ABSTRACT

Comprehensive Model for Modern Lagoonal Patch Reef Systems
in Discovery Bay, Jamaica

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Interpretations of ancient carbonate organic structures have relied upon the modern forereef environment of fringing or barrier reefs. However, data collected over the past thirty years suggests that lagoonal patch reefs may serve as a more useful model.

Observations made at the Red Buoy Patch Reef in Discovery Bay, Jamaica suggest that lagoonal patch reefs may develop in a cycle similar to that of Early Pennsylvanian bioherms by Bonem (1978). This project focuses on analysis of the biological and sedimentologic development of the Red Buoy Patch Reef to identify changes in the reef's history to support this model of cyclic development.

Data gathered in this study indicate that there are strong correlations between the texture and composition of the reef sediments and the biotic zonation. The distributions of the biotic zones on the reef correlate with the stability of environmental factors such as temperature, depth, and sedimentation flux. Cyclic development such as that seen in previously studied bioherms was observed on the reef following major storm events.

Comprehensive Model for Modern Lagoonal Patch Reef Systems
in Discovery Bay, Jamaica

by

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A Thesis

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To a friend who knew when I was nervous, knew when I was comfortable, and knew when I was confident. He was the projection of my dreams and when we were together, he provided the wings that I had lacked. . . .

-Shango

CHAPTER ONE

Introduction

Objective of Study

Ancient carbonate build-ups have customarily been interpreted based on the investigations of modern carbonate analogues. Although modern depositional environments are the most representative analog to ancient build-ups, many reefs in the geologic record have displayed characteristics that are not adequately explained by the conventional fringing or barrier reef model (Twenhofel, 1950, Troell, 1962, Schmidt, 2006). Many ancient bioherms are associated with calcareous mudstones, in contrast to the coarser-grained carbonate sands associated with modern fringing and barrier reef systems. Comparisons of ancient bioherm characteristics with the modern biological zonation of the Red Buoy Patch Reef in Discovery Bay, Jamaica, suggests that modern lagoonal patch reefs may provide a more useful model for bioherm interpretation that the traditionally used fringing or barrier reef model.

Modern lagoonal patch reefs are supported by a calcareous mud substrate, which is similar in composition to the micrite and calcareous shale and mudstones that are associated with many ancient bioherms. The developmental history of the biota on a modern lagoonal patch reef also suggests a new model may serve as a more accurate comparison. The developmental histories of a series of bioherms in the Lower Pennsylvanian Morrow Series in northeastern Oklahoma have been documented by Bonem (1975). From this investigation, she concluded the bioherms developed in a cyclic, three phase pattern beginning with an initiation phase characterized by stabilization of the substrate by cyanobacteria. As the bioherm becomes inhabited by outside organisms, a diversification phase is initiated in which species richness increases. The final phase of development is the complete termination of organism growth, which may be recognized by domination of the community by encrusting bryozoans or cyanobacteria. Following this termination phase, growth is then reinitiated following the stabilization of the substrate by cyanobacteria. This observed cyclicity may be a response to fluctuating sedimentation rates, which are a common feature of the backreef lagoonal environment. The development of these ancient reefs may be understood by closely examining and analyzing the past and present ecology of a modern lagoonal patch reef like the Red Buoy Patch Reef. This reef demonstrates faunal assemblages and reef geometries that are to a great extent controlled by periodic environmental disturbances (Bonem, 1978).

Initial observations of the Red Buoy Patch Reef by Bonem in 1974 and 1981 suggest that this patch reef developed in a similar cyclic manner. In 1977, a sudden influx of sediment covered this thriving patch reef and left behind a thick layer of sediment. This episodic event is similar to the termination phase identified in ancient bioherms. In 1978, all evidence for this sudden sediment influx had been removed and the patch reef had entered the diversification phase, also identifiable in ancient biohermal assemblages. The similarity in developmental phases among lagoonal patch reefs and ancient bioherms may contribute to the validity of using this new model for interpretations (Bonem, 1978).

Another similarity between modern lagoonal patch reefs and bioherms, aside from substrate composition and developmental phases, is a unique biotic zonation associated with the lagoonal reefs. In 1974, preliminary surveys of the Red Buoy Patch Reef indicated that this particular reef contains a unique biotic zonation that is composed of fauna typically found at greater depths on the fringing and barrier reef. This unique zonation is the result of reduced light penetration caused by the turbid lagoonal waters. It is hypothesized that for similar reason, algal taxa are commonly found to dominate over tabulate and rugose corals in many Paleozoic bioherms. Constraining reef interpretations using forereef coral zonation will result in an incorrect water depth assumption for bioherms that existed in turbid waters (Bonem, 1978).

The similarities between modern patch reefs and ancient bioherms include: substrate composition, fauna developmental history, and biotic zonation assemblages. For these reasons, it is suggested that lagoonal patch reefs may serve as a better modern analog to many ancient bioherms previously interpreted as fringing reef assemblages. The purpose of this study is to construct a comprehensive modern model of a lagoonal patch reef system by investigating the bathymetry, sedimentologic character, and biotic zonation at the Red Buoy Patch Reef.

Location and Setting of Study Area

Jamaica is located in the center of the Caribbean Sea approximately 200 miles south of Miami, Florida (fig. 1). The island is approximately 150 miles long, and averages 50 miles wide.

Regionally, the north coast of Jamaica is in close proximity to the Cayman Trench. This location contributes to Jamaica's narrow north continental shelf, with extremely deep water occurring relatively close to land. The majority of the north coast is bounded by a fringing reef, which is periodically interrupted by river outflow or absence of an island shelf. The island's position along the Cayman Trench causes tilting and uplift of the island resulting in steady erosion of the north coast and erosion of the south coast.

Jamaica lies in the belt of the northeasterly trade winds; however certain local factors alter the pattern of prevailing surface winds in different parts of the island. On the north coast, winds above 15 miles per hour blow from a northeasterly direction 75 percent of the time. There is a well defined westward current located on both the northern and southern coasts. This current annually increases during the trade wind season between April and December. The documented surface water temperatures range seasonally between 24 and 28º. Typically, circulation in the Discovery Bay lagoon is restricted and surface water temperatures are higher in contrast to the open ocean (Goreau, 1959).

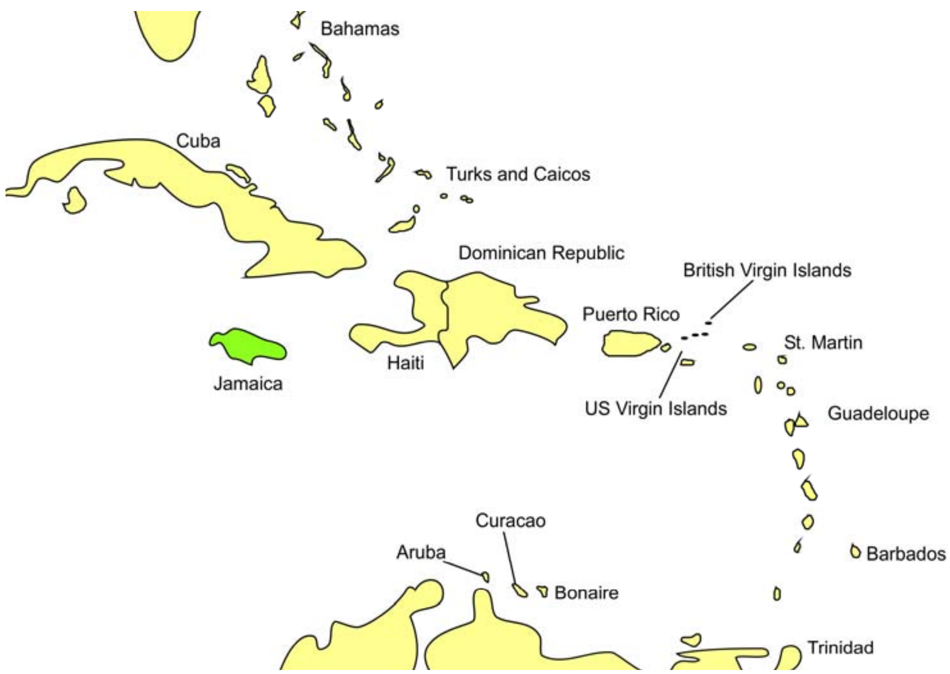

Figure 1. Location map of Jamaica.

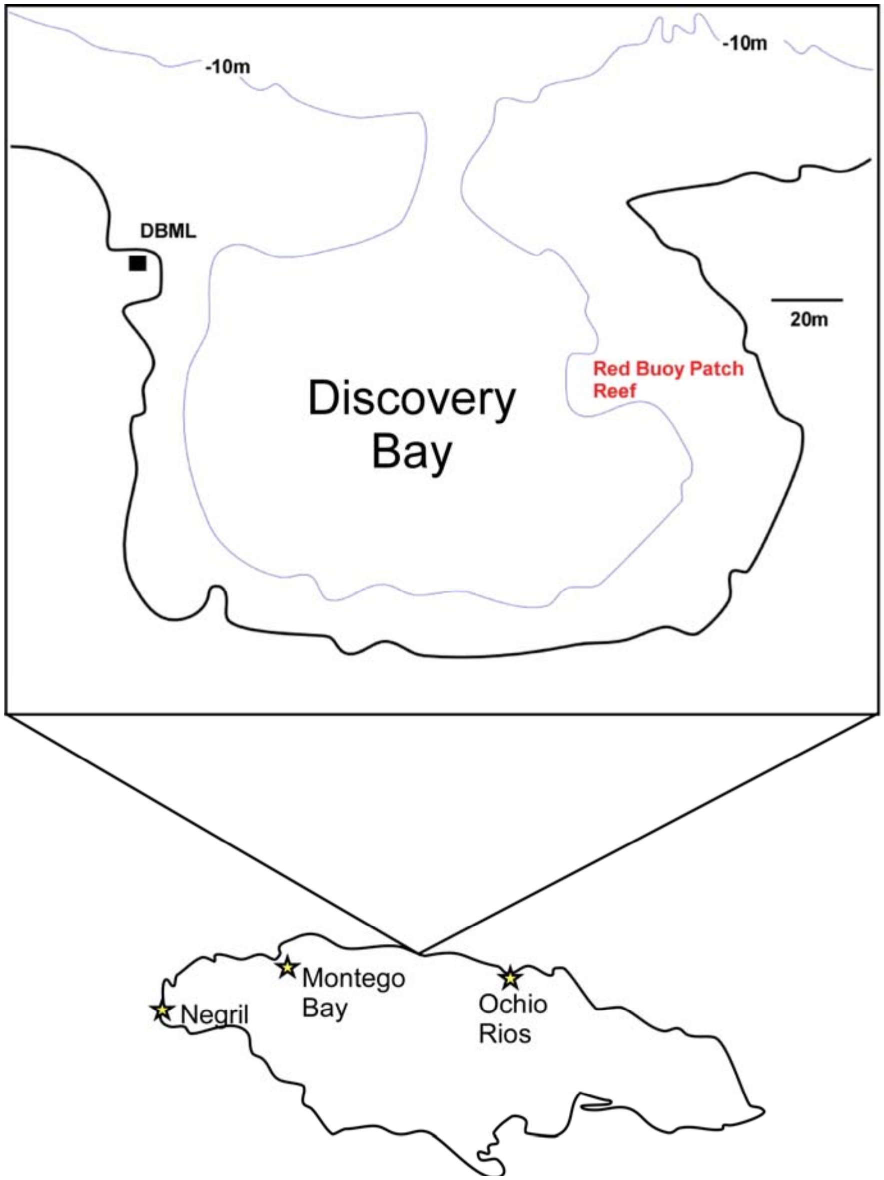

Figure 2. Map of Discovery Bay off the north coast of Jamaica. Note the location of the Red Buoy Patch Reef and the Discovery Bay Marine Laboratory.

Field work was conducted at the Discovery Bay Marine Laboratory on the north coast of Jamaica, about 33 miles east of Montego Bay. The bay forms a backreef lagoon behind the barrier reef that extends across the mouth of the bay. The Red Buoy Patch Reef is situated on a narrow bank extending southwest from the shore into the northeastern part of Discovery Bay (fig. 2) at a depth of 18 to 70 feet. The composition of the substrate consists of carbonate muds and skeletal material. The bank this reef is situated on is a direct reflection of the karst topography of the underlying Pleistocene bedrock. This bedrock discharges freshwater submarine springs throughout the bay. Suspended sediments in the bay decrease light penetration and effects visibility. The visibility in the bay typically ranges from 15 centimeters to 5 meters depending on environmental factors.

Previous Studies

Background information and baseline data were drawn from a variety of sources. Jamaica’s geologic history and regional setting is discussed in general terms by Woodley and Robinson (1977). Geographically specific geologic information is covered by Lidell and Ohlhorst (1981).

There have been limited studies of modern lagoonal patch reefs in the Caribbean. The ecology and sedimentology of the patch reefs located off Belize have been discussed by Wallace and Schafersman (1977). Jordan (1973) also investigated sedimentation rates and facies changes off the coast of Bermuda. For this study, Goreau (1959) and Goreau and Land (1974) have served as the primary sources for reef descriptions and zonations.

Bonem and Stanley (1977) originally described the biotic zonation of the Red Buoy Patch Reef in 1974. Implications of the developmental phases in lagoonal patch reefs for Paleozoic bioherm interpretation have been published by Bonem (1978).

Unpublished data has been collected on the Red Buoy Patch Reef since 1977.

CHAPTER TWO

Geology of Jamaica

Regional Setting

Jamaica is situated on the northern edge of the Caribbean Plate only a few miles south of the Cayman Trench (fig. 3). The Trench is approximately 6000 meters deep, and separates the Caribbean Plate from the North American Plate. The Caribbean Plate not only contains the island the Jamaica, but also a portion of Central America near its west-southwestern border with the Coccos Plate in the Pacific Ocean along the Middle America Trench (Pindell & Barrett, 1990). The southern border of the Caribbean Plate and the northern border of the South American Plate are marked by a series of fold and thrust belts along both borders. The location of Jamaica on the Caribbean Plate places the island at the northeast end of the Nicaraguan Rise.

The Nicaraguan Rise extends on the west-southeast from Nicaragua and Honduras, to the Greater Antilles on the east-northeast. The origin of the rise has been the subject of many studies and varying interpretations. Meyerhoff (1977) postulates that the rise is an extension of the Northern Central American Orogeny, and that it is underlain by continental crust. Arden (1969), however, maintains that the rise is underlain by oceanic crust rather than continental. Despite these two speculations, it is known that the shallowness of the rise and its proximity to sea level indicate that it is buoyed by continental crust, which is lighter than oceanic crust. The crustal thicknesses recorded beneath the Nicaraguan Rise are comparable with those beneath California, where continental crust is known to be present (Meyerhoff, 1977).

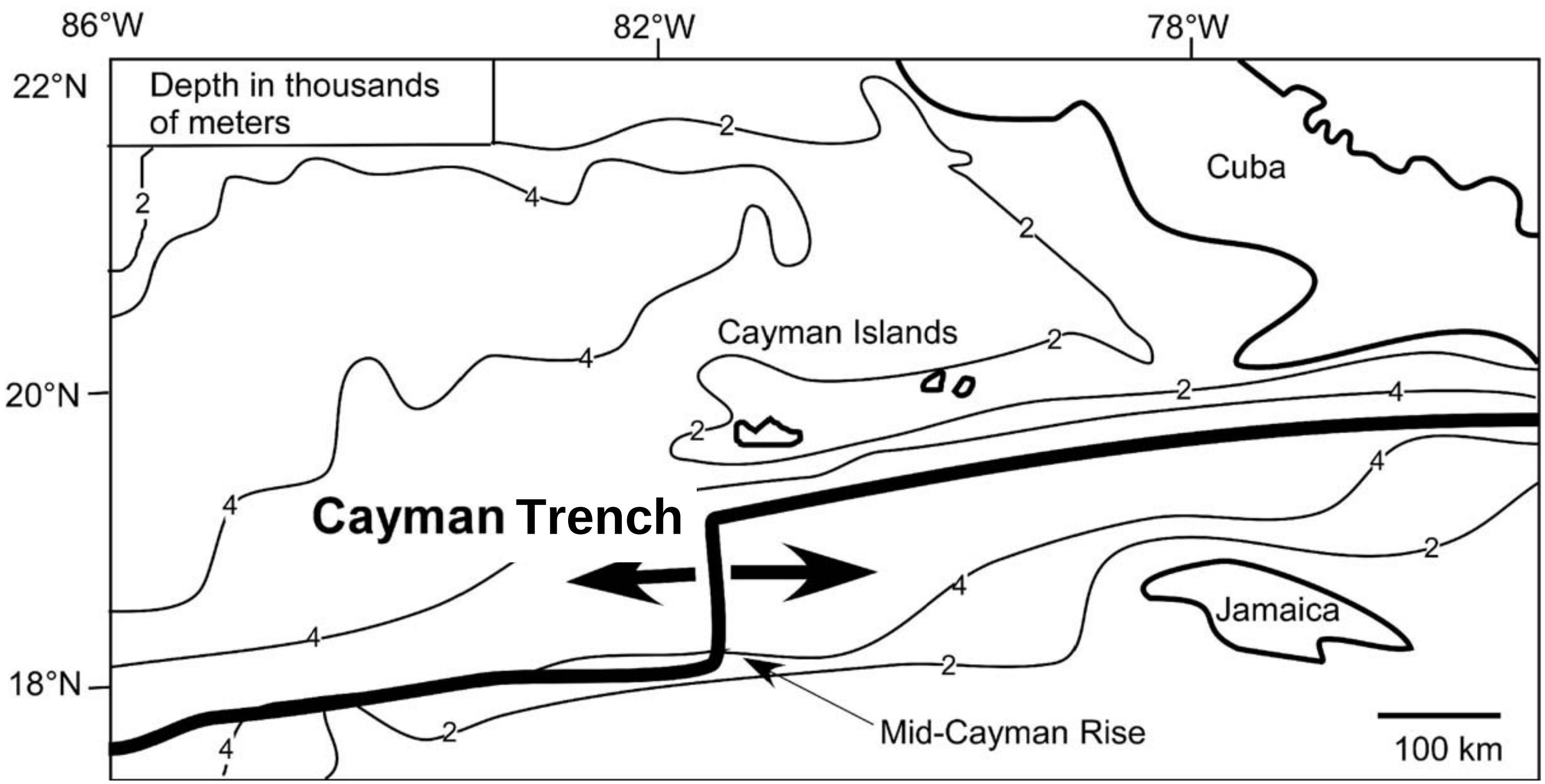

Figure 3. Map of Caribbean regional tectonics. The northern boundary of the Caribbean Plate is a left lateral transform margin (modified from Pindell & Barrett, 1990).

According to Donelly (1989), the Caribbean Plate has been relatively stable since the Late Jurassic. Since this time, the Cayman Trench has represented the northern border of the Caribbean Plate providing a left-lateral strike-slip fault in this area. The actual island of Jamaica began to develop during the Early Cretaceous (approximately 105 million years ago). It began as an island arc where a section of the Cayman Trench began thrusting under the Nicaraguan Rise. The Caribbean Plate is still active today having an average slip rate of 2.0-2.2 cm/ year along the Cayman Trench (Molnar & Sykes, 1969).

Structural Background

Lewis and Draper (1990) identified six morphotectonic regions throughout Jamaica. These six major structural units are divided into three blocks on Jamaica (fig. 4). The block furthest west is the Hanover Block. This unit is composed exclusively of shale from the Upper Cretaceous, as well as sandstones and limestones in a 4,000 meter thick sequence. The Montpelier-Newmarket Belt lies east of the Hanover Block. This unit is composed of Tertiary sedimentary rocks. Along the north coast lies the North Coast Belt. The central part of the island is the morphotectonic unit of the Clarendon Block, which is south of the North Coast Belt. This unit is the most diverse consisting of sedimentary Cretaceous rocks as well as volcanic inliers. The eastern border of the Clarendon Block, as well as the North Coast Belt, consists of the Wagwater Belt. This unit is composed of Paleocene and Eocene sequences an average of 7,000 meters thick. To the east of the Wagwater Belt lies the final unit, the Blue Mountain Block. This block is dominated by volcanic intrusions of the Late Cretaceous as well as regionally metamorphosed rocks interbedded with limestone horizons.

