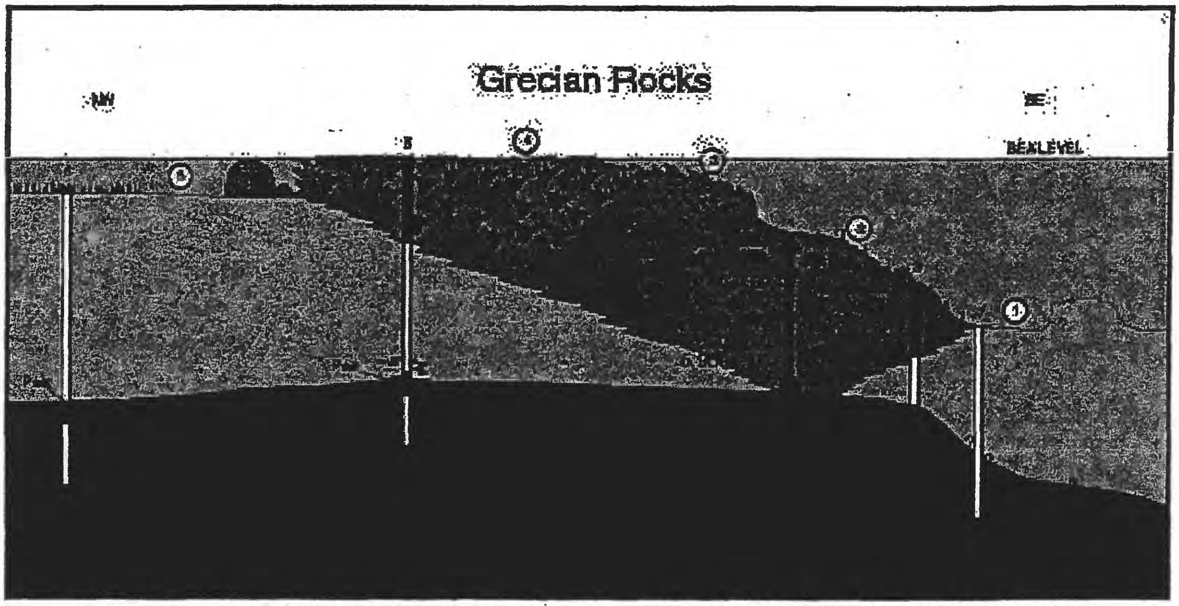

Figure 9. Cross section of coral zonation (see Fig. 8 for locations) at Grecian Rocks based on cores. Notice that the reef was initiated on a Pleistocene terrace by massive head corals about 6,000 years ago and that *A. palmata* arrived more recently. The major part of the reef overlies carbonate sand, indicating the reef has migraded landward. Also note that the underlying Pleistocene limestone consists of cemented carbonate sand beneath uncemented Holocene carbonate sand and that massive Pleistocene head corals lie beneath the Holocene head-coral zone. Pleistocene *A. palmata* was present. Presence of calcrete and peat at the Pleistocene/Holocene contact indicates terrace exposure sometime before about 6,000 years ago. From Shinn et al. (1980).

limestone was exposed. The species of peat was not determined and there was insufficient material (and $) for age dating. The internal composition of this and other reefs that have been core drilled shows that the reefs have been migrating landward while growing upward and keeping pace with the Holocene transgression. Observations following Hurricane Donna (Ball et al., 1967) clarified these processes. Corals broken from the bottom in front of the reef were thrown landward and deposited behind the reef flat to provide a base for later coral recruitment and growth. The process has been repeated many times during the last few thousand years while the sea continued to rise.

Forereef Zones

In the surf zone seaward of the reef flat, *A. palmata* assumes a distinctly different growth form. Here the branches are principally oriented away from the sea. Branches that extend perpendicular to wave motion are broken off during storms, as was observed after Hurricane Donna in 1960. Constantly shifting sand in the grooves hampers coral recruitment and growth. Farther seaward, the zone of oriented *A. palmata* spurs gives way to a relatively flat terrace composed of large massive head corals. Many of the sand-lined grooves between the oriented *A. palmata* extend into the deeper *Montastrea* zone. Seaward of the *Monstastrea* zone, the bottom deepens and merges with coral rubble populated mainly by gorgonians. The common sea fans, which orient themselves parallel to waves, occur throughout the seaward side of the reef and were once especially abundant in the *Montastrea* zone. The hydrozoan fire coral, *Millepora* sp., encrusts many parts of the *Montastrea* zone and produces flat fan-like growths oriented parallel to the waves. Farther seaward, the coral rubble and gorgonian zone merges with an extensive area of carbonate sand. The sand extends more than 1 km seaward of the reef.

Notice in Figure 9 that core number 4 in the *Montastrea* zone encountered a continuous record of *Montastrea* sp. The oldest C^{14} date in this core shows the reef began growing about 6,000 years ago. Core borings show that *Montastrea* was growing at Grecian Rocks a few thousand years before *A. palmata* took over. The reason for this change in species is probably related to offshore topography. When sea level was lower, only small waves and swells could reach Grecian Rocks. With the rising sea, wave action increased until conditions were favorable for the faster growing acroporids to out-compete and overwhelm the slower growing massive head corals.