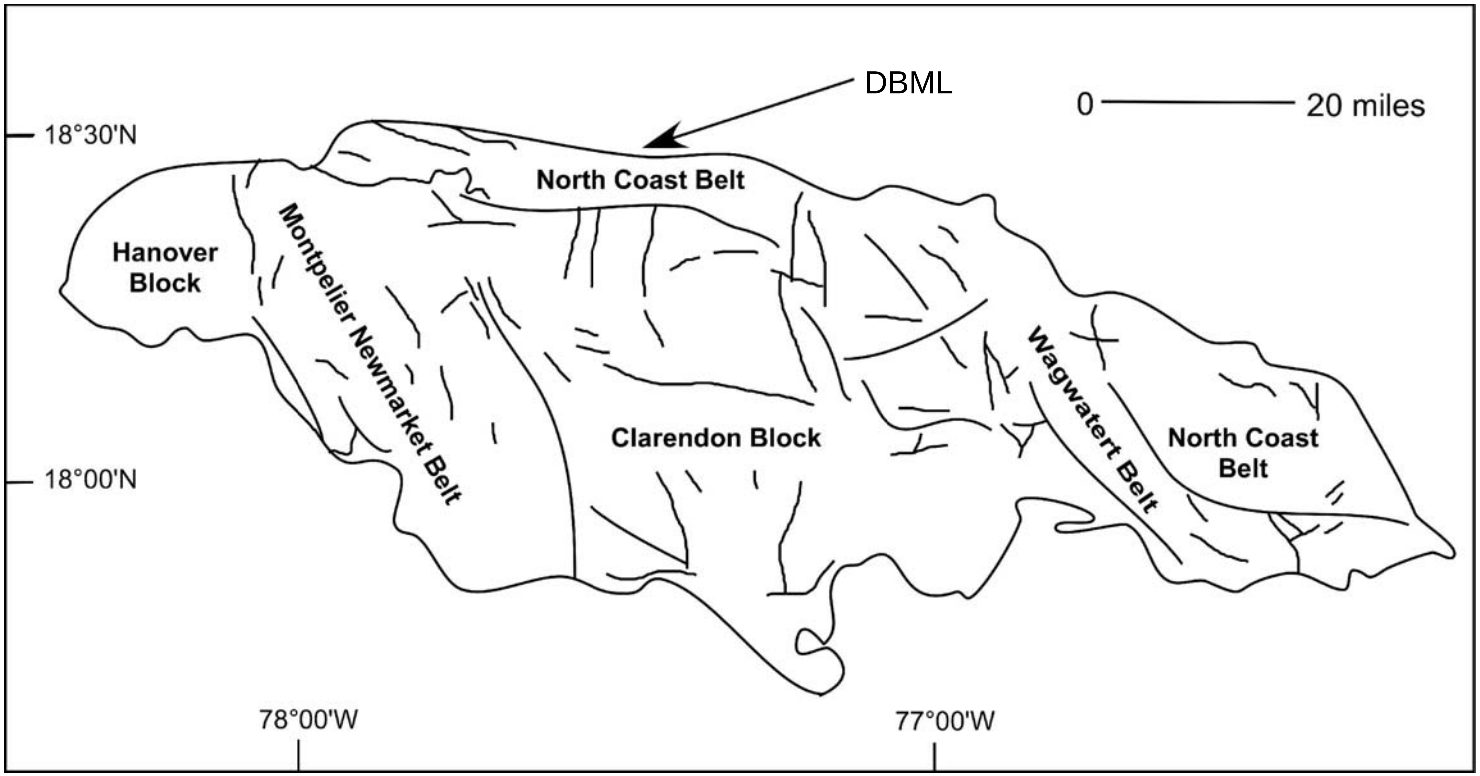

Figure 4. Map of the six morphotectonic regions of Jamaica. Note the location of Discovery Bay which lies in the North Coast Belt (modified from Woodley and Robinson, 1977).

Most major faults within the Cretaceous Inlier originated during the Cretaceous or earlier. They trend east-west, whereas the Tertiary faults have a northwest-southeast trend. Various grabens as well as the northwest-trending anticlinal belts were established by the end of the Cretaceous. Faulting took place along high angle fractures and movement along the fault systems reached a climax at the end of the Eocene. This climax coincided with the cessation of major volcanic activity in Jamaica, as it did in all of the Greater Antilles (Meyerhoff, 1977).

Normal displacement is more common along the faults than reverse displacement. Strike-slip movement has taken place along many of the major faults, including various minor faults as well.

Deformation by folding is not as common as deformation by associated with vertical fault movement. Most folds in Jamaican Tertiary rocks are broad, open structures with wavelengths of the order of one mile and nearly vertical axial planes. The present vertical relief and the region's earthquake history suggest that many faults, particularly the major ones, are still active (Pindell & Barrett, 1990).

Stratigraphic Description

Jamaican stratigraphy can be simplified by dividing the bedded rocks into five major cycles (Pindell & Barrett, 1990). The first cycle includes two areas of metamorphic rocks; one in the western part of the Blue Mountains and one just west of Kingston on the southern coast. Two belts of metamorphic rocks are present in the southwestern part of the Blue Mountains (fig. 5). The eastern belt, the Mt. Hibernia Schist, consists of low-grade metamorphic rocks. The western belt, the Westphalia Schist, consists of high-grade metamorphic rocks.

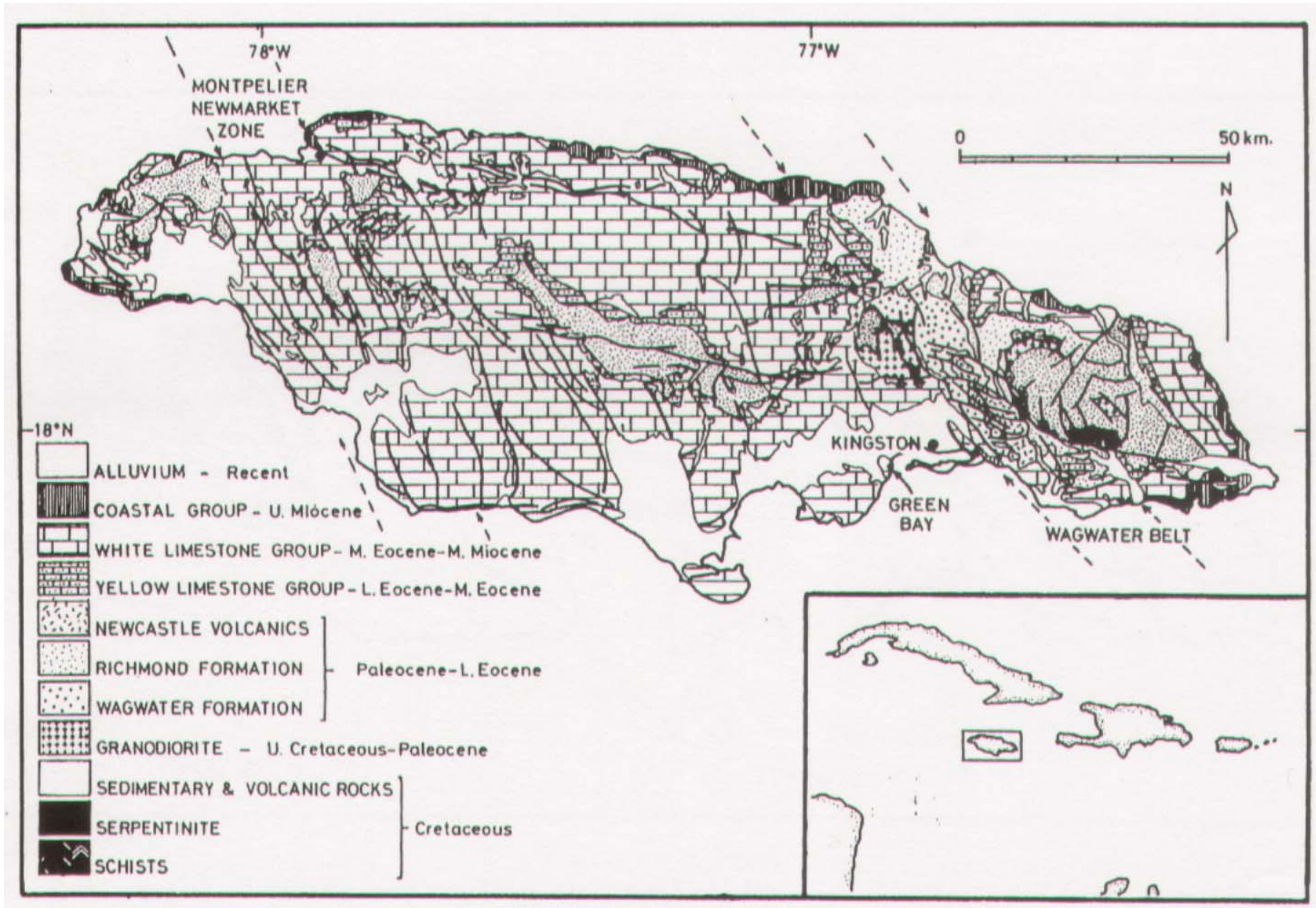

Figure 5. Map of Jamaican geologic units. Note the location of Discovery Bay in the Coastal Group (Zans, 1962).

The second cycle includes the Cretaceous sequence of Jamaica. These rocks are present in the Blue Mountain Block, along with inliers found in the Wagwater Belt, the Clarendon Block, the North Coast Belt, and the Hanover Block. Rocks within this cycle exhibit lateral and vertical abrupt facies changes.

Cycle three rocks are from the Paleocene to early Eocene units and are found from the northern flank of the Blue Mountains, from the Wagwater Belt, and the St. Ann Inliers. These cycle three rocks are overlain by the fourth cycle deposits of the middle Eocene Yellow Limestone Group. This marine group, along with the overlying White Limestone Group at one time covered nearly all of Jamaica. The yellow color from which the Yellow Limestone Group derives its name comes from a minute quantity of terrigenous clastic material incorporated in the limestone. As the source areas for the terrigenous clastic material were buried by the sea, the limestone sequence became pure assuming a white color- the White Limestone Group. Deposition of the White Limestone Group terminated as the Caribbean Orogeny began.

The fifth cycle consists of terrigenous clastic material concentrated along the southern part of the island. These deposits are a consequence of uplift, southward tilting, and fault movements causing deposition in valleys and coastal regions from the late Miocene time to the present.

CHAPTER THREE

Geomorphology of Northern Jamaican Reefs

Model of Reef Zonation

There have been numerous studies recognizing the depth-related and light-dependent nature of reef communities world-wide. These communities and the classic zones that they form have been well-documented on the northern coast of Jamaica by several authors (Goreau and Goreau, 1973; Kinzie, 1973; Lang, 1974; and others). In 1959, Thomas Goreau constructed a model for Caribbean reef zonation which acted as a standard by which all reefs in the Caribbean could be studied and compared. Jamaican reefs can further be divided into regions and zones based on local differences in topography and species composition (fig. 6). The zonal structure of the reef is apparent by taking a profile across the fringing reef from the shore to deep water. The specific zones and associated regions are assigned according to their most conspicuous faunal or topographic characteristic (Goreau, 1959). Transects across mature reefs demonstrate the existence of three main regions: the back reef, reef crest, and forereef. These regions can be further subdivided according to their most prominent faunal or structural feature. Studies show zonal structure and species succession is fundamentally similar on both the northern and southern coast reefs. It is also documented that storms have the ability to alter the basic pattern of species dominance and zonal succession in the upper parts of the reef climax (Goreau, 1959). Hurricanes Allen (1980) and Gilbert (1988) and the mass mortality of the *Diadema antillarum* in 1983 (Moses, 1999) have resulted in modifications of the reef model. The following descriptions include these modifications.

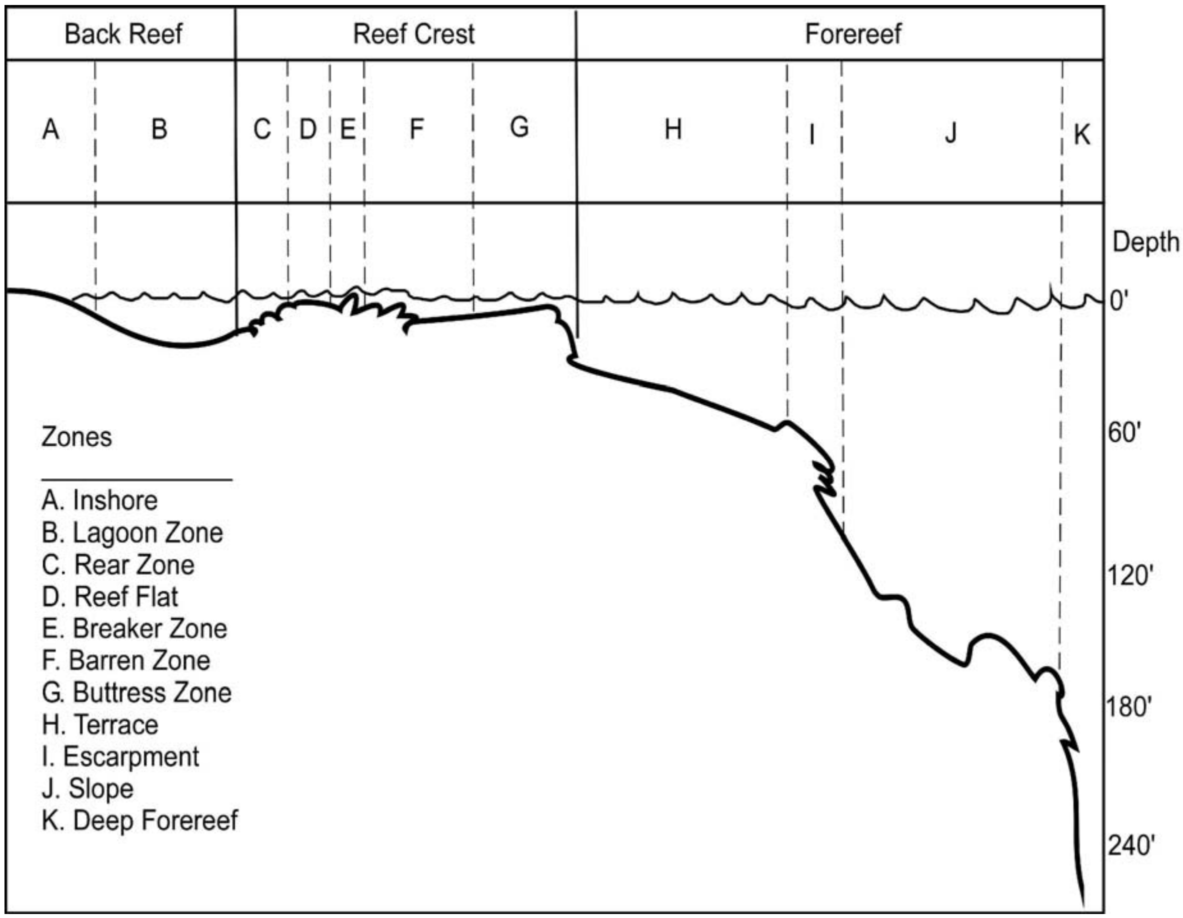

Figure 6. Classic model of Caribbean reef zonation (modified from Strykowski and Bonem, 1993). The absence of horizontal scale is due to variability of shelf widths.

Backreef

The backreef lagoon is the area of focus for this project. This zone is located landward of the reef crest, and is typically subdivided into the inshore and lagoonal zones. The backreef is variable and may include mangrove swamps or rocky shorelines several miles long. The inshore zone is the region adjacent to the land and frequently contains wetlands or mangroves, both of which act as buffers between outflow from the land and the reef. This area generally consists of calm waters with grassy beds, patch reefs, and dominantly silty bottoms (fig. 7).

Work done by Christopher Moses (1999) depicts Jamaican backreefs as being composed of only 0.8% coral due to their intolerance of the muddier waters. The most common species of the corals that are found in the area include *Montastrea annularis*, *Porites asteroides*, and *Porites porites* which together generally represent 75% of the corals in the lagoonal zone. The remaining portion of the community is typically represented by algae, which accounts for 75% of the total biota of the lagoonal community.

Reef Crest

The reef crest is the area in which the reef comes in contact with the water surface. At Discovery Bay this zone, prior to hurricane impact, was located approximately -5ft below the water's surface with periodic episodes of complete aerial exposure. The reef crest is dominated by high-energy and shallow water with low biotic diversity. The local geomorphology governs the width of the reef crest, which can range from tens of meters wide to a few meters wide.

The crest is the portion of the reef which absorbs nearly all the force of waves and tides allowing the backreef to maintain a quiet, low-energy environment (fig.8). Given the high-energy associated with the reef crest, organisms that colonize this area typically are of two forms: branching and encrusting. These branching corals are often oriented towards the direction of wave incidence. This uniform orientation produces a natural barrier which absorbs the wave energy. Prior to 1980, *Acropora palmata* comprised approximately 98% of the coral species (Liddell and Ohlorst, 1987).

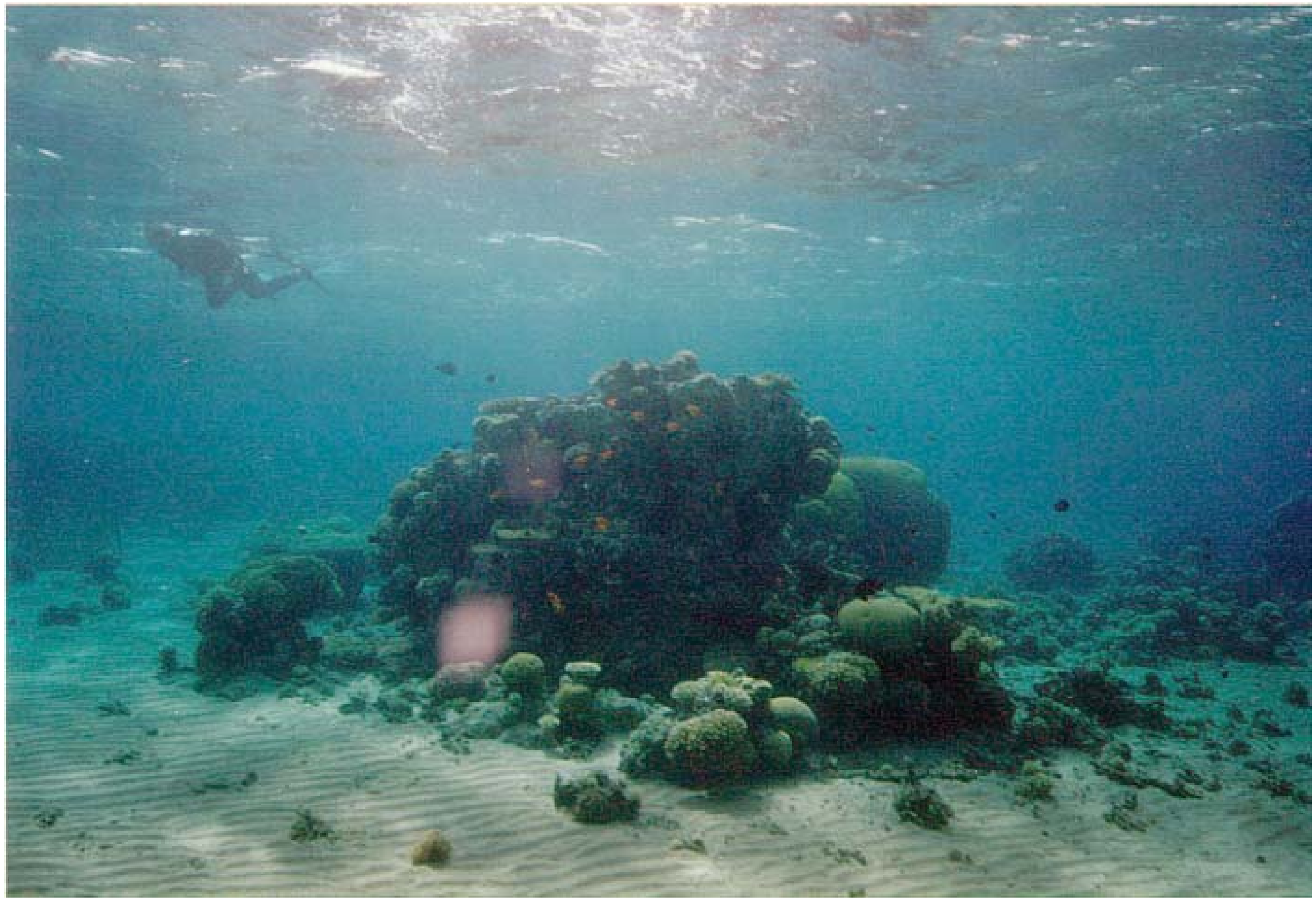

Figure 7. Photograph of a typical patch reef in the Caribbean located in the backreef region. photograph taken by Jade Sheetz (2004).

Forereef

Spatially, the forereef constitutes the largest portion of a Caribbean reef (fig. 8). This area represents the entire reef that is seaward of the reef crest. The forereef can be further broken down into zones based on organism's body types and environmental energy. These six zones include: the mixed zone, buttress zone, forereef terrace, forereef escarpment, forereef slope, and the deep forereef.

Mixed Zone

Beginning adjacent to the reef crest, this section of the forereef is typically very prominent and can extend for quite a distance seaward in the absence of a buttress zone. There is a notable increase in species diversity in this zone with an average of 30 species of coral (Goreau and Goreau, 1973). The corals thrive on a gently sloping plane which is dominated by *Montasrea annularis* as well as *Porites asteroides*. A major component in this portion of the forereef is algae, which covers approximately 36% of the surface area in the mixed zone (Moses, 1999). Wave energy is much lower in the mixed zone than at the reef crest, however there is still too much energy to support substantial soft coral or sponge colonization.

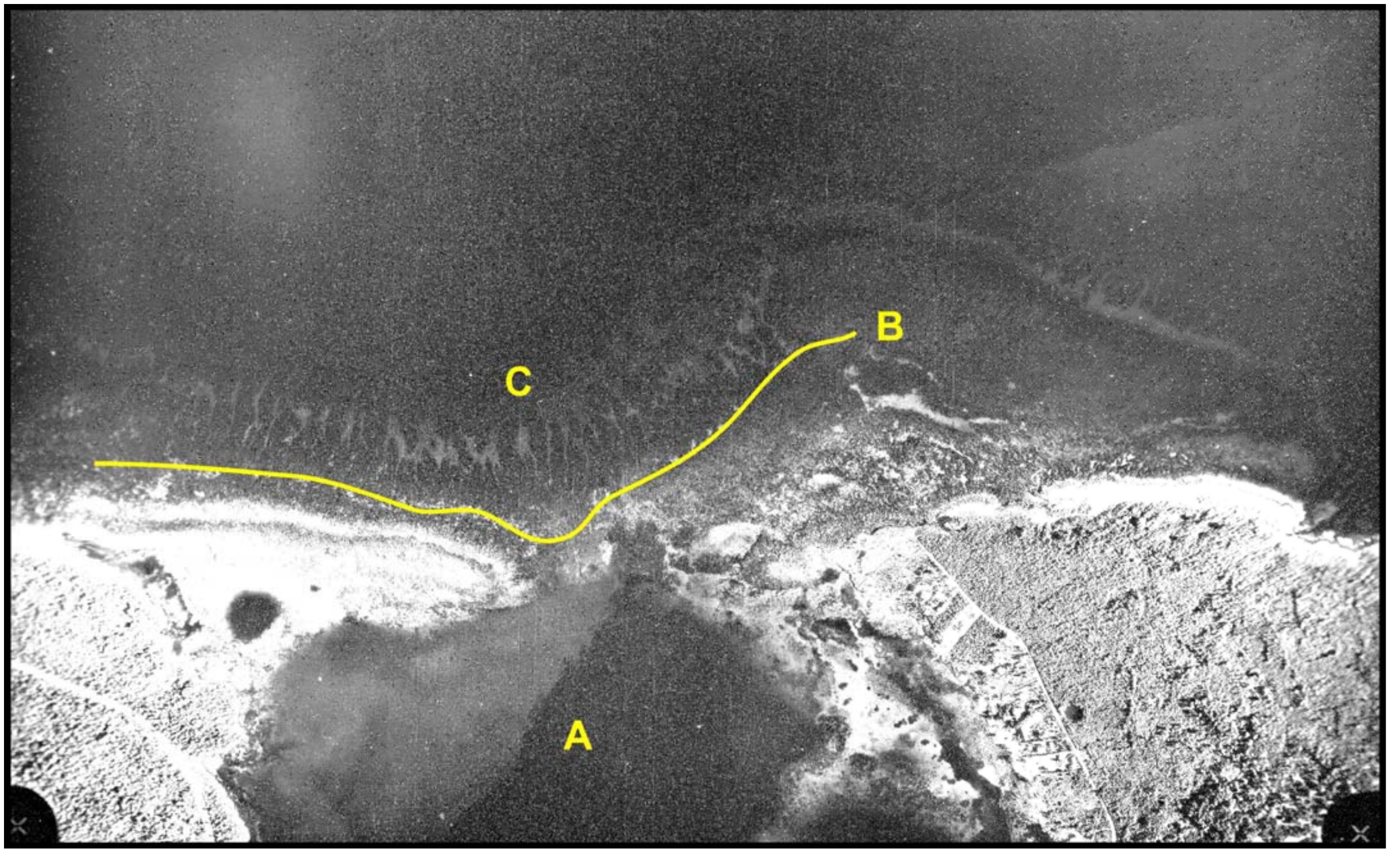

Figure 8. Aerial photograph of Discovery Bay, Jamaica showing the basic subdivisions of classic reef morphology. A: backreef; B: line of the reef crest; C: forereef. Photograph provided by the Geological Survey Department, Kingston, Jamaica,.

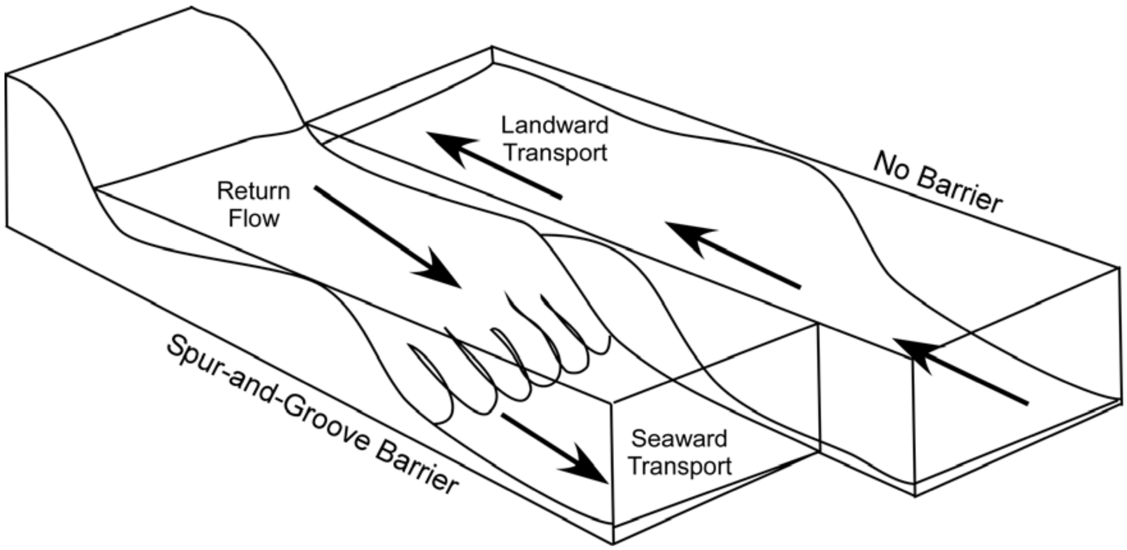

Figure 9. Sediment transport via spur and groove features in the buttress zone of the forereef (modified from Lang, 1974).

Buttress Zone

In many cases, this zone is not well-developed, and may be replaced with an extended mixed zone. However, when a buttress zone is present, it is the richest biotic habitat in the reef environment (Goreau and Goreau, 1973). This zone is commonly intergrown into the mixed zone and is characterized by steep-sided coral buttresses, which can reach heights of up to 10ft, separated by narrow sand channels. These channels are responsible for the movement of sediments seaward form the reef crest under the power of present wave action (fig. 9). Overall, the buttress zone exhibits similar environmental conditions such as high-energy and minimal sediment accumulation. These similar conditions facilitate similar biological communities (Lidell and Ohlhorst, 1987).

Forereef Terrace

The forereef terrace lies seaward from the mixed zone or the buttress zone. This zone typically has a much gentler slope than the previously mentioned zones. This area consists of corals that form scattered colonies in large sand patches similar to the backreef. Given that the depth of this zone is much greater than the zones above it, the forereef terrace is characterized by much lower wave energy and is typically only disturbed during storm events. Between the forereef terrace and the forereef escarpment is a sill of much higher coral growth than the surrounding coral colonies (Strykowski and Bonem, 1993). The sill prevents sediments from being transported downward onto the forereef escarpment. This biological community consists dominantly of corals as well as sponges, which take advantage of the firm substrate and low-energy associated with the forereef terrace.

Forereef Escarpment

At the base of the forereef terrace lies a drastically steeper slope known as the forereef escarpment. This region of the reef is notable by the sill at the edge of the forereef terrace and the obvious break in slope that can commonly exceed angles of 45º (Liddell and Ohlhorst, 1981). Sediment that cuts through the notches in the sill has the ability to travel down the forereef escarpment and accumulate on the forereef slope. Although the escarpment is overall steeper than the forereef terrace, areas where there are no notches in the sill are generally steeper than surrounding areas (Strykowski and Bonem, 1993). Due to the depth of this region, there is intense competition for light. The restriction of sunlight causes the corals in this zone to fan and flatten out. Plate corals are typically the most dominant coral while sponges also flourish along the steep slopes (fig 10). The overall algal cover appears to diminish due to the light restriction.

Along the base of the forereef escarpment, a deep wave-cut notch can be observed in many locations along the north coast of Jamaica. This notch is believed to have been created during a time of lower sea level in the Pleistocene (Goreau and Goreau, 1973).

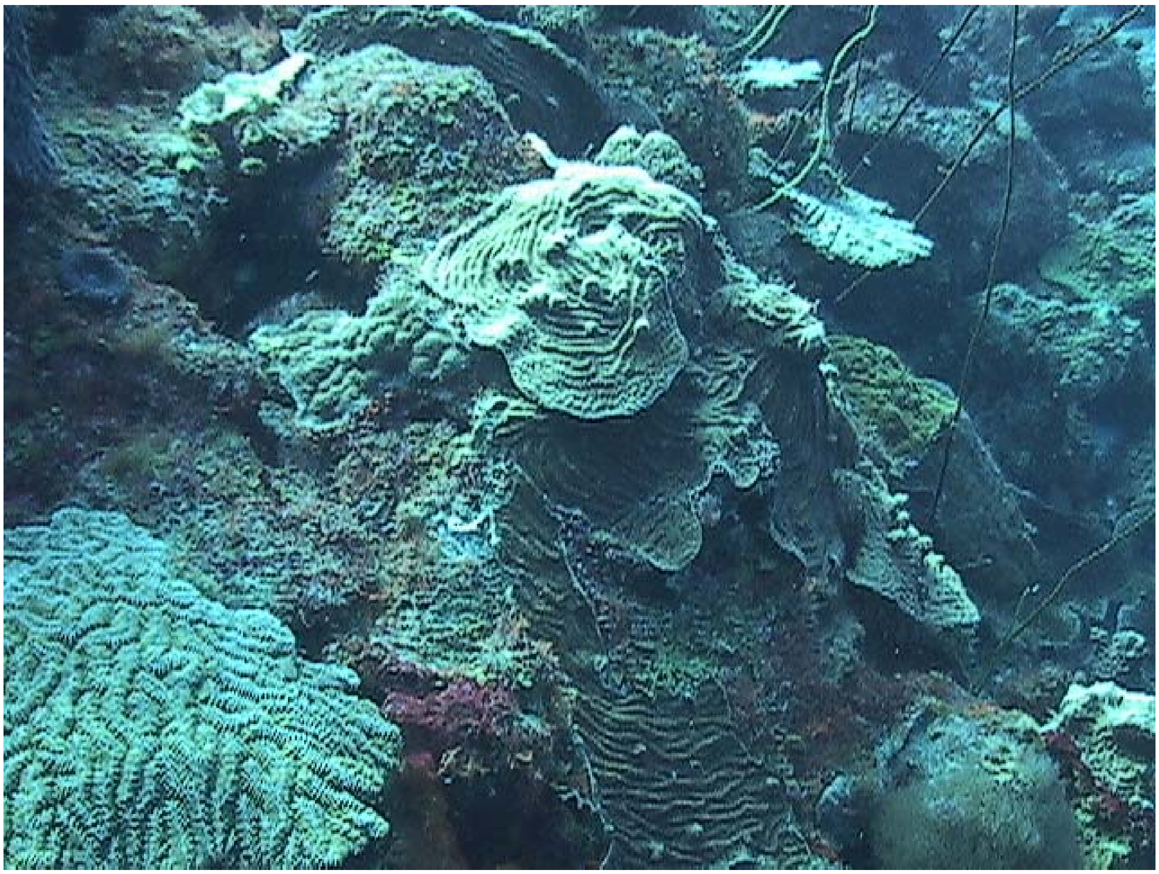

Figure 10. Photograph of the plate coral *Agaricia agaricites* found on the forereef escarpment (photograph taken by Jade Sheetz).

Forereef Slope

As mentioned previously, sediment that travels down the forereef escarpment accumulates on the forereef slope. This pile of sediment consists of boulders and coral pieces that have been shed off the reef crest and zones that are seaward from the crest.

This portion of the forereef has a much gentler slope than the forereef escarpment. In this zone, corals grow in scattered mounds along with sponges in the accumulated sediment pile. The density of coral in this zone, however, is considerably lower than what is found on the forereef escarpment (Goreau and Goreau, 1973). Similar to what is found on the forereef escarpment, the dominant coral type is platy.

Deep Forereef

Other wise known as the "wall," this portion of the forereef lies at the base of the forereef slope (fig. 11). This region exhibits a sudden increase in slope to nearly 90º or possibly overhanging. The deep forereef may slope downwards to as deep as -360ft. (Liddell and Ohlhorst, 1987). The steepness of the slope rarely allows any sediment accumulation. Dominant members of the biological community consist of gorgonians, sponges, antipatharians, and sclerosponges (Strykowski and Bonem, 1993). There are often no hermatypic corals along the surface of the deep reef due to the restriction of light penetration.

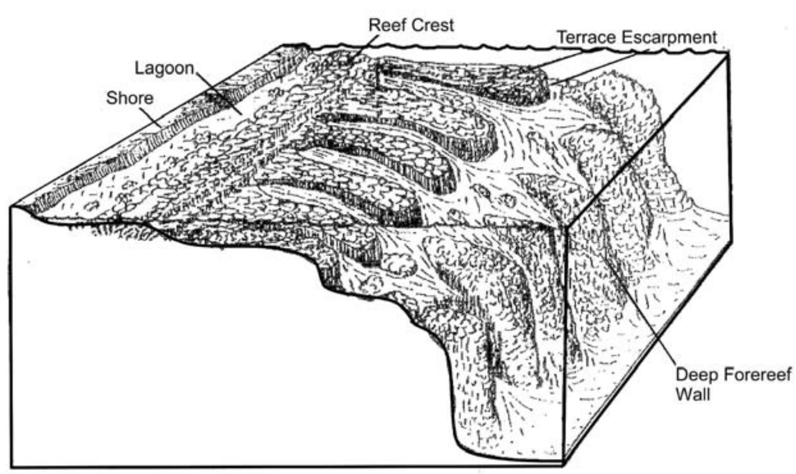

Figure 11. Classic model of reef morphology, highlighting the deep forereef wall. This model is typical of the north coast of Jamaica (modified from Strykowski and Bonem, 1993)

CHAPTER FOUR

Methodologies and Procedures

Field Methods

Investigations of the Red Buoy Patch Reef were conducted over two field seasons, one in August of 2005 and the second in May of 2006. Both field seasons consisted of two-weeks of field work in Jamaica. Discovery Bay Marine Laboratory of the University of the West Indies provided housing, diving, and laboratory facilities during both seasons. All sample collecting and observations were accomplished using conventional SCUBA equipment given that the depths in Discovery Bay range from 6 meters to 21 meters. Field data collection consisted of bathymetric surveying, biotic zone identification, and loose sediment grab samples.

During the first field season a new bathymetric survey of the Red Buoy Patch Reef was conducted using methods established by Bonem in 1974 for the purpose of documenting any short term changes of the reef. The survey conducted in 2005 also served as a base map for the location of sediment samples collected from the reef in 2006. The recently conducted survey serves for comparison with maps produced by Bonem in 1974, 1978, 1980, 1981, and 1982.

The bathymetry was mapped using a polypropylene line marked at 25 ft, 50 ft, 75 ft, and 100 ft intervals. One end of the line was attached to the buoy and the other end of the line was extended horizontally by a diver to 25, 50, 75, and 100 feet successively (fig. 12) intervals for 25 and 50 foot radii and at 10 intervals for 75 and 100 foot radii by using an underwater compass.

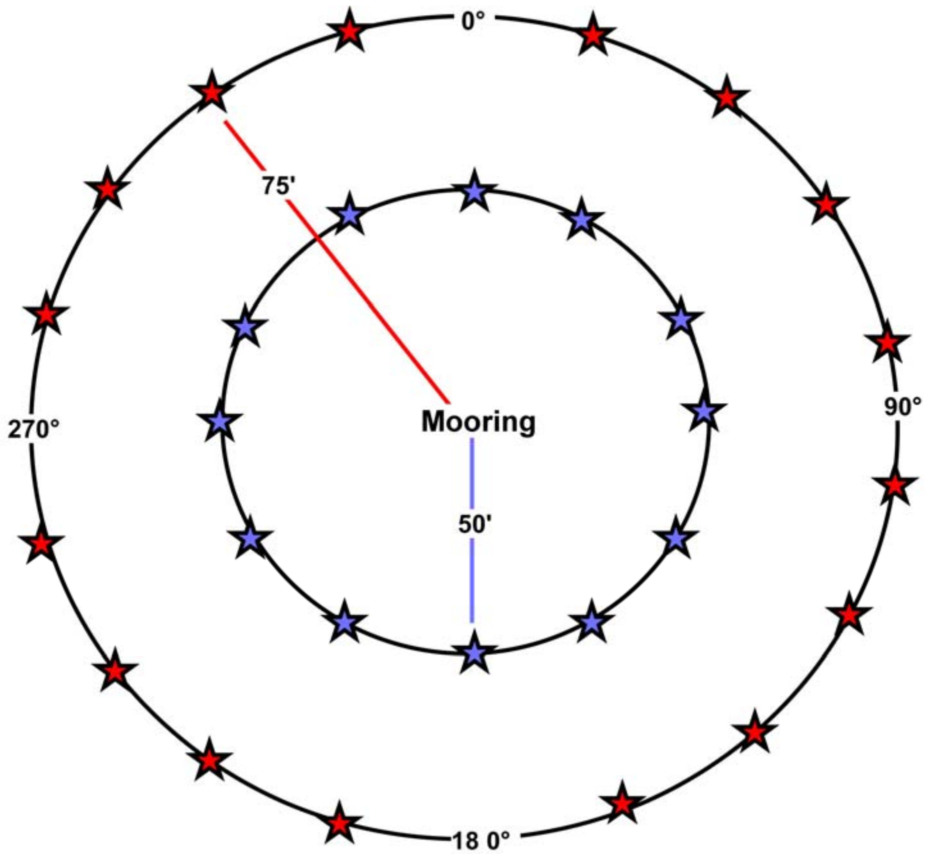

Figure 12. Diagram depicting the method used for the bathymetric surveys at the Red Buoy Patch Reef at a 50 and 75 foot radii. This method has essentially remained consistent since the first survey in 1974. Red and blue stars indicate degree positions where depth was measured corresponding to 20º increments; 20º, 40º, 60º, 80º, etc. for the 75 foot radius and 20º for the 50 foot radius.

The depth at each survey point was established using a computer depth gauge that has an accuracy of 1 foot. With this data, a bathymetric map was constructed for the year 2005, upon which the biotic zonation was superimposed.

The biota was described using a zonation established by Bonem and Stanley (1977). The five major biotic zones that are recognized include: *Porites* Zone, *Madracis* Zone, Mixed Sponge Zone, Massive Coral Zone, and the *Agaricia* Zone. The distributions of these zones were noted as bathymetric measurements were taken.

The sedimentologic character was examined by collecting eleven surface sediment samples from the reef along two linear transects at right angles to each other (fig. 13). For comparison, one sediment sample was also taken at a much greater depth (90 feet) on the east forereef of the fringing reef at Discovery Bay. The sample site locations were chosen based on core samples extracted from Nash (1982). The complete sedimentologic history of the reef has been constructed by combining the core sample descriptions with analysis of the surface sediment samples taken in 2006.