It should be pointed that most of the interpretations presented here were based on observations made prior to 1983 when the reef was flourishing. Recent demise of corals, especially *A. palmata* and *A. cervicornis,* is discussed below.

Recent Ecosystem Changes

In 1983 the herbivorous sea urchin, *Diadema* sp., experienced a massive Caribbean-wide die-off causing a severe change in the ecological balance. Their absence quickly led to overgrowth of corals, principally dead areas, by various fleshy and calcareous algae. At the same time the *Diadema* were dying, acroporids whose numbers had been diminishing since the late 1970s were severely attacked by various unidentified diseases. Acroporids experienced a massive die-off throughout the entire Caribbean during 1983. In addition, a large number of the massive head coral species died. Later, during the El Nino warming event of 1987, many coral species including sponges and even foraminifera expelled the essential symbiotic photosynthesizing zooxanthellae (dinoflagellates) that give corals and other organisms their color. In corals these symbionts aid in respiration, metabolism, and growth. When expelled, the coral tissue and skeleton are snow white. The commonly used term for this condition is "bleaching." Although most corals regained zooxanthellae and continued to flourish after water temperatures returned to normal in 1987, many died during the more severe bleaching events that occurred in 1990 and 1998. Minor bleaching events have occurred throughout the 1990s. *Diadema* made a slight comeback in 1990 but suffered yet another die-off (J. H. Hudson, personal communication). During this same period of time, various coral diseases spread throughout the Keys and Caribbean. At least half the massive coral heads that grew at Grecian Rocks prior to 1980 have died. Recent coral monitoring studies conducted over the past 5 years show that coral populations have continued to decline.

Stop 6, Molasses Reef

Molasses Reef is typical of platform-margin reefs in Florida. The origin of its name is unclear but legend says that it was named after a ship carrying Molasses ran aground here in the 19th century. Molasses Reef is noted for its well-developed spur and groove system and underwater topography and is probably the most popular scuba diving attraction in the Florida Keys. The 3- to 4-m-high, 5- to 10-m-wide spurs are coated with *Millepora* and here and there support huge centuries-old heads of *Montastrea* sp. and *Colpophyllia* sp. A few remaining *A. palmata* colonies are scattered about. What constructed the spurs cannot be readily observed because of encrusting *Millepora* and other organisms. Using special techniques, Shinn (1963) produced what can be termed an "explosure" (Fig. 10) that revealed that the spurs were constructed by A. *palmata*. At that time, the initial stages of the process could be seen at Grecian Rocks, where *A. palmata* was still living and producing spurs. More recently, in 1984, a huge cargo ship named the WELLWOOD crashed into the reef and produced additional observation windows into the reef interior. Again, *A. palmata* was seen as the principal builder.

Carbon-14 dating of fossil *A. palmata* from within a Molasses Reef spur showed it was approximately 2,000 years old. Because the tops of the spurs are flat, similar to the reef flat at Grecian Rocks and elsewhere, it is thought that their upward growth was constrained by sea level. It should be noted that this species grows rapidly and can easily produce spurs that reach the surface in a short time.

Figure 10. Underwater cross section through a spur at Molasses Reef. Internal structure consists entirely of *in-situ A. palmata*. Notice the relatively flat surface encrusted with *Millepora* sp. From Shinn (1963).

For example, *A. palmata* grows around 10 cm/year under optimum conditions and thus could have formed the spurs in less than 100 years. Why these corals died is not clear but it is possible they grew to the surface and suffered from overcrowding. They could not grow laterally because of sand in the grooves and constant pounding by waves. An additional stress was created by rising sea level. The rising sea created Florida Bay and the tidal passes that allowed the inimical bay waters to flow onto the reef tract. Coring has shown (Robbins et al., 1981; Shinn et al., 1989) that other reefs constructed by A. *palmata*, such as

Alligator Reef, once flourished off the middle Keys. Tidal passes are larger and more numerous in the middle Keys. The lack of reef growth off the middle Keys passes was noted earlier by Vaughan in 1914. Much has been recently written about the effects of Florida Bay waters on offshore coral reefs. Even before the 1980s die-off, there were few living *A. palmata* at Molasses Reef. However, farther north at Carysfort Reef, which is protected from bay waters by Key Largo, *A. palmata* flourished. It too succumbed to disease in the 1980s (Dustan and Halas, 1987).

The carbonate sands in the grooves separating spurs are thin, and the grooves are frequently scoured clean during large storms. Examination of the rock underlying the sand shows that *A. palmata* growth began on the underlying Pleistocene limestone. In places, a calcrete coating that formed during subaerial exposure can be observed on the rock. In fact, there are many areas in the reef tract where exposed calcrete-coated limestone shows that coral growth and sediment deposition failed to occur over the past 6,000 years of submergence. This could be the result of larger more numerous hurricanes in the past, extreme temperature variations, or periodic attack by coral diseases.

Coral Diseases in the Past?