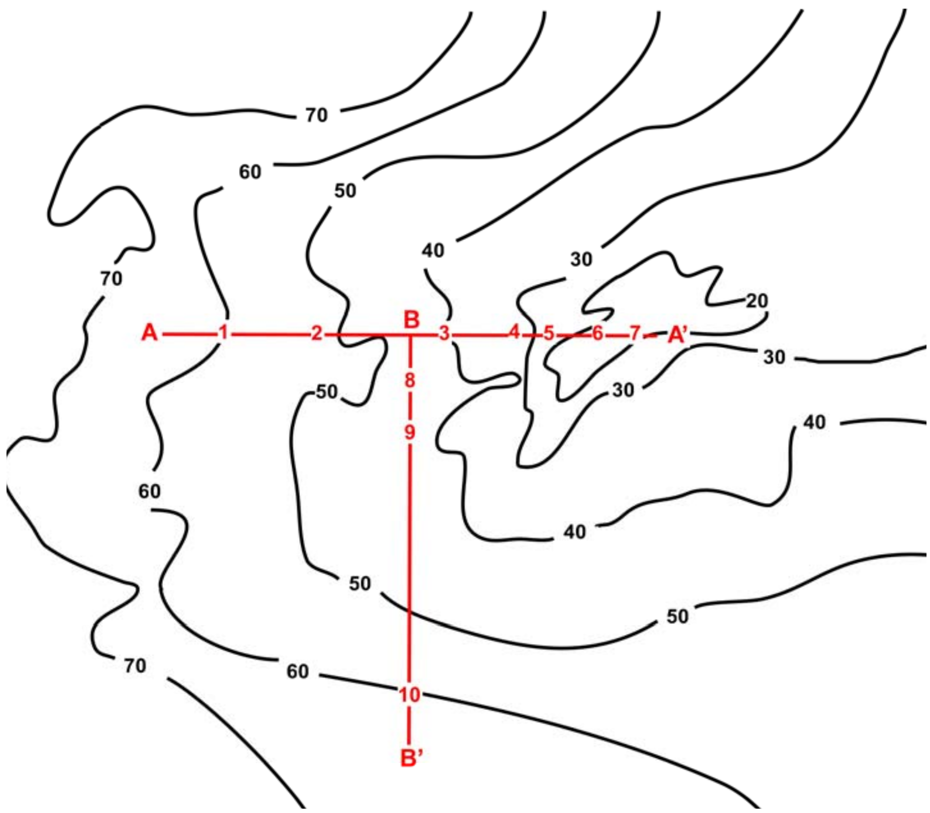

Figure 13. Bathymetric map of the Red Buoy Patch Reef from 1982. The two linear transects across the reef show locations where surface sediment samples were collected. Transect A – A' runs east and west from the stationary mooring, while transect B – B' runs north and south from the mooring. Numbers along the transects indicate locations of samples. Sediment was collected in plastic storage containers for secure transport back to the marine lab.

Laboratory Methods

A bathymetric map was constructed by plotting depth measurements and locations. Once the base map was constructed, the biotic zones were overlaid. Bathymetric maps from previous surveys were also redrafted. Comparing the present bathymetric maps with past surveys depict major changes in biotic zonation.

Sediment samples were transported back to Baylor University for analysis. The eleven surface sediment samples were wet sieved at one phi intervals. The sieved samples were allowed to dry completely for 48 hours at room temperature. Each sieve fraction was then carefully weighed and recorded. The weight percentage of each size fraction was used to generate textural grain-size statistics. Statistical analysis of these data follows standards originally established by Folk and Ward (1957). The weight percentages were plotted on a cumulative probability curve (fig. 14) and were used to generate median, standard deviation, skewness, and kurtosis for each surface sediment sample (table 1).

Skeletal abundances were used to determine the major composition of each sample. Random point counts of 200 uncemented sand-sized grains were conducted to establish the relative abundances of skeletal fragments derived from sediment-producing organisms in each zone. The principal components identified include: *Halimeda*, mollusks, echinoderms, arthropods, annelids, and coral. Grains that were unidentifiable were placed in the category miscellaneous. Once skeletal abundance was established for each sample, histograms were generated to visually compare sediment compositions of different biotic zones (fig. 15).

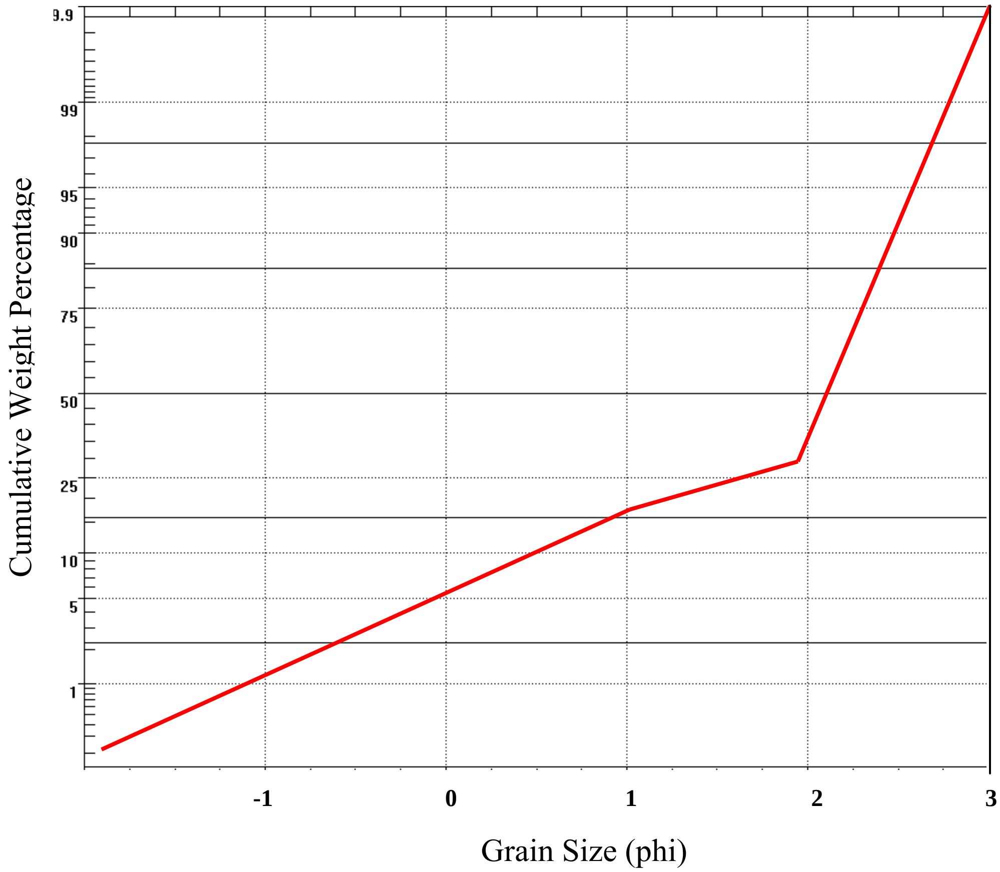

Figure 14. An example of a cumulative probability curve from which textural grain-size statistics can be generated (modified from Folk & Ward, 1957).

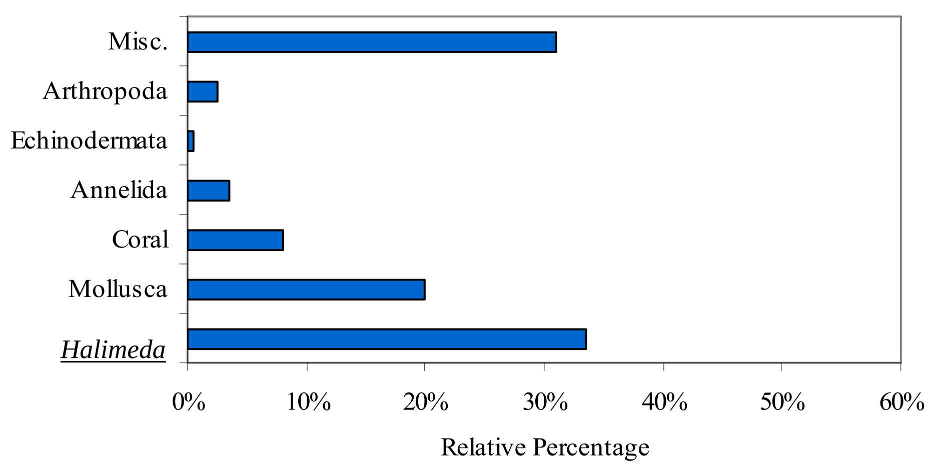

Figure 15. Histogram depicting relative percentages of sediment composition for sample #3 from transect B.

Table 1. Equations used to generate textural grain-size statistics for surface samples from the Red Buoy Patch Reef in Discovery Bay, Jamaica (modified from Folk and Ward,1957).

Statistic	Normal Distribution	Non-normal Distribution
Median	$Md\varphi = \varphi_{50}$	$Md\varphi = \varphi_{50}$
Mean	$M\varphi = \frac{1}{2}(\varphi_{16} + \varphi_{84})$	$M\varphi = \dfrac{(\varphi_{16} + \varphi_{50} + \varphi_{84})}{3}$
Standard Deviation	$\sigma\varphi = \frac{1}{2}(\varphi_{84} - \varphi_{16})$	$\sigma\varphi = \dfrac{(\varphi_{84} + \varphi_{16})}{4} + \dfrac{(\varphi_{95} + \varphi_{5})}{6.6}$
Skewness	$\alpha\varphi = \dfrac{M\varphi - Md\varphi}{3}$	$\alpha\varphi = \dfrac{(\varphi_{16} + \varphi_{84} + 2\varphi_{50})}{4} + \dfrac{(\varphi_{5} + \varphi_{95} + 2\varphi_{50})}{6.6}$
Kurtosis	$\rho\varphi = \dfrac{\frac{1}{2}(\varphi_{95} + \varphi_{5}) - \sigma\varphi}{\sigma\varphi}$	$\rho\varphi = \dfrac{\frac{1}{2}(\varphi_{95} + \varphi_{5}) - \sigma\varphi}{\sigma\varphi}$

CHAPTER FIVE

Faunal Zonation of the Red Buoy Patch Reef

Previous Work

Most modern reefs are developed on pure carbonate sand, however many ancient reefs are associated with carbonate mud accumulations. The Red Buoy Patch Reef was originally selected to examine the influence of a mud substrate on the development of reef associations. This site was chosen because this reef contains a well-developed association of corals and sponges in a turbid environment, which is characterized by a carbonate mud substrate (Bonem and Stanley, 1977).

Initially, six biotic zones were established across the Red Buoy Patch Reef by Bonem in 1974. This work described the basic composition and spatial distribution of each of the six zones: *Porites* Zone, Mixed Sponge Zone, *Madracis* Zone, Massive Coral Zone, *Agaricia* Zone, and the Deep Water Zone. The relationship between the bathymetry and relative abundances of hermatypic scleractinian corals on the forereef were described by Goreau and Goreau (1973) and have remained relatively stable (fig. 16). This same relationship is also recognized on the Red Buoy Patch Reef.

The biotic zones established in 1974, have been used to produce maps of the Red Buoy Patch Reef in 1974, 1978, 1980, 1981, 1982, and 2005. These zones exhibit distributional patterns based on growth response to light penetration, turbidity, water circulation, and substrate slope and composition (Bonem, 1977). Given that the zonation has remained constant, it is possible to monitor changes in the zonation on this particular lagoonal patch reef.

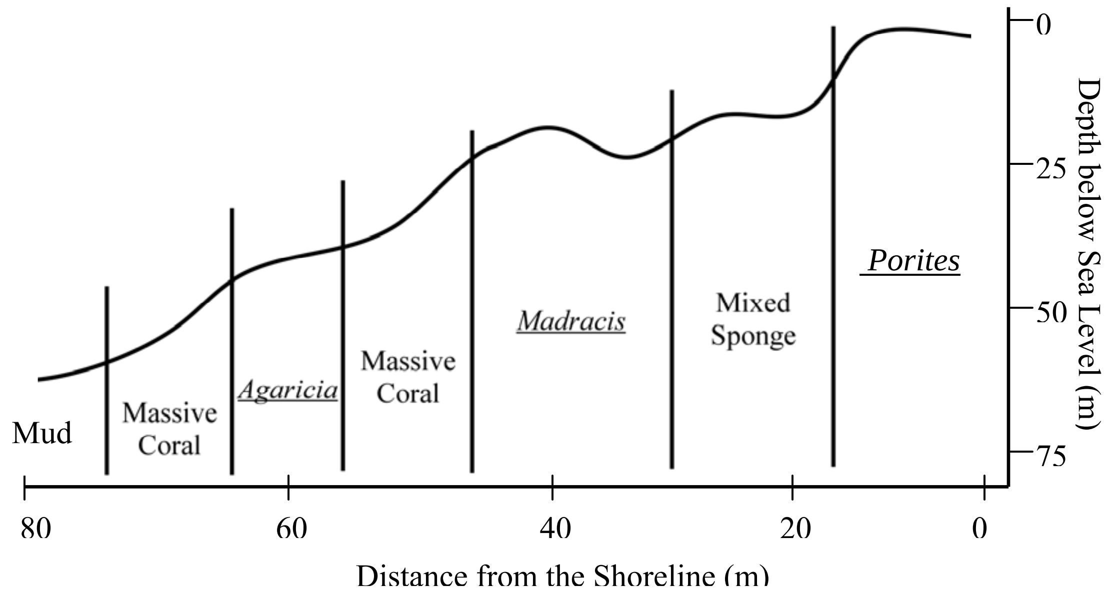

Figure 16. Diagram depicting the relationship between biotic assemblages and depth at the Red Buoy Patch Reef. Note as the depth increases, eventually no scleractinian coral are found, and mud dominates the seafloor (modified from Bonem & Stanley, 1977).

Detailed Description of Biotic Zones

Porites Zone

This zone is the shallowest at the Red Buoy Patch Reef, ranging in depths from fifteen to thirty feet. This zone covers approximately twenty-five percent of the Red Buoy Patch Reef. Because the *Porites* Zone is the shallowest zone found at the Red Buoy Patch Reef, it is within typical wave base and experiences well-circulated sea water with the greatest light penetration and the least amount of suspended material. This zone is composed of abundant rubble from the common finger coral, *Porites porites* (fig. 17). This area is located on the top of a shallow bank and typically has little topography related to it. This zone contains large amounts of broken debris from the finger coral, *Porites porites*, however the debris is most commonly encrusted by coralline algae. This finger coral only comprises 1.7 percent of the living organisms in the *Porites* Zone (Bonem & Stanley, 1977). The dominant living species found in this zone include: the red rope sponge *Haliclona rubens*, the black spiny urchin *Diadema antillarium*, and *Porites astreodies*. Also common in this zone is the hydrozoan *Millepora complanata*, commonly referred to as the fire coral.

Figure 17. Photograph illustrating the *Porites* Zone. This coral, commonly referred to as the mustard hill coral, is the dominant species. Photograph taken by Frederic Charpentier, Ottawa, Canada.

Madracis Zone

This zone is present at depths ranging from 31 to 57 feet, and is dominated by the branching coral *Madracis mirabilis*, which makes up approximately 87% of the zone. Other organisms found in this zone include various sponges and boring worms. This zone characteristically exhibits an irregular distribution (fig. 18). Throughout the short-term biotic mapping, this zone typically represents only 5% - 10% of the entire Red Buoy Patch Reef (Nash, 1982). In this zone, high mounds form hill-like features from which brackish water springs emanate. Unlike the other zonal boundaries that appear to grade into each one another, the *Madracis* Zone has sharp boundaries.

Mixed Sponge Zone

This zone comprises approximately 10 percent of the study area originally mapped and is dominated by various vase, frond-like, and branching sponges (fig. 19). This was the most diverse zone documented by Bonem and Stanley in 1977 containing a total of 27 taxa, including 11 species of sponge. The most common sponges found in this zone include *Haliclona dora* and *Haliclona rubens*. The red algae, *Ceramium nitens*, is found in highest percentages in this zone (Bonem, 1977). Other major constituents in this zone include the bivalve *Isognommon alatus*, the flower coral *Eusmilia fastigiata*, and *Porites asteroids*. Although the individual sponge species occur in only small percentages, together the sponges comprise a dominant component of the zone.

Massive Coral Zone

The Massive Coral Zone has the greatest aerial extent of all the mapped biozones and covers approximately 40% of the entire patch reef. The distribution of this zone forms a broad band that typically conforms to the map contours. This zone is dominated by the massive corals *Agaricia agaricites* and *Montastrea cavernosa*.

Figure 18. Photograph illustrating the *Madracis* Zone. This coral, commonly referred to as the yellow pencil coral, is the dominant species. Photograph taken by Frederic Charpentier, Ottawa, Canada.

Figure 19. Photograph illustrating the Mixed Sponge Zone. Photograph taken by Frederic Charpentier, Ottawa, Canada.

Other corals present in this zone include, but are not limited to: *Siderastrea siderea*, *Madracis mirabilis*, *Leptoseris cucullata*, *Mycetophyllia*, *Manicina areolata*, *Scolymia*, and *Porites porites* (fig. 20). The boundaries of this zone are difficult to distinguish given the patchy distribution and gross morphologies of the corals in the area. The boundaries of this zone are not distinct, but rather merge with those of the Mixed Sponge and *Agaricia* Zones.

Agaricia Zone

This zone is present at depths ranging from thirty-three to sixty-six feet, and is dominated by the large, platy, shingle-like coral, *Agaricia lamarcki* (fig. 21). Other forms of these platy coral are found in this zone, and include corals such as; *Montastrea annularis*, *Erythropodium*, and *Agaricia agaricites*. This zone forms a broad belt adjacent to the Massive Coral Zone and typically constitutes 10% of the Red Buoy Patch Reef. The *Agaricia* Zone is commonly restricted to the edge of the patch reef, where the steepest slopes are present. This particular type of coral is commonly found at these greater depths; however it has also been mapped in areas as shallow as thirty feet.

Deep Water Zone

Common organisms such as corals and sponges are extremely sensitive to environmental factors including, but not limited to, salinity, water temperature, turbidity, nutrient influx, and water depth. At the edge of the Red Buoy Patch Reef depths exceed 52 feet and visibility declines to approximately 1 foot signifying an increase in suspended materials (fig. 22).

Figure 20. Photograph illustrating the Massive Coral Zone. Photograph taken by Frederic Charpentier, Ottawa, Canada.

Figure 21. Photograph illustrating the *Agaricia* Zone. This coral, commonly referred to as the plate coral, is the dominant species. Photograph taken by Frederic Charpentier, Ottawa, Canada.

The common reef organisms mentioned above cannot exist beyond this point, and the area is therefore characterized by a muddy region dominated by mounds of burrowing organisms and coiled, whip-like antipatharians (fig. 23).

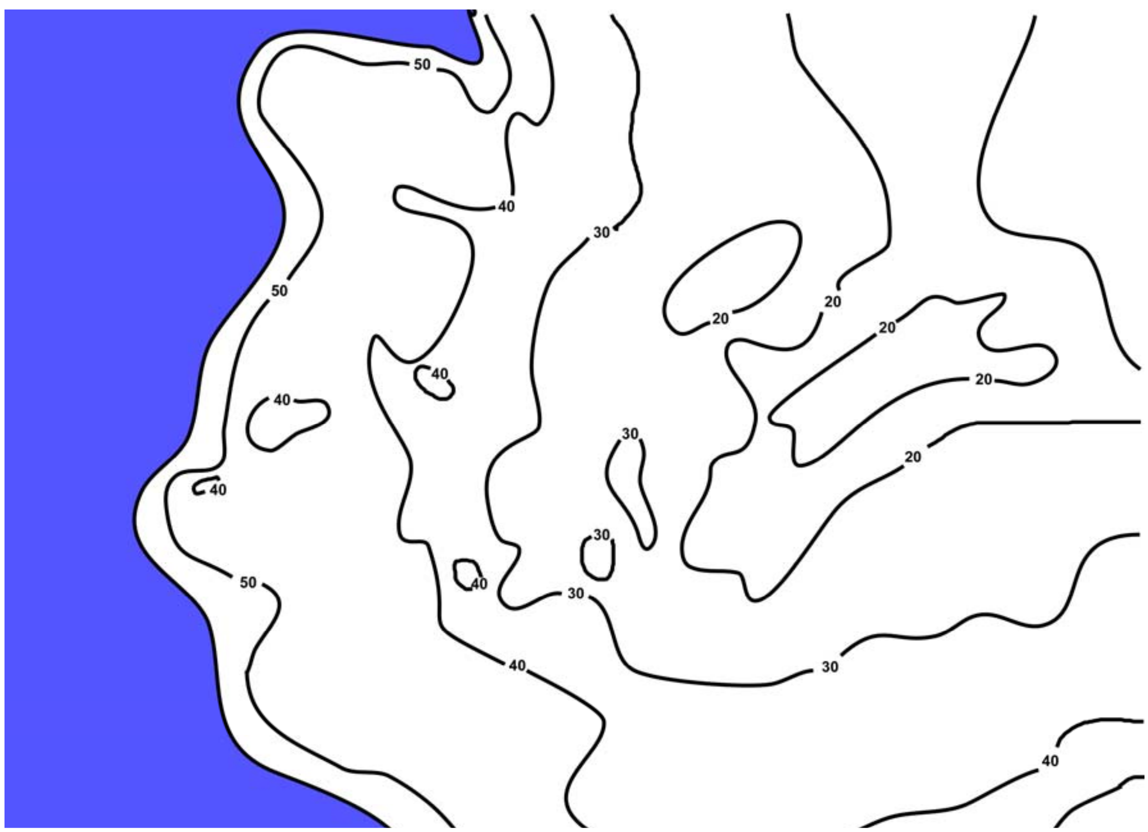

Figure 22. Bathymetric map of the Red Buoy Patch Reef. The part shaded (in blue) signifies the edge of the reef where the Deep Water Zone is located.