Based on the coral declines seen during the past 25 years, we can speculate that the *A. palmata* at Molasses and along the rest of the reef tract may have succumbed to earlier episodes of coral diseases. If we look at the problem from a geologic-time viewpoint, we should consider several facts. (1) The slowest growing corals, even the ones that do not contribute significantly to reef development, should have kept pace with the documented rise of sea level. (2) The coral species that actually built the reefs grow many times faster than non-reef builders. (3) The Florida reef tract became flooded about 6,000 years ago, as shown by radiometric dating of peats and corals that grew on the underlying limestone. (4) The acroporids, both *palmata* and *cervicornis*, have the potential to grow vertically about 600 m in 6,000 years. Clearly, vertical growth is prevented by sea level (maximum depth on the reef tract is only 10 m), but horizontal growth and continual fragmentation and dispersal of fragments by periodic hurricanes should have filled in all the areas presently lacking coral reefs. (5) The reef-building massive head corals grow around 1 cm/year or 10 m/1,000 years. This rate of growth would result in upward and lateral expansion of 60 m during the past 6,000 years. Cut the growth rate in half and the amount is 30 m for the past 6,000 years. This conservative rate of growth far exceeds the average sea-level rise of about 1 m/1,000 years. Considering that there are few places on the reef tract deeper than 10 m and that relatively slow-growing head corals could have grown 30 m during the past 6,000 years, it becomes apparent something must have happened to retard growth in the past. The growth rates of common coral species are shown in Figure 11.

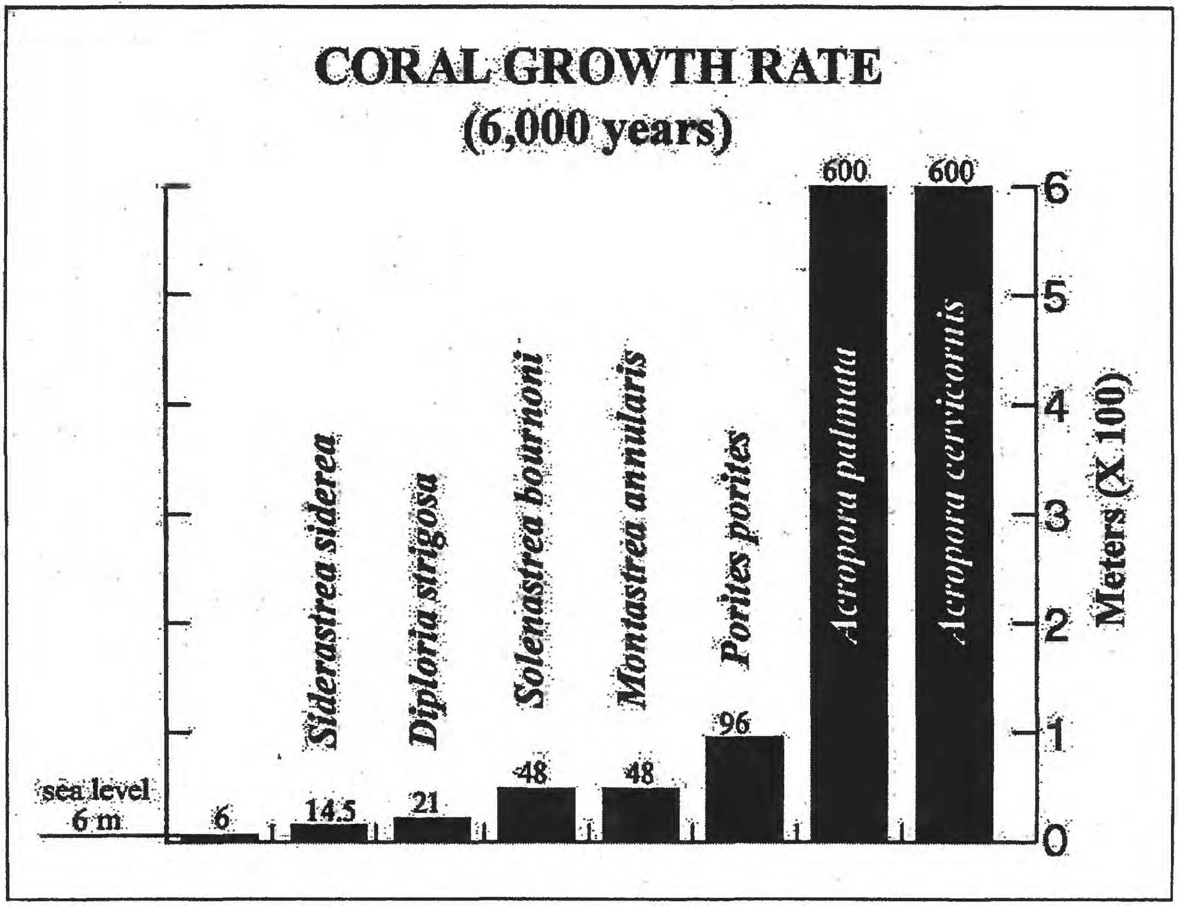

Figure 11. Graph showing theoretical rates of growth over 6,000 years based on documented annual growth rates of some selected species. Compare growth rates with the degree of sea-level rise over the past 6,000 years.

GIS mapping of the area covered during this field trip shows that only about 0.02% of the reefs (those with reef flats awash at low tide) have actually kept pace with the rise in sea level over the past 6,000 years. As geologists, we are left with the implication that something prevented coral growth from attaining its potential during the history of the Florida reef tract. Clearly, there is much more to learn regarding the history of coral reefs in the Florida Keys.

Historical Tidbits

In 1933 a steel underwater observation chamber called the Seaquarium was placed in about 5 m of water off the southeast end of Grecian Rocks. The chamber consisted of an 8-m-long by 2-m-diameter steel cylinder fitted with glass windows. The cylinder stood vertically and was entered from the top. The Labor Day hurricane of 1935 knocked the chamber on its side. The first author was shown the chamber from an airplane 1949. In the early 1950s, the chamber was salvaged by the Hempstead Brothers Salvage Company of Miami and used as a mooring in Garden Cove on Key Largo. It was eventually taken to the scrap yards in Miami and sold as scrap iron.

In the mid-1960s, the Cressi family in Italy (Cressi swim fins and other diving equipment) commissioned the casting of two bronze Christ statues called "Christ of the Deep." The first one was placed in the Mediterranean Sea. The second one was donated to the Underwater Society of America to be placed somewhere in the Great Lakes. The Society decided that a more suitable place would be in the Florida Keys. In 1965 when the area was a State Park, a group of volunteers in Miami installed the statue on a cement base in 8 m of water at what is now called Key Largo Dry Rocks. The statue is featured on billboards and postcards and literally hundreds of divers and snorkelers visit the "Christ of the Deep" each week.

Grecian Rocks were named after a yacht named the Grecian that wrecked there early in the 1900s. Dry Rocks (now Grecian Rocks) were so named because rocks protrude from the water at low tide.

In 1957, a salver named Craig Hamilton recovered 18 Spanish cannons from a pile of ballast stones off the south end of what was then called Key Largo Dry Rocks. They were sold for scrap iron, as were many other cannons at that time. Scrap iron was worth $65 a ton at salvage yards on the Miami River due to the Japanese market for scrap.

A Short History of the Parks and Sanctuaries

The area we have examined was originally designated as Pennekamp State Park. It was named after John Pennekamp, a long-time editor of the *Miami Herald* newspaper. Pennekamp had been instrumental in acquiring the land for Everglades National Park in 1946. In 1976, a Supreme Court decision limited state waters on the east side of Florida to 3 n.mi., leaving the most ecologically diverse coral reefs unprotected. Legal jurisdiction was soon turned over to an emerging program in a new agency called NOAA (National Oceanographic and Atmospheric Agency under the Department of Commerce). Enforcement was handled by the state and financed by NOAA. The new federally mandated park was called the Key Largo National Marine Sanctuary. Pennekamp Park still exists but its jurisdiction extends only 3 miles. An additional coral reef sanctuary was created in the lower Keys at Looe Key Reef. The Looe Key National Marine Sanctuary was the last bill signed into law by President Billy Carter.

On November 16, 1990, a bill was signed by President George Bush creating the 26,000 n.mi.^{2} Florida Keys National Marine Sanctuary (FKNMS). Jurisdiction includes all the waters and the sea floor out to a depth of 300 ft (91 m). Waters within 3 miles of the Keys, including some 3-mile-diameter halos around small offshore sand islands in the lower Keys, are administered jointly by the State of Florida and the FKNMS.

Acknowledgments

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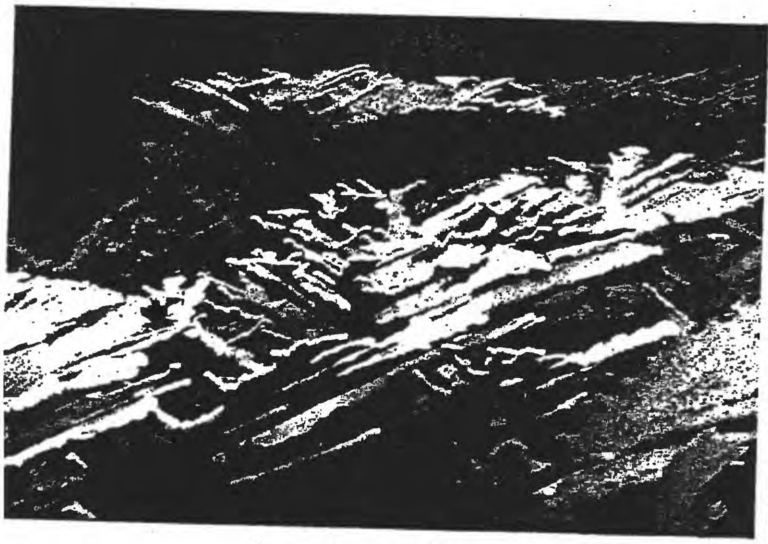
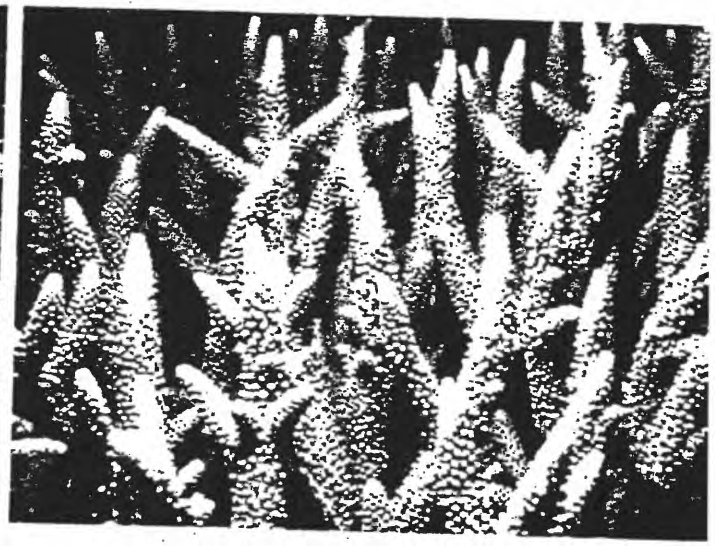
APPENDIX