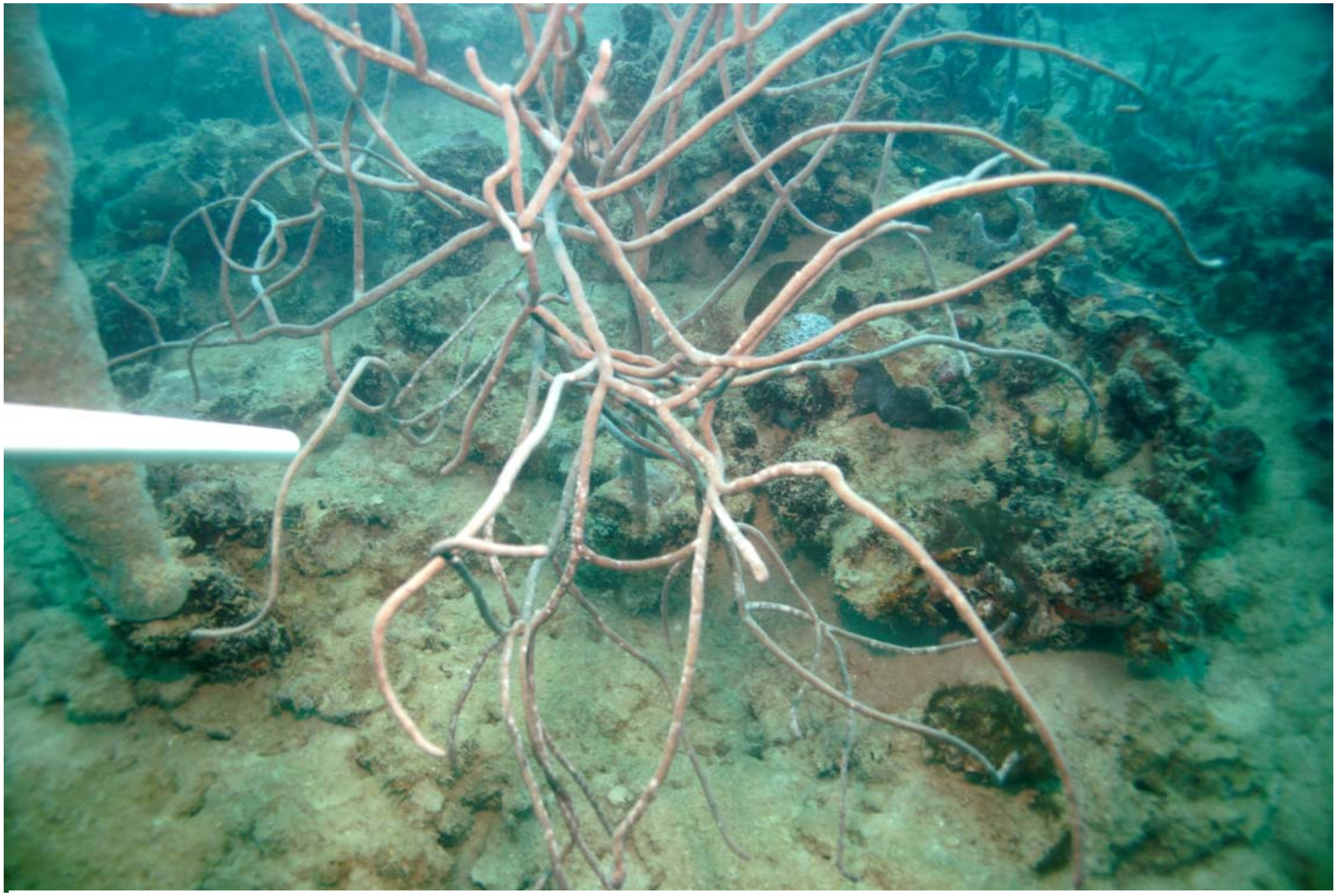

Figure 23. Photograph illustrating the Deeper Water Zone. Photograph taken by Frederic Charpentier, Ottawa, Canada.

Zonal Distribution

Earliest work done on the Red Buoy Patch Reef by Bonem and Stanley (1977) concluded that the six recognized biotic zones appeared to parallel depth contours. Exceptions in this trend, however, were recognized in the *Madracis* and Mixed Sponge Zones. Nash (1982) and others since then recognized the distributions of these two zones ranging in depth from 20 to 50 feet. Unlike the lateral continuity of the *Agaricia* and Massive Coral Zones, the distributions of the *Madracis* and Mixed Sponge Zones appear to be patchy and irregular. It is believed that this zone was more continuous in the past, but blasting for the ship channel left isolated pockets of *Madracis*.

Most zonal boundaries appear to be distinct and stationary with relatively few exceptions. Any overlap and transitions within zones may be recognizable when the zonal distributions from previous years are compared to the present (figs: 24, 25, 26, 27, and 28). The most obvious zonal change occurs between the Mixed Sponge, Massive Coral, and *Agaricia* Zones. One explanation for this trend may be that many of the same organisms are found within these zones (such as sponges and massive corals).

In contrast to transitional zonal boundaries, the biotic assemblages of the *Porites* and *Madracis* Zones are more stationary. The *Porites* Zone is always identified in the shallow water on the flat top of the bank where light penetration and water circulation are at an optimum. The *Madracis* Zone (characterized by patches of *Madracis mirabilis*) is generally associated with upwellings of brackish water springs. These patches of *Madracis mirabilis* are located on topographic highs where water circulation is typically increased. The biotic zonation of the Red Buoy Patch is controlled by specific environmental factors.

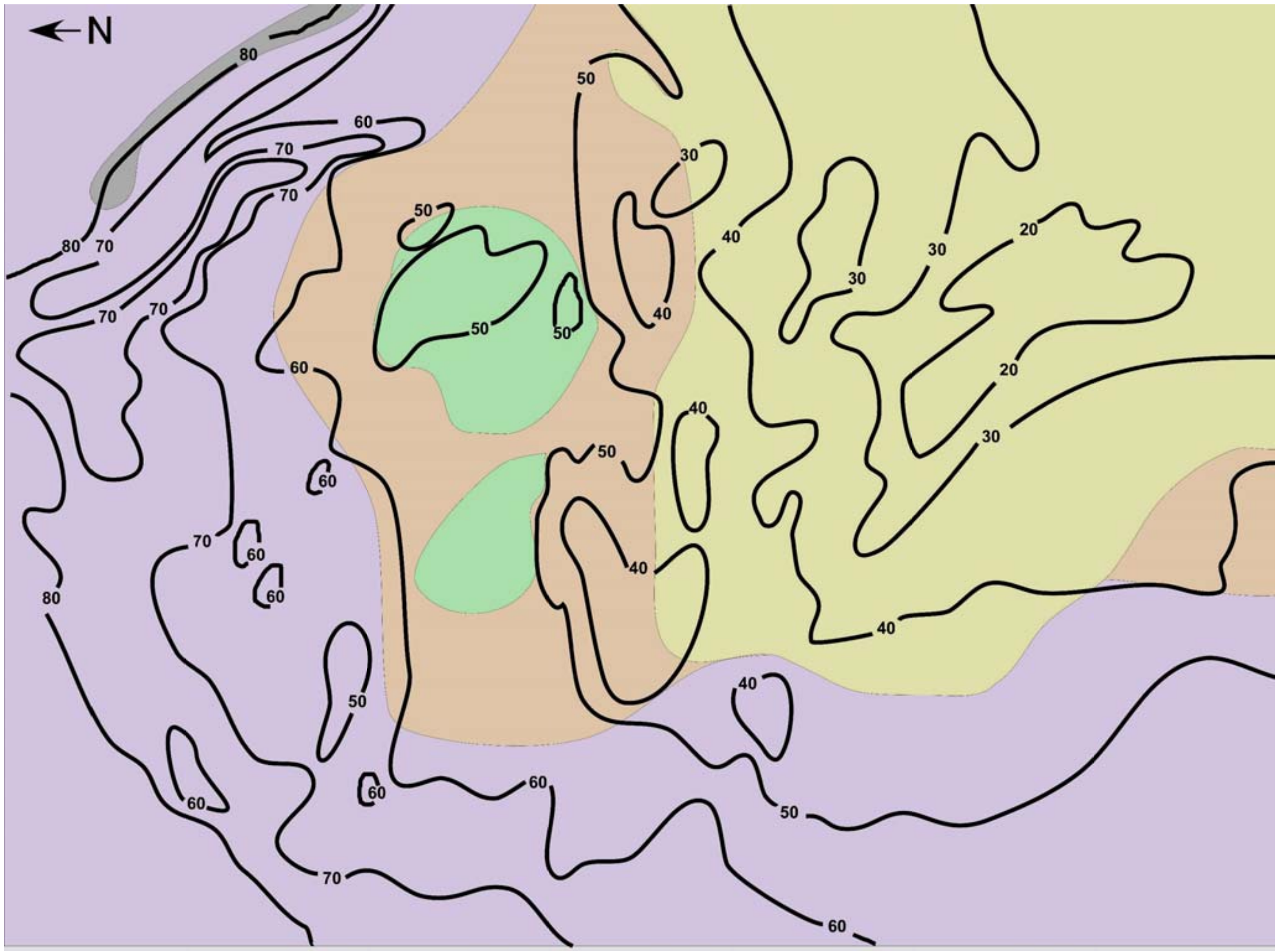

Figure 24. Bathymetric map of the Red Buoy Patch Reef recorded in feet from 1974. Biotic zones have been overlaid on the bathymetry and consist of the <u>*Porites*</u> Zone (yellow), the <u>*Madracis*</u> Zone (green), the Massive Coral Zone (purple), the Mixed Sponge Zone (orange), and the <u>*Agaricia*</u> Zone (dark grey).

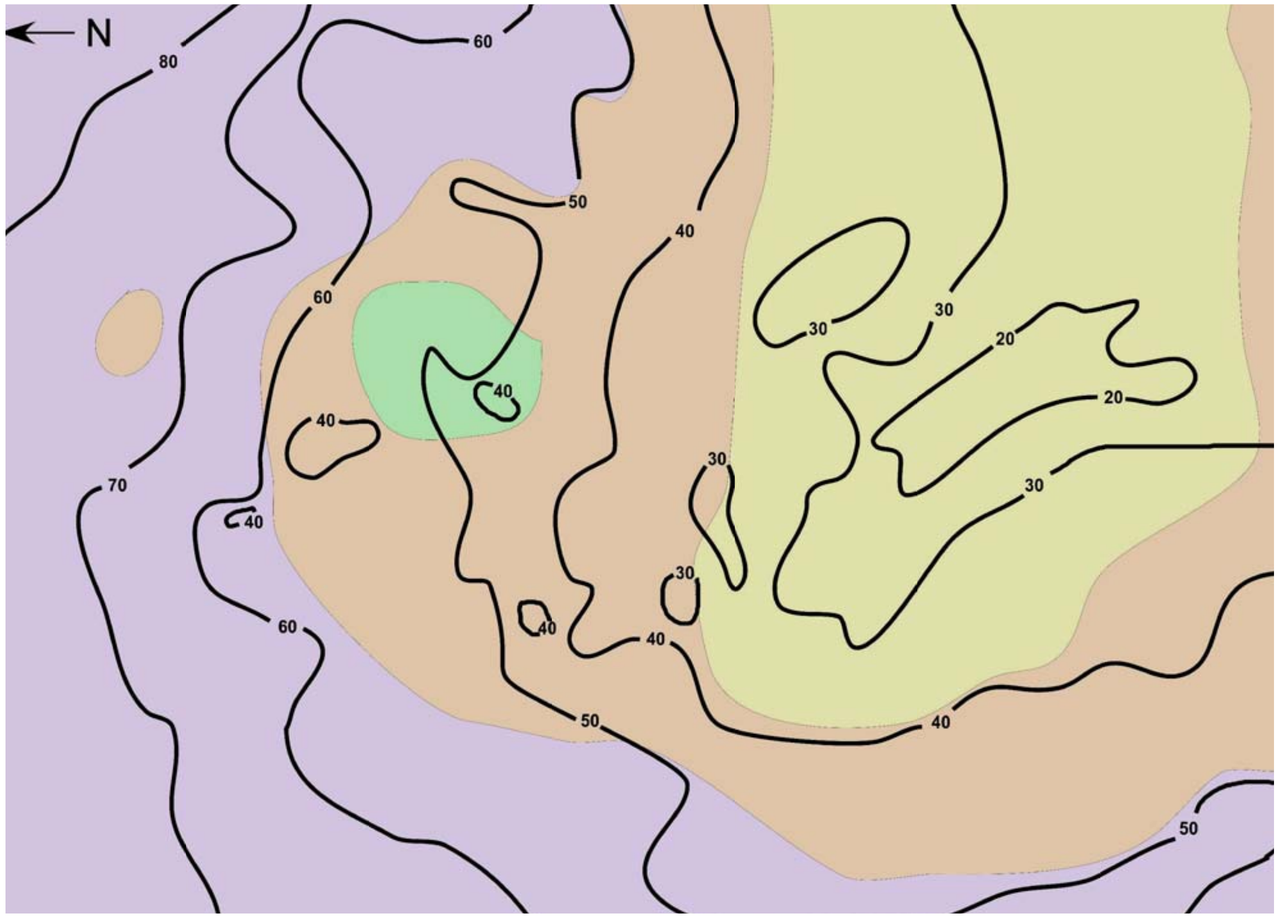

Figure 25. Bathymetric map of the Red Buoy Patch Reef recorded in feet from 1978. Biotic zones have been overlaid on the bathymetry and consist of the *Porites* Zone (yellow), the *Madracis* Zone (green), the Massive Coral Zone (purple), and the Mixed Sponge Zone (orange).

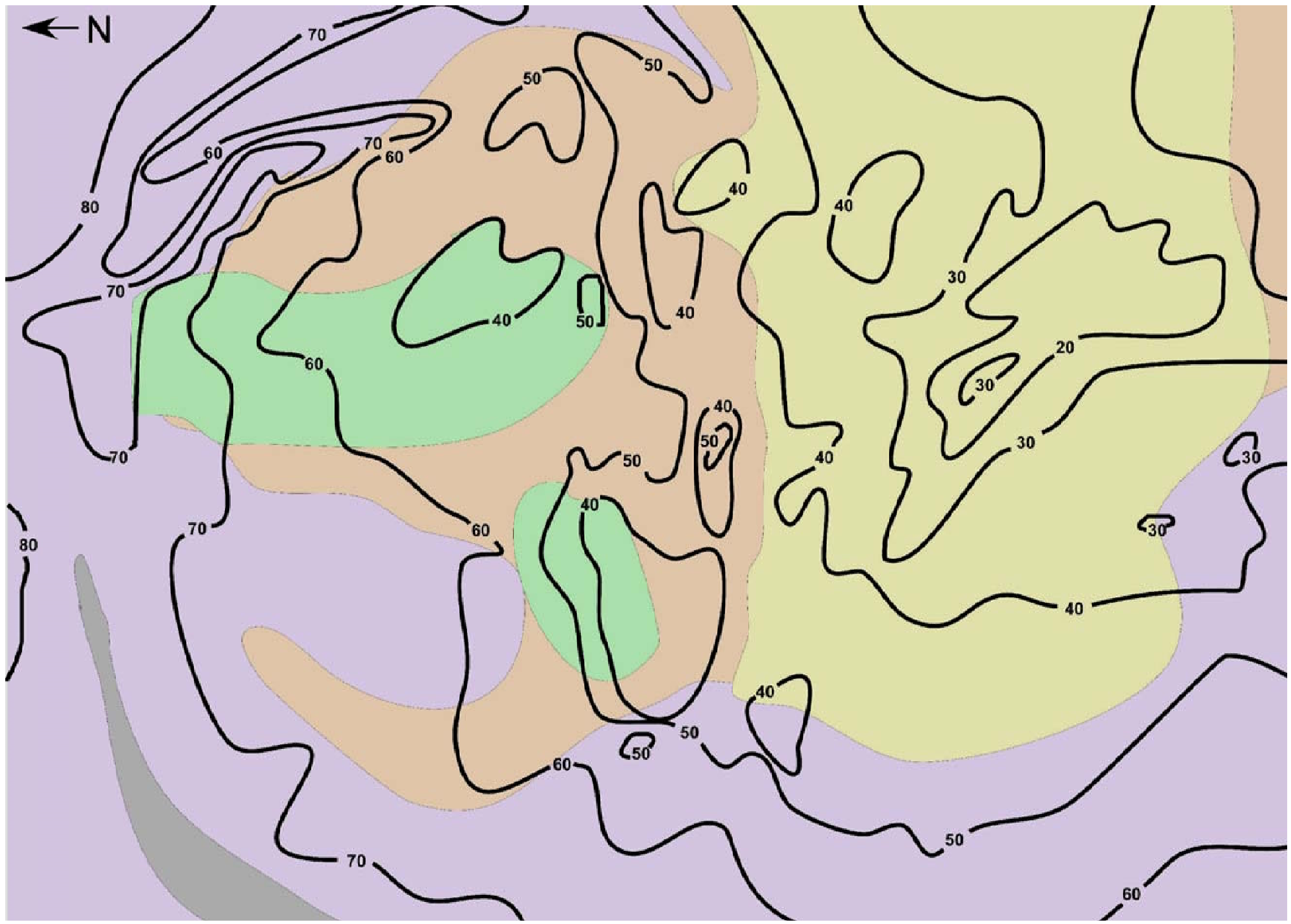

Figure 26. Bathymetric map of the Red Buoy Patch Reef recorded in feet from 1980. Biotic zones have been overlaid on the bathymetry and consist of the *Porites* Zone (yellow), the *Madracis* Zone (green), the Massive Coral Zone (purple), the Mixed Sponge Zone (orange), and the *Agaricia* Zone (dark grey).

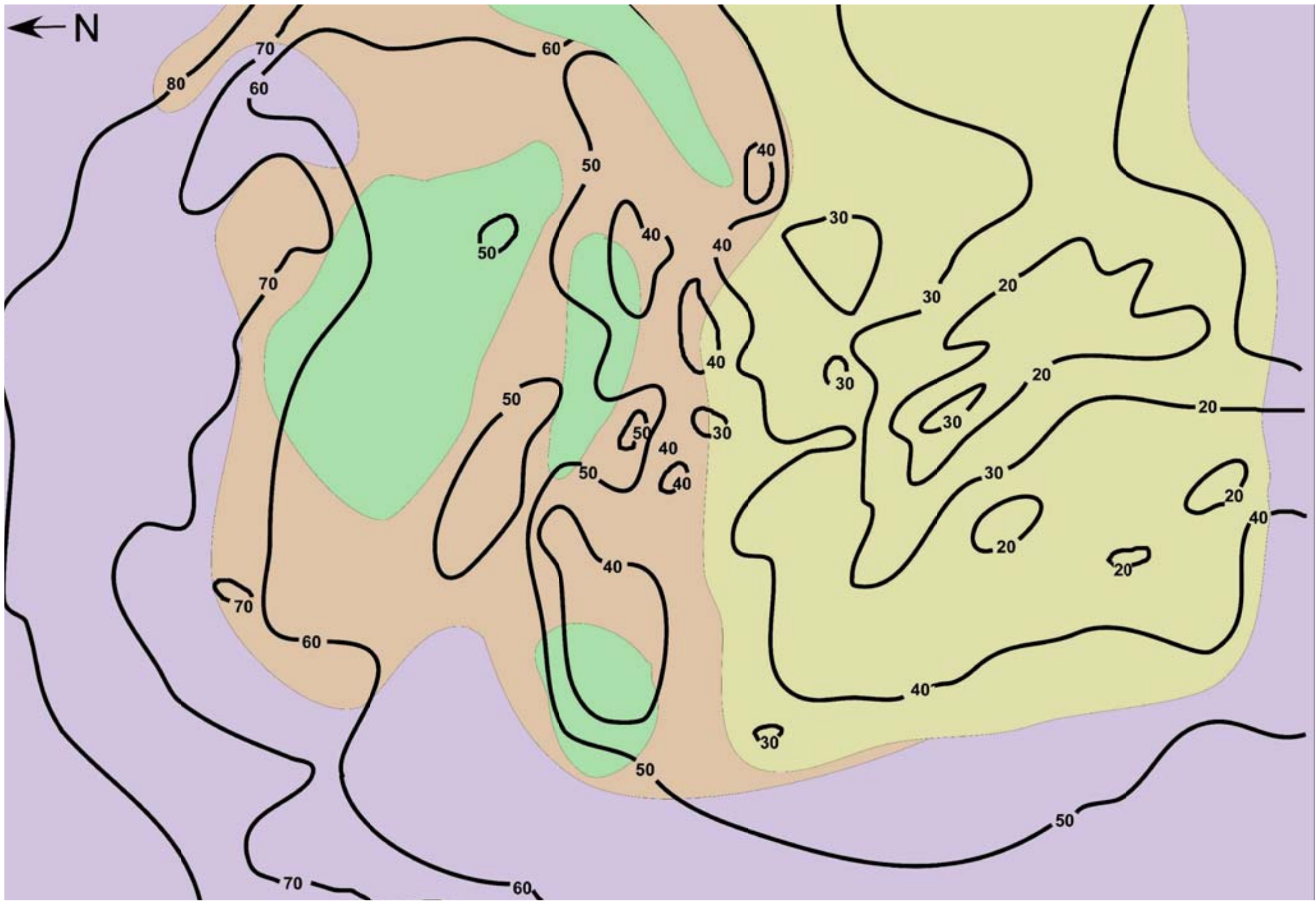

Figure 27. Bathymetric map of the Red Buoy Patch Reef recorded in feet from 1981. Biotic zones have been overlaid on the bathymetry and consist of the <u>*Porites*</u> Zone (yellow), the <u>*Madracis*</u> Zone (green), the Massive Coral Zone (purple), and the Mixed Sponge Zone (orange).

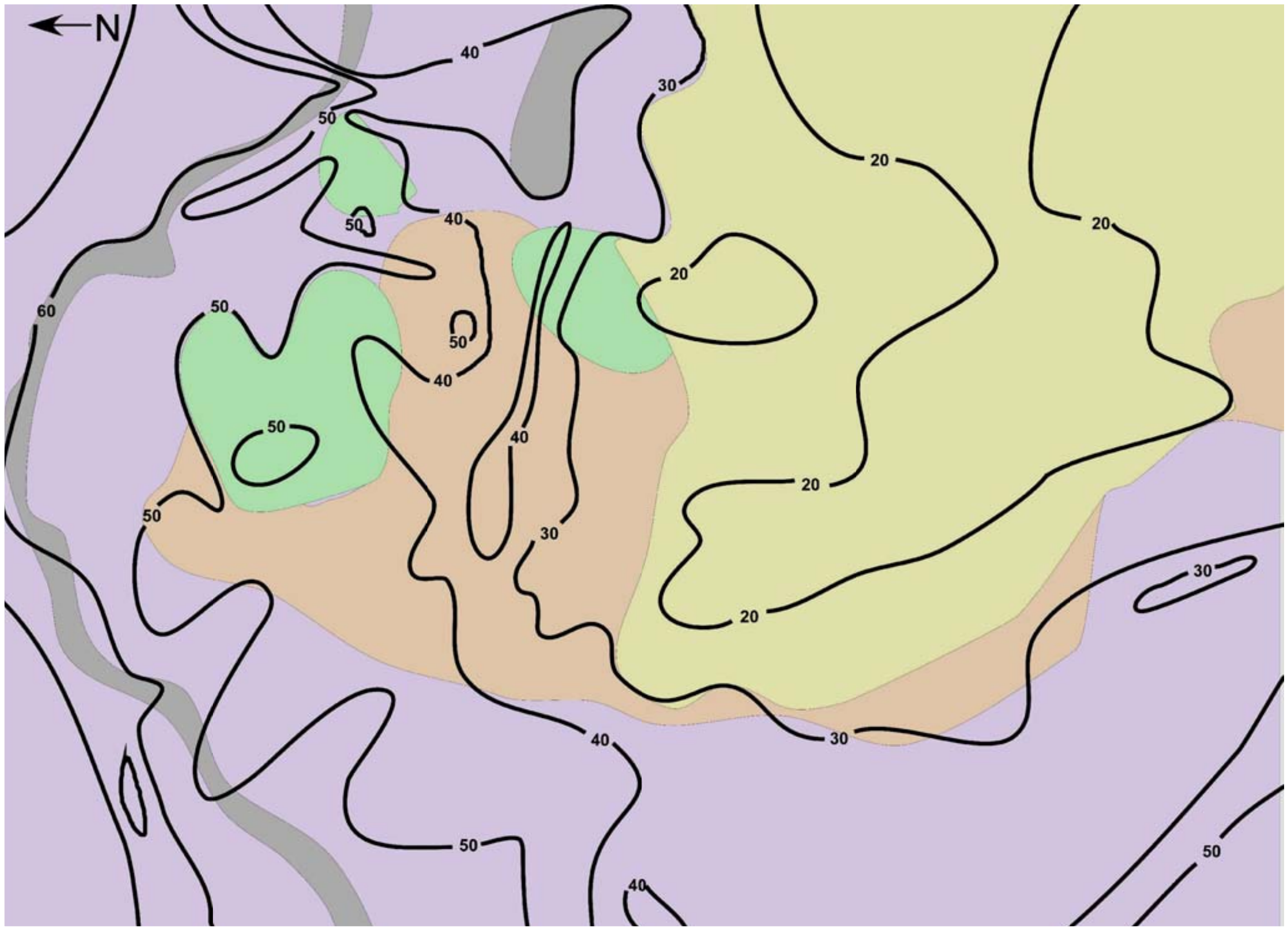

Figure 28. Bathymetric map of the Red Buoy Patch Reef recorded in feet from 1982. Biotic zones have been overlaid on the bathymetry and consist of the _Porites_ Zone (yellow), the _Madracis_ Zone (green), the Massive Coral Zone (purple), the Mixed Sponge Zone (orange), and the _Agaricia_ Zone (dark grey).

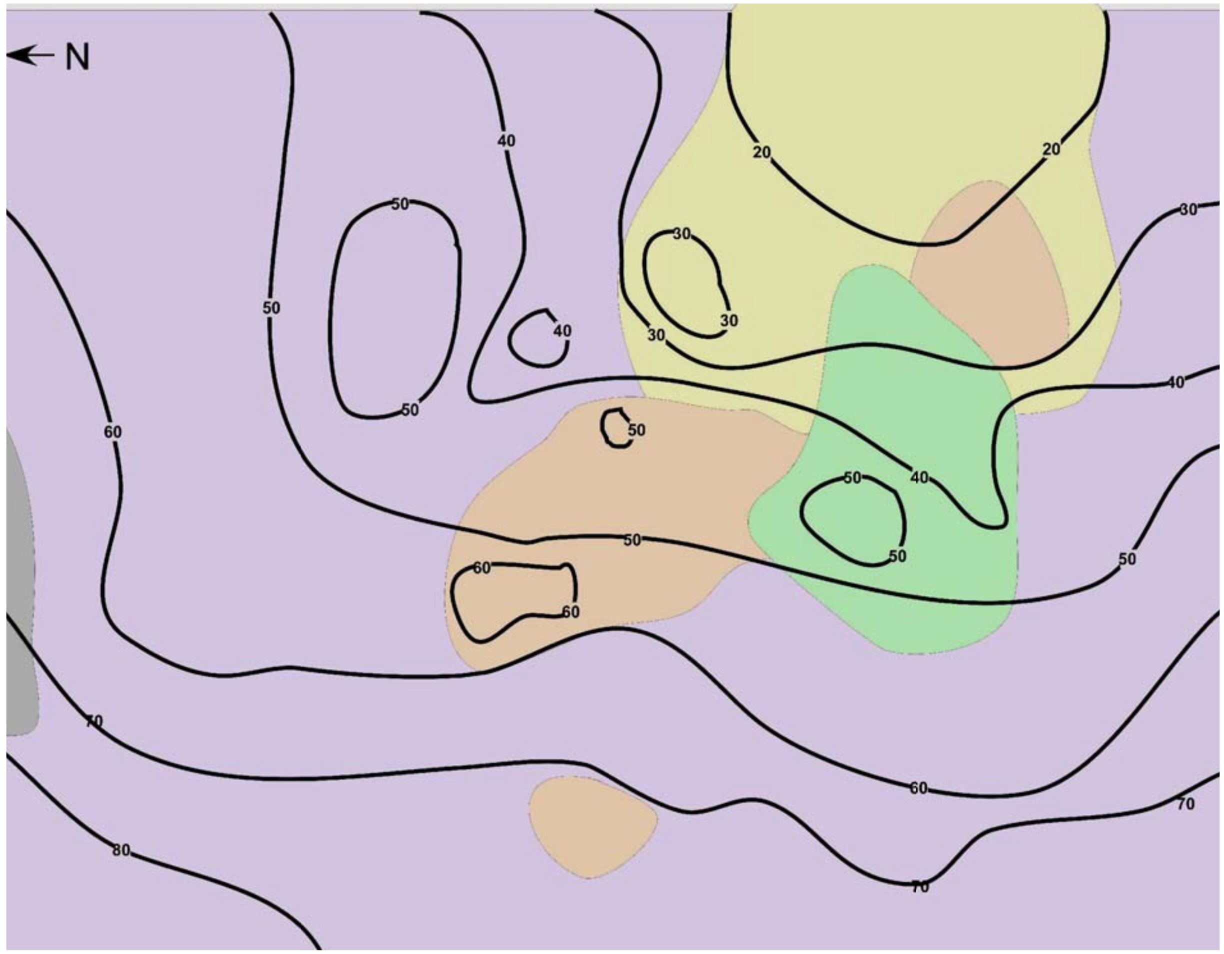

Figure 29. Bathymetric map of the Red Buoy Patch Reef recorded in feet from 2005. Biotic zones have been overlaid on the bathymetry and consist of the _Porites_ Zone (yellow), the _Madracis_ Zone (green), the Massive Coral Zone (purple), the Mixed Sponge Zone (orange), and the *Agaricia* Zone (dark grey).

CHAPTER SIX

Results

Sediment Composition

In addition to recognizing the biotic assemblages present in each of the zones, characterization of the sands in these zones has also been carried out. To determine the composition of the sand, a compositional analysis, determined by point counting 200 sand-sized grains, should reflect the relative proportions of the sediment-producing organisms in each zone. Analyzing surface sediment samples and comparing them to cores taken in 1982 will demonstrate these shifts in biotic zonation. Any changes in zonation that have occurred since the core description from Nash in 1982 will be reflected by a change in sediment composition.

Ten surface sediment samples were collected in locations where core had been extracted in 1982. An eleventh sample was also taken at approximately 90 feet on the forereef for comparison with the backreef. In the lab, compositional percentages were determined for six major constituents: arthropods, echinoderms, worms, corals, mollusks, and *Halimeda*. Particles other than those listed were either unidentifiable due to weathering or produced by organisms too small a percentage to have their own category. These constituents were placed in the category "miscellaneous" and include grains of bryozoans, forams, sponge spicules, and other unidentifiable grains. The point count data of all eleven samples are listed in Table 1 of Appendix A. It is noted that there is a large amount of local variability in the sediment which is caused by the patchy distribution of the living source material and the mixing of sediment from bioturbation (Nash, 1982).

However, each biotic zone is typified by a unique assemblage of sediment composition, which can be recognized throughout the core sample. It has been demonstrated that a ternary compositional diagram effectively discriminates between the different biotic zones (fig. 30). This diagram, from Nash (1982) was constructed using the sum of the percent abundance of corals as compositional end member A; the sum of *Halimeda* and other minor grains as end member B; and the percent abundances of mollusks for end member C. These percent abundances were determined from the cores samples extracted in 1982. The variability of sediment composition in each zone is apparent and the overlap of boundaries demonstrates the transitional nature of these zones on the patch reef.

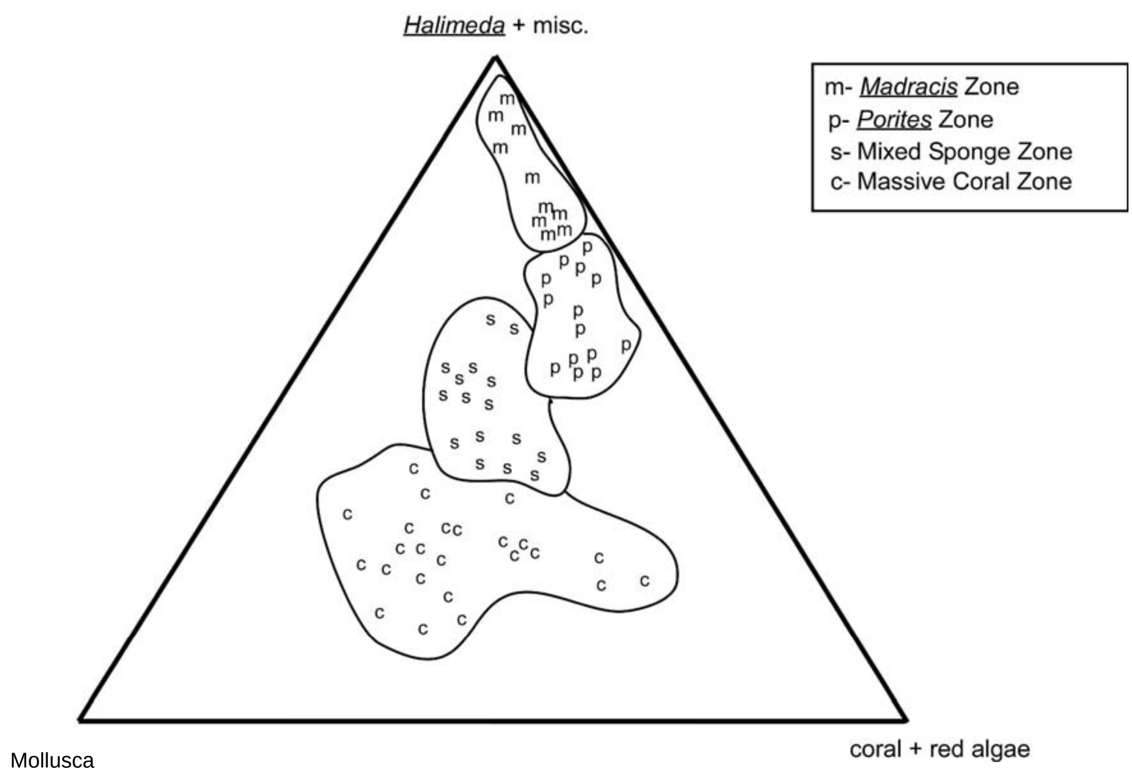

Figure 30. Ternary diagram of the sediment composition at the Red Buoy Patch Reef (modified from Nash, 1982).

Madracis Zone

This zone is easily distinguishable on its relative abundance of *Halimeda* which ranges from 40 – 50 percent (fig. 31). These high numbers give it the greatest amount of *Halimeda* grains than any other zone. The *Madracis* Zone is almost entirely dominated by *Halimeda* grains and appears to be relatively stationary throughout the core sample (Nash, 1982). This characteristic is observable with this zone's distinct boundaries and very little overlap occurring with other zones. This zone also demonstrates a variable abundance of encrusting algae as seen in the core samples. Increases in *Halimeda* coincide with decreases in red algal content.

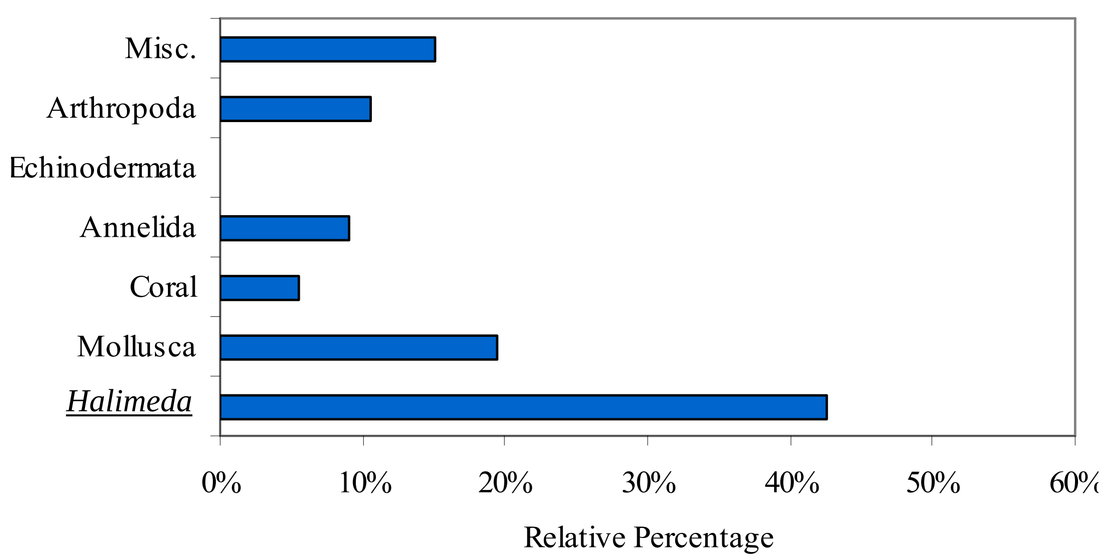

Figure 31. Relative abundance of grain composition of a sediment sample taken at 66 feet from the mooring on the East transect in the *Madracis* Zone in 2006.

Porites Zone

The most abundant constituent is *Halimeda* (20 -30 percent) and some of the least abundant are the corals and mollusks (5 - 20 percent). Nash (1982) demonstrates that as the percent abundance of coral increased, the abundance of mollusks decreased. The compositional trends of the core analysis also demonstrate that an overlap in sediment composition exists between the *Porites* Zone and the Mixed Sponge Zone. The surface sediment analysis for 2006 demonstrates similar trends in overlapping between the *Porites* Zone and the Mixed Sponge Zone.

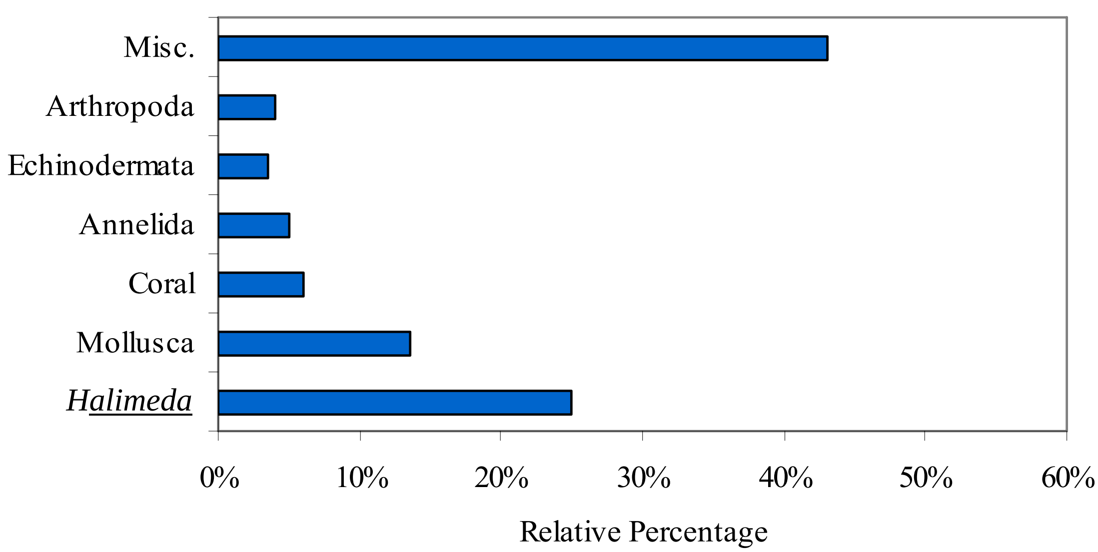

Figure 32. Relative abundance of grain composition of a sediment sample taken at 33 feet from the mooring on the East transect in the *Porites* Zone in 2006.

Mixed Sponge Zone

In both the core analysis and the 2006 sediment analysis, the Mixed Sponge Zone appears to be the most diverse with respect to sediment composition (fig. 33).

Conclusions from examining the surface sediment sample include that the Mixed Sponge Zone is a transitional phase that is compositionally intermediate between the *Porites* Zone and the Massive Coral Zone. The composition of the most recent sediment sample is characterized with an even distribution of *Halimeda* and mollusk grains (both at approximately 23 percent). Arthropods, worms, and coral constituents comprise less than 30 percent of the sample .