Selected photographs of corals, coral disease, time series, and carbonate sediment producers



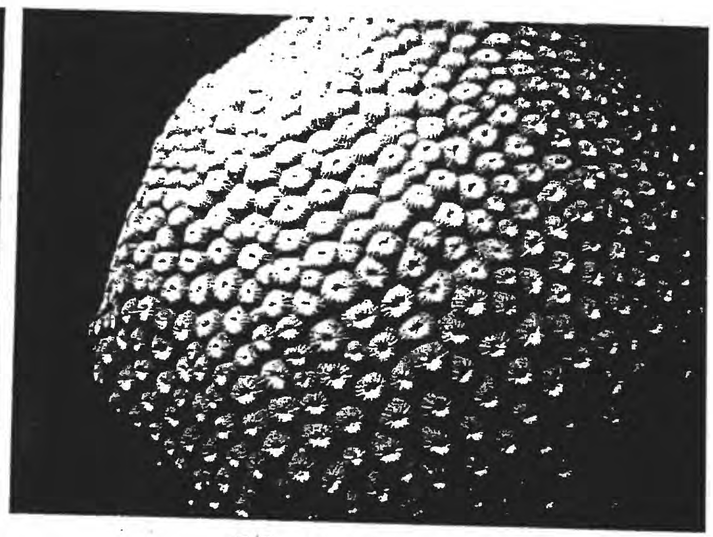
Acropora palmata



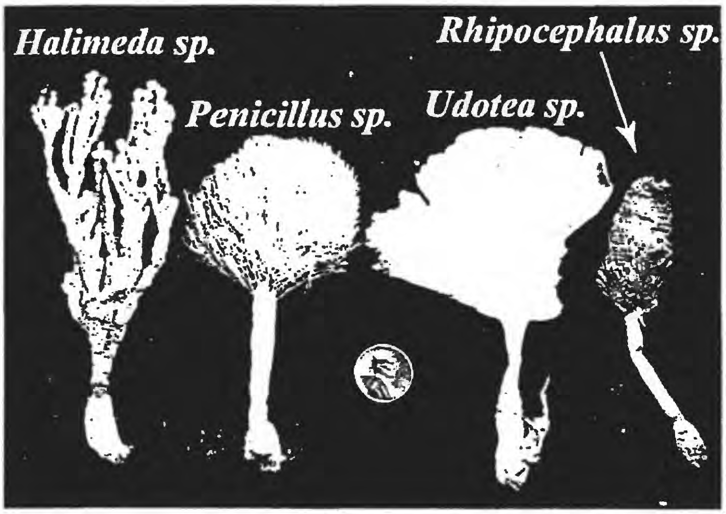
Acropora cervicornis

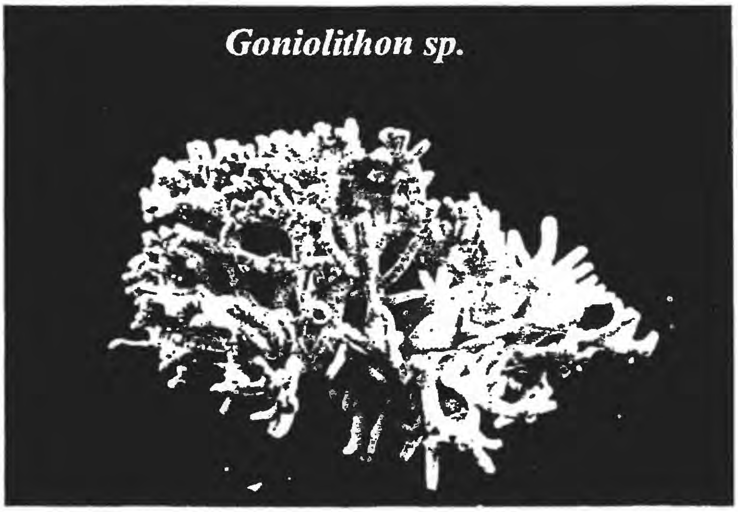
Both species of *Acropora* grow approximately 10cm (4 inches) per year.

***Montastrea annularis* infected with Black Band disease.**

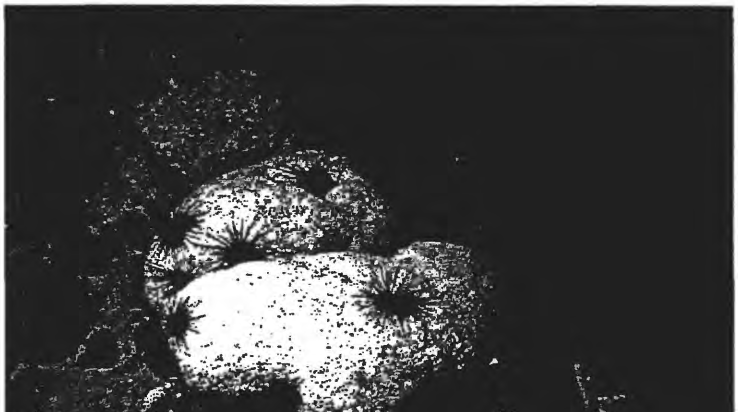


Montastrea cavernosa





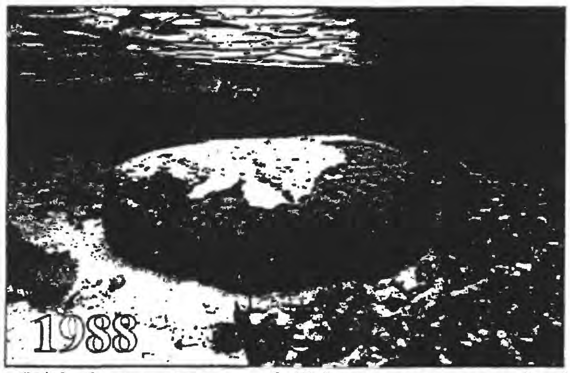
Common sediment producers on the Florida reef tract.



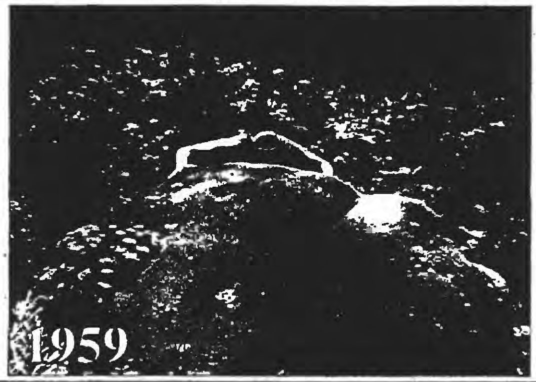
he sea urchin *Diadema antillarum* was ɔmmon before 1983. Notice the white clean ırface due to grazing by *Diadema.*

Typical example of algal overgrowth that ha: occurred since 1983 when *Diadema* suffered mass mortality throughout the Caribbean.

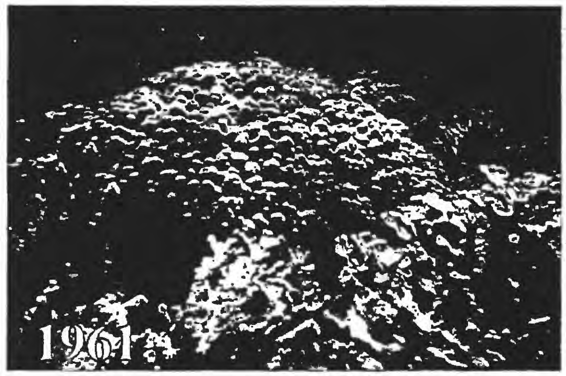
GRECIAN ROCKS



This large star coral *(Montastrea annularis)* was being attacked by black band disease in 1988 and was mostly dead by 1998.