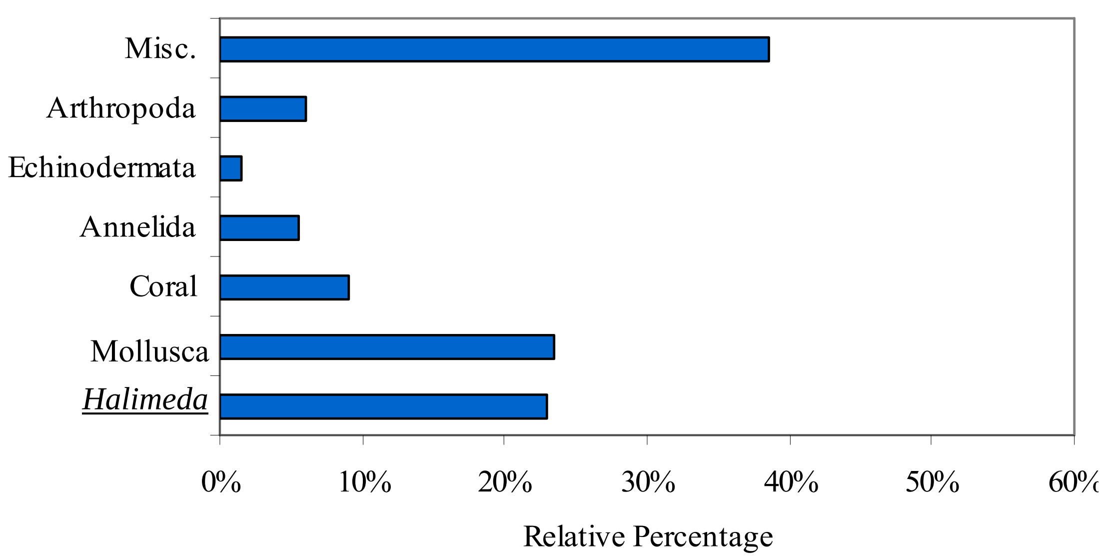

Figure 33. Relative abundance of grain composition of a sediment sample taken at 82 feet from the mooring on the West transect in the Mixed Sponge Zone in 2006.

Massive Coral and Agaricia Zones

The boundary between the Massive Coral and *Agaricia* Zones is defined solely by the abundance of different coral species. In the sediment point count, coral species were not identified; therefore distinguishing between these two on the basis of composition does not seem possible. The abundance of coral is the most distinct characteristic of these zones and ranges from 5 - 10 percent in the sediment sample (fig. 34). The mollusk content ranges from 20 - 30 percent, and the *Halimeda* content ranges from 40 – 50 percent. These relative percentages have remained relatively stable throughout the core samples, allowing for easy recognition of these zones in the core (Nash, 1982).

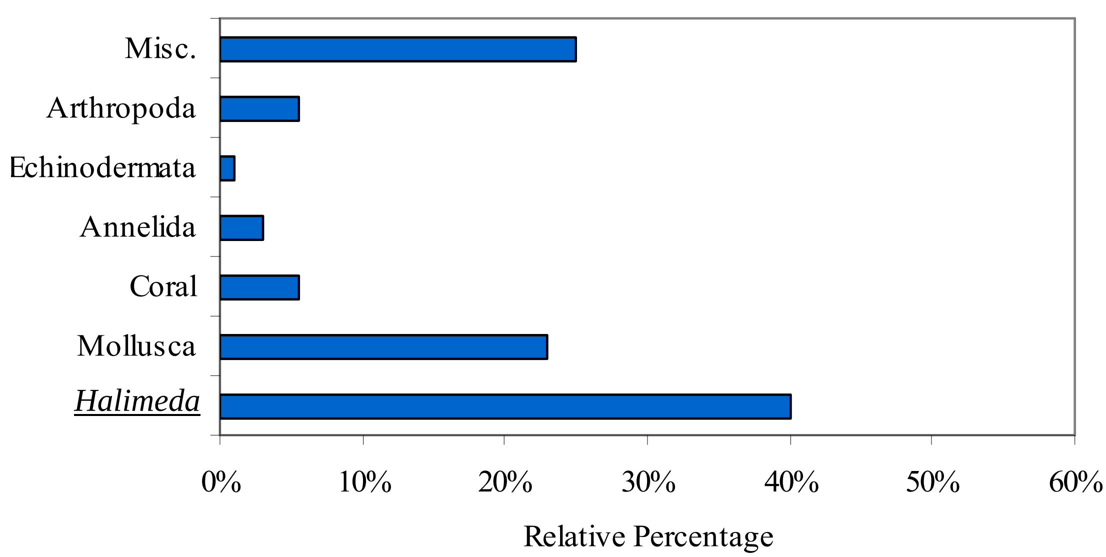

Figure 34. Relative abundance of grain composition of a sediment sample taken at 50 feet from the mooring on the West transect in the Massive Coral Zone in 2006.

Sediment Texture

The grain size of the eleven samples collected on the Red Buoy Patch Reef was analyzed using standard statistical techniques. These statistical measures were first introduced by Folk and Ward (1957) who recognized the relationship between grain-size statistics and depositional environment. Both graphic and statistical methods of data representation have been developed for the interpretation of grain size analysis.

The first parameter is a measurement of central tendency. The median grain size is the grain size that separates 50 percent of the sample from the rest of the sample (Folk & Ward, 1957). The second statistical parameter is the degree of scatter or the sorting of the sediment. Sorting is defined by the standard deviation of the sample grain size distribution. The third statistical parameter is the degree of “peakedness” of the curve when the cumulative percentage of grain size is plotted against phi on a cumulative probability curve. This degree of peakedness is defined by the kurtosis of the sample. The fourth property of statistical sediment analysis is the curve’s skewness, or degree of asymmetry.

When computing grain size statistics, the calculations and graphic representations are much simpler when phi intervals are used rather than microns or millimeters. One phi unit is equal to one Udden-Wentworth grade. The phi diameter is computed by taking the negative log of the diameter in millimeters. These parameters were computed for each of the samples, and their values are listed in Table 2.

Table 2. Statistical grain-size analysis for surface sediment samples taken along transects A and B (fig. 13) across Red Buoy Patch Reef.

Sample ID	Mean	Sorting	Skewness	Kurtosis
Massive Coral Zone (1)	Medium Sand	Poor	Very Fine	Platykurtic
Massive Coral Zone (2)	Medium Sand	Poor	Very Fine	Mesokurtic
Madracis Zone (3)	Fine Mud	Medium Sorting	Symmetrical	Very Platykurtic
Madracis Zone (4)	Medium Mud	Medium Sorting	Very Fine	Platykurtic
Mixed Sponge Zone (5)	Fine Sand	Poor	Very Fine	Platykurtic
Porites Zone (6)	Fine Sand	Medium Sorting	Very Coarse	Very Platykurtic
Porites Zone (7)	Very Fine	Medium Sorting	Very Coarse	Platykurtic
Mixed Sponge Zone (8)	Medium	Poor	Very Fine	Platykurtic
Mixed Sponge Zone (9)	Fine	Poor	Very Fine	Very Platykurtic
Agaricia Zone (10)	Very Fine	Poor	Very Coarse	Very Platykurtic
Forereef	Medium Sand	Poor	Fine	Platykurtic

Mean Grain Size versus Sorting

Mean grain size is a function of the size range of the available material and the current strength of the transporting water. Sorting is also a function of the type of deposition and the strength of the currents. A scatter plot of these two statistics, mean grain size and sorting, shows a curve that supports Folk's sinusoidal relationship between size and sorting (fig. 35). This figure shows that particular size modes define particular biotic zones. It is possible that a change in texture might indicate a change in zonation.

Due to limited water circulation in the lagoonal environment, patch reef sediments are moderately sorted at best (Folk, 1974). The best sorted sediments at the Red Buoy Patch Reef occur in the *Madracis* Zone. These sediments are also the coarsest sediments found on the reef as seen by the abundance of *Halimeda* plates and coral rubble from the sediment samples. This grain size distribution is caused by sorting from the upwelling of submarine springs. The heavy *Halimeda* plates are blown up and deposited while the mud is dispersed. The most poorly sorted sediments occur in the Mixed Sponge Zone. This poor sorting is a reflection of the variable size of sediment produced by the organisms (sponge and coral) and the lower energy found in this zone.

As grain size decreases, the sediment appear to become progressively better sorted. Sorting appears to become better transitioning up through the *Agaricia* Zone, to the Massive Coral Zone, and finally the *Porites* Zone. The *Porites* Zone is composed of the coarsest sediments and appear to be better sorted than the *Agaricia* and the Massive Coral Zones.

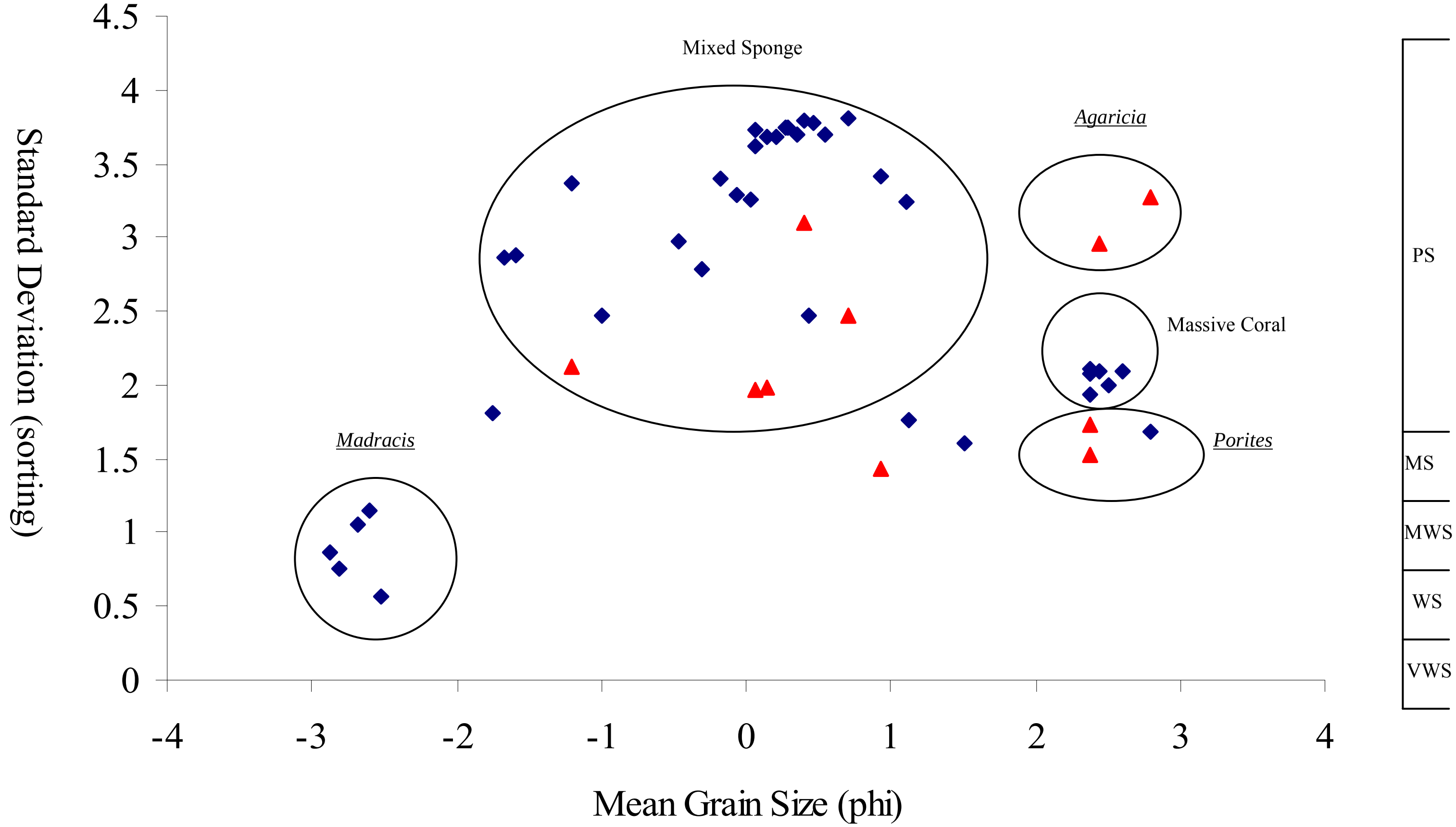

Figure 35. Scatter diagram of the phi mean grain size versus the phi standard deviation (sorting). VWS- very well sorted; WS- well-sorted; MWS- moderately well-sorted; MS- moderately-sorted; PS- poorly sorted. The diamonds represent data from Nash (1982) and the triangles represent data collected in this study from 2006. The large circles represent distinct biotic zones as labeled on the figure.

Skewness versus Kurtosis

Skewness and Kurtosis are measures of how closely a grain size distributions approaches the Gaussian probability curve (Folk, 1974). The more extreme the values, the more abnormal the distribution. A scatter plot of skewness versus kurtosis using values from the core samples as well as the loose sediment samples are shown in Figure 36.

Negative skewness, such as that in the *Porites* Zone, can result from the winnowing of the fine materials (Duane, 1964). Negative skewness can also results from the addition of coarse material to the sediments (Jordan, 1973). The abundant rubble found in the *Porites* Zone contributes significantly to the coarse material. The rubble and winnowing both result from the high energy of the water in this zone.

The positive skewness see in the *Madracis* Zone is an indication that little winnowing of fine material occurs in this zone. The large patches of *Madracis mirabilis* act as baffle, trapping material between the corals. In addition, the *Mirabilis* Zone also occurs at the greater depths that on the *Porites* Zone, where the wave action and the water turbulence is reduced.

Between the *Madracis* and *Porites* Zones, sediments of the *Agaricia* and Massive Coral Zones are found. These sediments show the smallest values of skewness, ranging from slightly negatively skewed to slightly positively skewed. Due to the depth of water in which these two zones are found, it is doubtful that any winnowing of fine material occurs. The Massive Coral heads do not readily fragment into gravel and sand-sized grains and therefore contribute very little to the coarseness of the sediments. The coral fragments that do appear are either caused by the feeding of parrot fish on the coral heads or are transported from the *Madracis* and *Porites* Zones, as corals do not survive well in muddy environments; it is not unusual that these sediments do not display large values of positive skewness. The sediment in this area is also influences by hurricane activity which increases the fragmentation of grains.

The widest range in skewness is seen in the sediments of the Mixed Sponge Zone. This is caused by the variable sizes of the organisms that exist in this zone and their patchy distribution throughout the zone. This is also an indication that a great deal of variability in the water turbulence might exist in this area. As sponges are more adaptable to an instable environment, and their ability to filter feed is superior to that of corals, the sponges are able to occupy areas that are too unpredictable for corals.

The primary significance of kurtosis is as an indication of the normality of the sediment distribution. The kurtosis values shown in Table II are all less than one, indicating a platykurtic distribution (Folk, 1974). This means the tails of the distribution are better sorted than the tails of the distribution are better sorted than the central portion, which may result from a bimodal or polymodal grain size distribution.

Grain Size Distribution

To fully describe the sediment texture of the Red Buoy Patch Reef, the percentages of gravel, sand, and mud were determined for each sample. The gravel percentage consists of anything coarser than -1 phi, the sand percentage includes -1 phi to 4 phi, and the mud percentage equals anything finer than 4 phi. A ternary plot of these three components is shown in Figure 37. The percentages plotted on this diagram are listed in Table A3 of Appendix A. The samples cluster in the same groups relative to one another. These clusters can be identified, based on textural and compositional similarity, as one of the five biotic zones. Gravel is the dominant particle size in the *Madracis* Zone. This is caused by the abundance of *Halimeda* plates and coral debris in this zone. Sand is the dominant particle size in the *Porites*, Massive Coral, and *Agaricia* Zones. The Mixed Sponge Zone appears to have approximately equal portions of both sand and gravel. The largest percentage of mud is found in the *Porites* Zone, and to some extent in the *Agaricia* and Massive Coral Zones.

Compositional and Textural Trends

Investigations of possible textural and compositional trends that might occur across the reef could reveal any changes that are related to the water depths of the morphology of the reef.

Compositional Trends

The principle mechanisms of sediment transport on a patch reef appear to be normal wave action, storm turbulence, and upwelling of submarine springs. Generally, sand-sized particles are not as easily transported as are the silt and clay-sized particles. Sand-sized particles of *Halimeda* are the most abundant constituent found on the reef. The trend of the *Halimeda* distribution on the reef appears to be controlled by the lack of transportation of particles from the source area. *Halimeda* is most abundant in the shallow water of the *Porites* Zone and in the *Madracis* Zone. From these two areas the abundance of *Halimeda* has been observed to grow abundantly in the *Madracis* Zone amongst the corals. *Halimeda* also originates in the shallow waters of the *Porites* Zone on the west side of the reef.

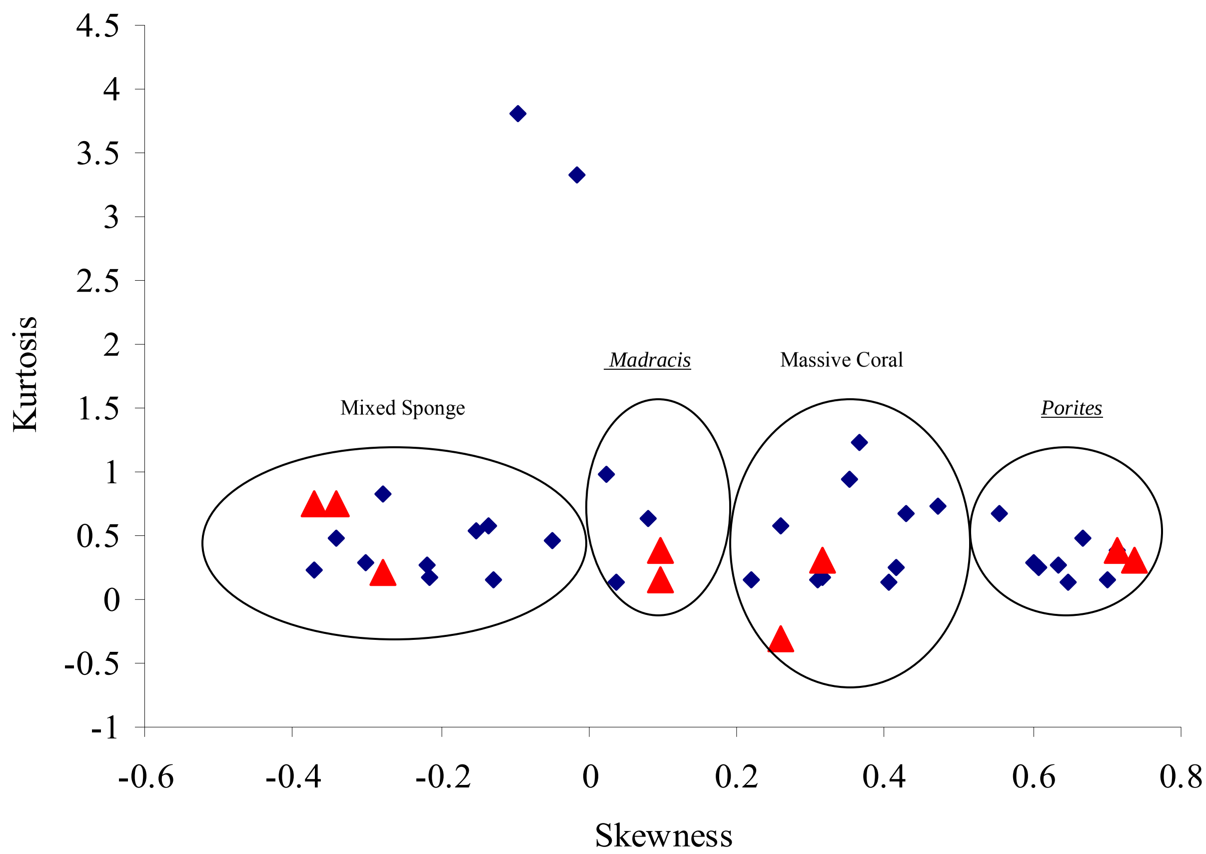

Figure 36. Scatter diagram of skewness versus kurtosis. Blue diamonds indicate plotted data from Nash (1982) and red triangles indicate data from 2006. The large circles represent identifiable biotic zones as labeled on the figure.

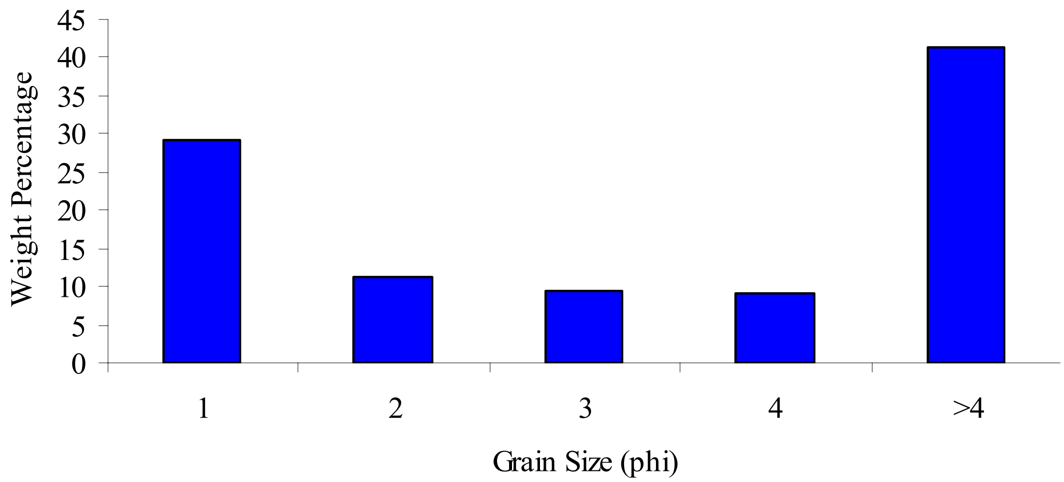

Figure 37. Grain size distribution for the <u>*Madracis*</u> Zone taken 50 feet from the mooring on the West transect.