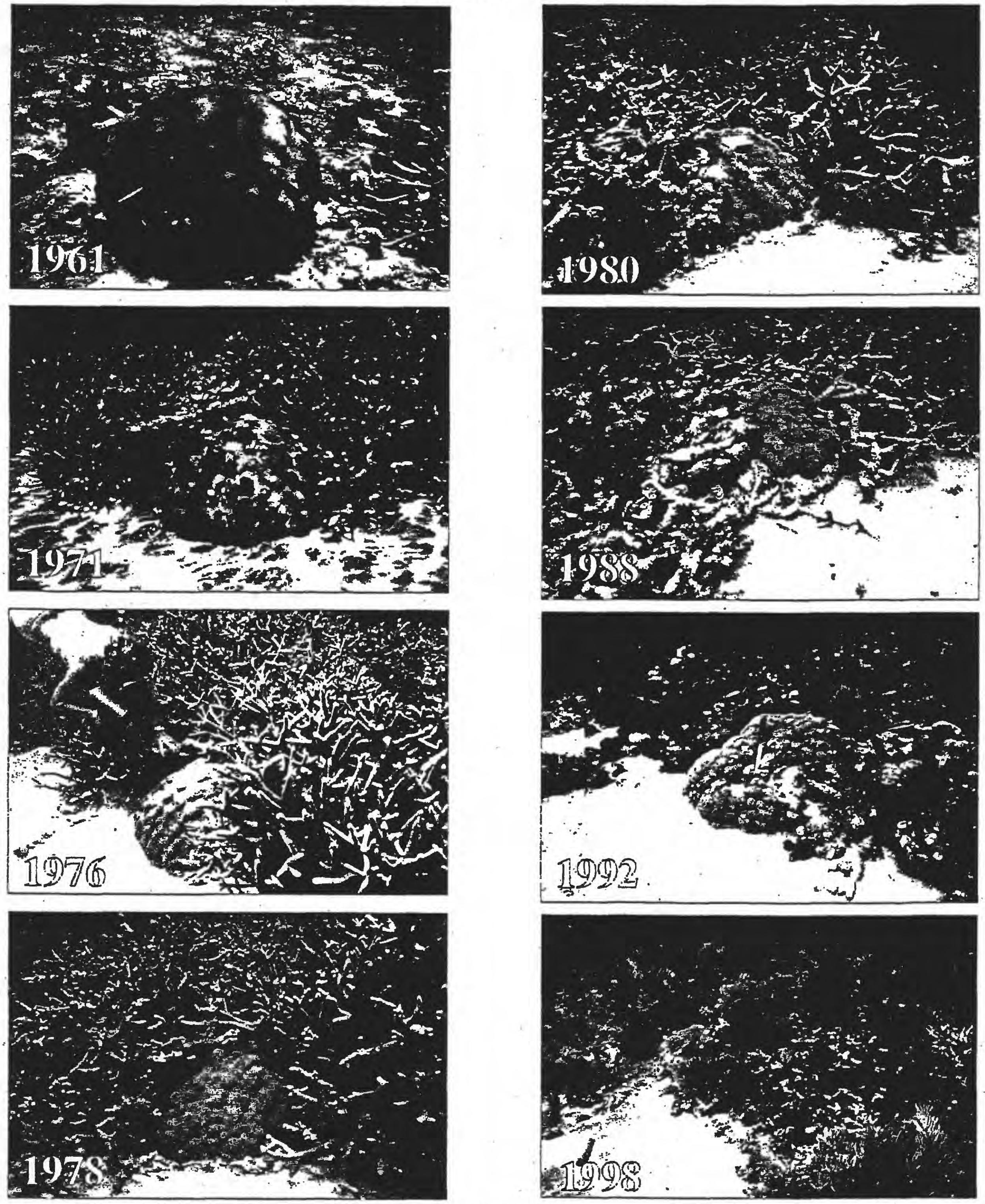


This large *Colpophyllia natans* (a type of brain coral) ad a star coral attached at left and a species of *Diploria* on the right. In 1988, the star coral was missing (note avity in foreground) but the *Diploria* at right remained (Hurricane Donna impacted this area after the 1959 photograph was taken). In the summer of 1998, the rain coral was slightly bleached, the *Diploria* to right s even more bleached. The brain coral is mostly dead and infested with algae and sea whips.



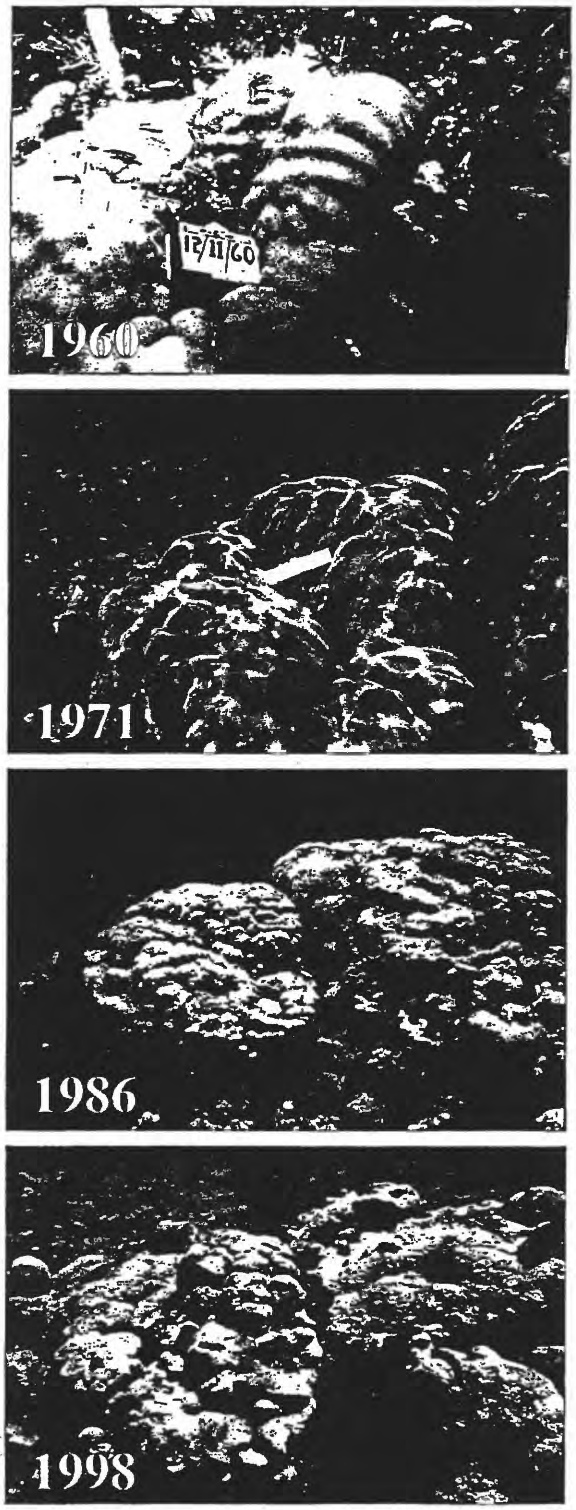
This large *Montastrea annularis* head, featured in several publications, was encroached upon by extensive staghorn and elkhorn growth by 1971 but the area was devoid of these branching corals by 1988. Diver is hovering over the same coral in 1971 and 1988.

GRECIAN ROCKS

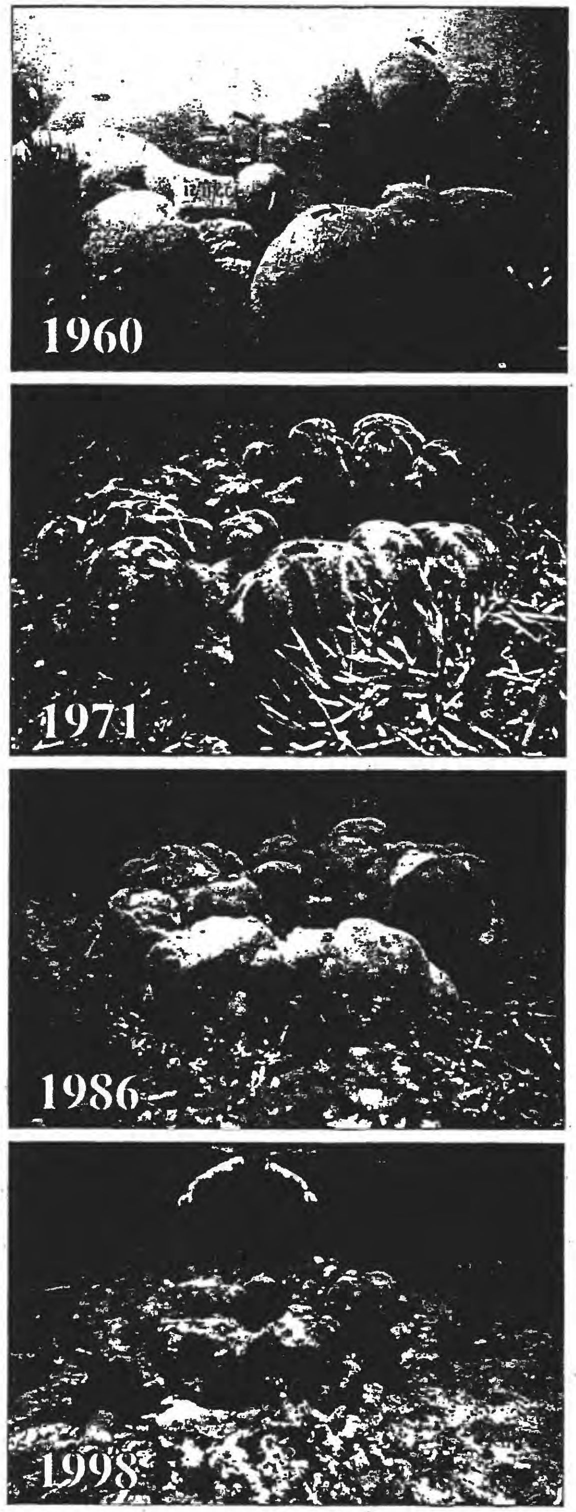


This star coral was tagged with stainless pins (sediment trap in concrete block in background) in 1961 following Hurricane Donna, which decimated Grecian Rocks. In 1965, studies of the actual staghorn coral showed it grew 4 inches per year. By 1971, staghorn and a colony of elkhorn corals were overgrowing the star coral. The staghorn began to die in 1978 and 1979 and was dead by 1980, except for the colony to the right of the head. Since 1980, there has been no staghorn present, the original star coral has changed growth shape, and by 1998 it was being overgrown by sea fans and sea whips. (Note the original head is visible in the center of all photographs).

CARYSFORT REEF



Above is a photograph of a large star coral *(Montastrea annularis)* taken in 1960. Arrows show spikes that were part of a growth-rate experiment. In 1998, only small portions of the coral were alive.



In 1960, this brain coral *(Diploria sp.)* was tagge with stainless pins (shown by arrows). By 1971, staghorn coral, once prevalent at Carysfort Reef was growing around the head. By 1986, the staghorn was dead, broken, and covered by flesh algae. In 1998, most of the brain coral was dead

Notes

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