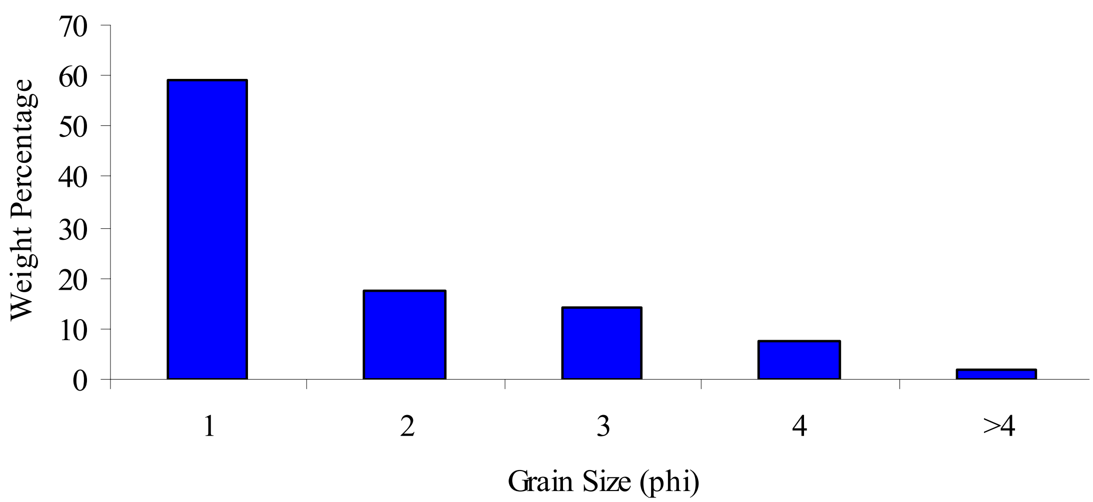

Figure 38. Grain size distribution for the <u>*Porites*</u> Zone taken 33 feet from the mooring on the East transect.

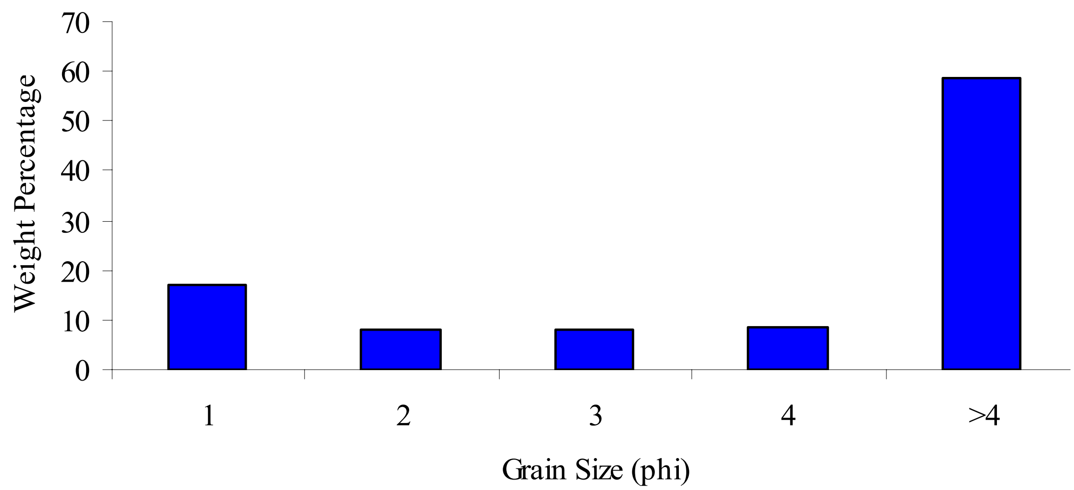

Figure 39. Grain size distribution for the Mixed Sponge Zone taken 82 feet from the mooring on the West transect.

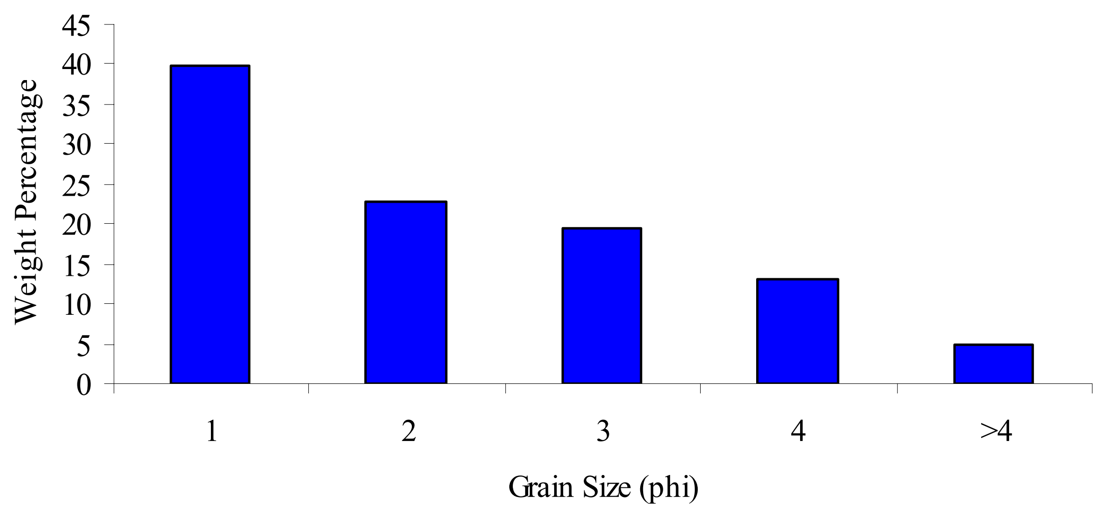

Figure 40. Grain size distribution for the Massive Coral Zone taken 66 feet from the mooring on the East transect.

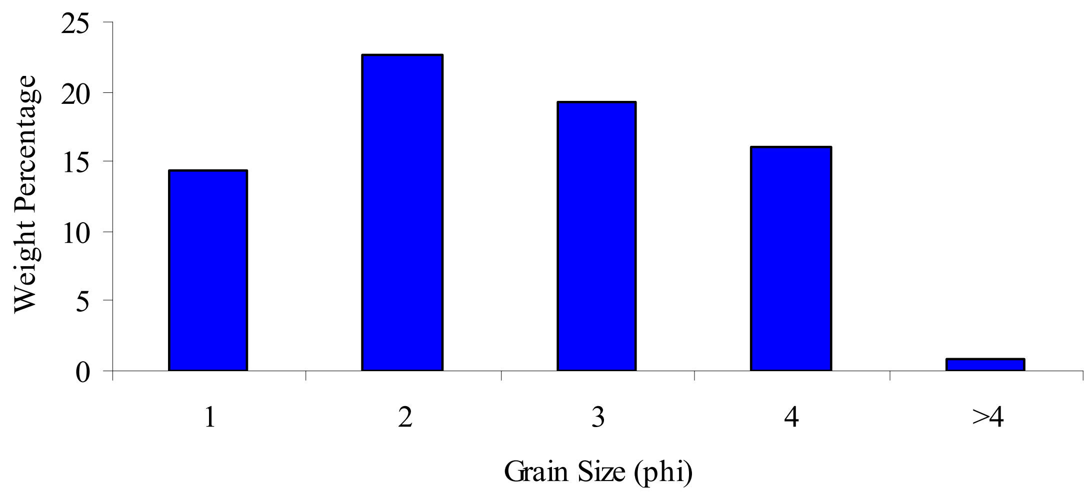

Figure 41. Grain size distribution for the _Agaricia_ Zone taken 20 feet from the mooring on the South transect.

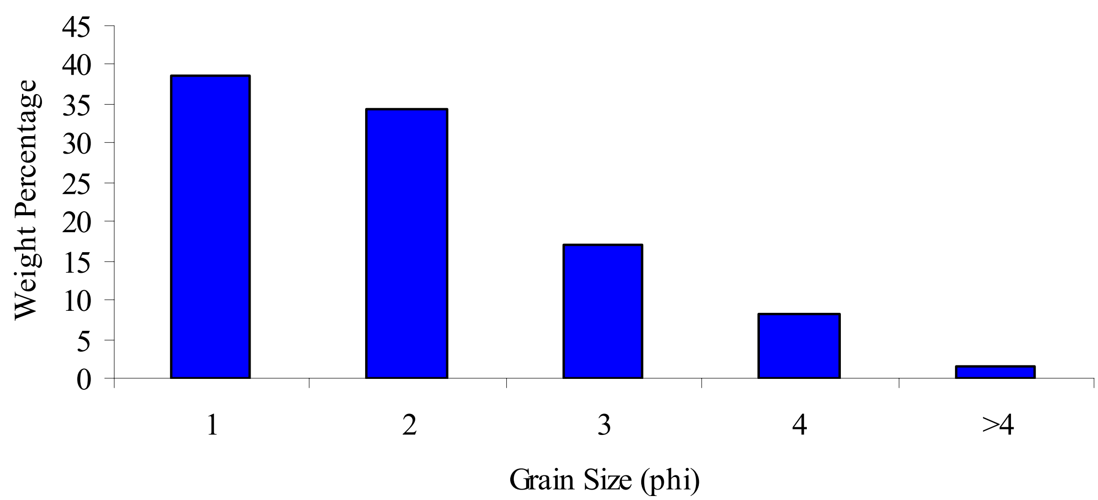

Figure 42. Grain size distribution for the Deeper Water Zone taken from a depth of 90 feet on the Forereef.

The distribution patterns of corals, mollusks, and encrusting red algae do not appear to be related to any transportation but instead vary with the location of the five biotic zones on the reef. This is significant in that it indicates that the deposition of these particular compositional components is in situ, unaffected by transporting mechanisms on the reef.

Textural Trends

The distribution of mean grain size and sorting across the reef for five successive time periods is shown in Figure 37. In deeper water areas, changes in mean grain size are directly proportional to changes in sorting. However, in shallower waters regions, the relationship between mean grain size is inversely proportional to sorting.

The shallower regions illustrate the most obvious changes in mean grain size and sorting. These changes indicate that shallower regions are affected more severely by storm turbulence than deeper portions. During periods of strong water turbulence, a great deal of debris and rubble from the corals is added to the sediment along with a large amount of fine material carried in by the rain run-off. Both of these factors combine to generally coarsen the grain size and to decrease the sorting. During normal time periods, water turbulence is not nearly as destructive, and sorting improves by normal wave action.

As seen in previous diagrams, the trends of mean grain size and sorting on the reef are complex and do not correlate strictly with the amount of water turbulence or depth. Another factor influencing the trend of sorting and grain size is known as the Sorby Principle of Particle Breakdown (Folk and Robles, 1964). This principle states that the statistical modes for particle sizes produced by their breakdown are controlled by the macrostructure and microstructure of the particle type. Therefore, the abundance of particular grain sizes is partially controlled by the abundance and structure of the dominant skeletal types in the zone. The trends of phi mean grain size and sorting seem to depend primarily on the distribution of the biotic zones on the reef.

CHAPTER SEVEN

Distribution of Biotic Zones through Time

Distribution

Environmental factors differ across the reef causing the various distributions of the biotic zones. These controlling factors include: water depth, wave energy, turbidity, temperature, salinity, dissolved oxygen, and substrate.

It was discussed by Wallace and Schafersman (1977) that these differences in zonation reflect the stability of the environment. It has also been discussed that corals develop in a succession related to their level of aggression (Lang, 1974). It is suggested that when the environment is conducive for coral growth and enough time has passed, massive corals such as *Montastrea annularis* and *Diploria* would eventually displace branching and finger corals such as *Porites porites*, *Porites asteroides*, and *Acropora*. Disturbances in the environment, such as hurricanes and other storm events, may restart the succession. By considering these factors, basic conclusions of the factors controlling the biotic zones can be drawn.

Madracis Zone

Madracis mirabilis thrives in areas where water circulation is good and water temperatures are somewhat colder than at the surface. These preferred conditions are typically found on the forereef of the fringing reef at depths around 50 -60 feet. On the Red Buoy Patch Reef, the distribution of *Madracis mirabilis* is irregular, occurring in spatially large patches on topographically high knolls. Around these knolls, water circulation appears to be somewhat better than the lower portion of the reef due to the upwelling of springs associated with these knolls. This particular coral appears to prefer the brackish, cooler water that emanates from the springs. Water circulation is also improved in these areas as a result of density currents that arise from the rising spring water. The growth characteristics of *Madracis mirabilis* results in very rapid growth of this coral allowing it to dominate and establish itself on the substrate before any other organism can establish itself. The observed substrates in this zone are relatively sandy rubble, similar to that of the *Porites* Zone.

Porites Zone

The *Porites* Zone is situated in very shallow water on the patch reef where extreme environmental variations occur. Given the shallow depth of this zone, storm events have been shown to cause abrupt changes in grain size and sorting due to the increased water energy. Constant series of storm events have transported sand to this zone giving this area a substrate consisting of sandy rubble. This zone is also directly adjacent to the shore allowing rain run-off to cause short-term variations in salinity, temperature, and turbidity, due to the influx of fresh, cold, sediment-laden rain water. Temperatures are normally higher in this zone given the shallow water. *Porites* is more capable of withstanding these higher temperatures than other corals in the area (Kinsman, 1964). This coral is one of the least aggressive in the area isolating it to an area where no other aggressive corals would dominate.

Mixed Sponge Zone

The distribution of this zone is the most variable and has shifted considerably throughout the history portrayed in the core samples. This is in part of the substrates that host this zone, which consist of either shifting sands on the steep slopes, or muddy sand in the low areas. The calculated textural statistics of the sediments collected in this zone indicate that this zone occurs in areas where the environment is extremely unpredictable. The flexibility of the sponge structure allows them to inhabit these areas where sand creep occurs on the step slopes of the reef bank. The Mixed Sponge Zone also occurs in topographically low areas that are protected from any constant current or wave action. The high percentage of suspended mud and mud in the fine-grained substrate is responsible for the dominance of sponge over corals (Bonem and Stanley, 1977). Massive corals are not completely excluded from these two areas; their distribution is sparse and patchy. Following the destruction of the Massive Coral Zone, sponges are the first to colonize and begin development in the area again.

Massive Coral Zone

Water depth and substrate stability determine the distribution of the corals in the Massive Coral Zone. The substrates that are found in this zone are generally muddy sands that provide a firm and stationary base for the corals to establish themselves and grow. The majority of corals found in this zone have the ability to handle the fine sediments. However, this zone is poorly developed in the soft muddy low lying areas where the water circulation is restricted. *Montastrea annularis* is dense in this zone, and is aggressive and capable of populating any area in which the conditions are favorable for its growth.

Agaricia Zone

This zone is dominated by the deep water scleractinian *Agaricia lamarcki*, whose distribution is related to depth and light intensity. The substrates found in this zone are similar to those found in the Massive Coral Zone. This zone is primarily found in areas where the light penetration is reduced by the increase in water depth and turbidity. Light penetration also appears to be an influential factor that prevents the infiltration of the corals found in the Massive Coral Zone. The dominant coral in this zone, *Agaricia*, appears to establish itself in areas where the slope is very steep.

At depths deeper than what is conducive for *Agaricia lamarcki* there lays the Deep Water Zone. Lower light penetration, decreased temperature, and reduced nutrient flux in this region contribute to the growth of antipitharians. These organisms are generally found deep on the forereef; however similar conditions are met at the base of the Red Buoy Patch Reef due to its muddy substrate.

The distribution of these zones is contributed to several environmental factors listed above. As these factors change, so too does the distribution of the biotic zones across the patch reef. The changes in distribution are clearly marked in the core samples by textural and compositional grain changes.

CHAPTER EIGHT

Comparison of Ecology and Sedimentation in Morrowan Bioherms with Modern Reefs

Site Location

The paleoecology and stratigraphic relations of bioherms occurring in the Lower Morrow Series in northeastern Oklahoma have been described and compared to modern patch reefs (Bonem, 1975). Exposures within the Lower Morrow sequence near Gore, Oklahoma (fig. 43) reveal a paleoecology that is similar to that of the modern Red Buoy patch reef previously described in Discovery Bay, Jamaica. The northeastern Oklahoma sequence includes marine limestones, shales, and sandstones with a well-preserved, diverse flora and fauna. Detailed biostratigraphy, including over 100 measured sections, has been conducted by Dr. Patrick Sutherland and Dr. Thomas W. Henry in the late 1970's and may be referenced for further details of this study site (Sutherland & Henry, 1975). Comparison of modern reefs with ancient is problematic for paleontologic interpretation. The scleractinian corals that currently form a significant portion of the framework of modern reefs do not exist in Paleozoic bioherms. However, the niches that they occupy were inhabited by other organisms. The Morrowan bioherms contain organisms which have similar functions as organisms found on modern reefs. This does not take into account, however, the large portion of reef biota that is not easily preserved in the fossil record. These organisms include sponges, noncalcareous algae, and bryozoans.

Lithostratigraphy

The Morrowan strata unconformably overlie Mississippian formations near Gore in northeastern Oklahoma. The unconformity decreases eastward into Arkansas as a result of tilting and differential Premorrowan erosion. North of Gore, on the Gore-Braggs Mountain High there is indication of up to 80 feet of relief on the erosional surface with a shallow basin lying to the northeast (Bonem, 1975). The Arkoma Basin is directly south of this site with its axis along the Choctaw Fault running eastward from Hartshorne, Oklahoma. The basis for division of the formations is a major regional unconformity that allows correlation with the Morrow strata of Arkansas.

The lowest member of the Sausbee Formation is the Braggs Member, consisting of limestones with minor sandstone, siltstone, and shale with a thin, locally developed, basal conglomerate. The Braggs Member has been interpreted by Bonem (1975) to have been deposited on a shallow carbonate platform. This platform falls rapidly into the Arkoma Basin.

Morrowan strata are exposed in a series of bands associated with elongated fault blocks that form a radial pattern around the southern part of the Ozark Dome. These strata are generally flat lying or dip gently south and southwest with dips exceeding three degrees only near radiating faults. These exposures are commonly capped by overlying resistant Atoka sandstones.

The bioherms described in this chapter occur in the Lower Morrow Group within the Braggs Member of the Sausbee Formation.

Paleoecology

Morrowan Bioherms

The Morrowan bioherm life assemblage is interpreted to have accumulated in place. The organisms do not appear to be current oriented or deposited as particulate material influenced by currents or waves. The bioherms have a boundstone framework that is formed by a variety of encrusting and cementing organisms and opportunistic accessory organisms such as rugose and tabulate corals that have found a stable substrate in the mound. The remains of organisms including trilobites, gastropods, nautiloids, and goniatites may have either been transported in the mounds after death or may have been part of the normal fauna associated with the mound given they show little evidence of transport. Many cavities within the bioherms contain transported debris, but there are also instances where organisms appear to have grown in place within cavities that were present during biohermal growth.

Mound Development

The mounds appear to begin development above skeletal lime wackestone. Sediment stabilization appears to be the first major problem of mound development. The lowermost layer of the Morrowan bioherms consists primarily of algal material. This was observed in three exposures in the higher mounding interval illustrating three successive stages in mound development. These exposures represent small mounds each underlain by a boundstone formed of stromatilitic bacteria and micrite. This stromatilitic bacteria binds sediment and grows upward while incorporating surface sediments forming a tough coating that stabilizes the sediment surface. This cyanobacteria not only forms a mat that is resistant to erosion, but also forms a stable substrate that is free of shifting sediments, even on a carbonate mud base. This mat then becomes a favorable habitat for other organisms to form. Thus, above the stromatolitic algae, a diverse assemblage of accessory organisms appears including rugose corals, fenestrate, arborescent, and encrusting bryozoans, and pediculate brachiopods.

The succession in the Morrowan bioherms begins with stabilization of the substrate by cyanobacteria. Most of the mounds in the quarry have a core of cyanobacteria, *Ottonosia*, and minor amounts of the red calcareous algae, *Archaeolithophyllum missouriensis*. The composition of the core may also be more complex incorporating other algal types including *Hedraites*-*Girvanella* and *Garwoodia*.

The mound core is overlain by a crust-like layer of bryozoans, either encrusting or fenestrate forms. These organisms further stabilize and prepare the substrate for habitation by other organisms including rugose and tabulate corals. Corals require a firm base for initial attachment, but as the colonies grow, they can obtain support by sinking into the soft cyanobacterial mud. Debris of bivalves and brachiopods seem to accumulate in irregularities on the bacterial or bryozoan crust. Many of the mounds exhibit a cyclic repetition of cyanobacteria and red encrusting algae. This may be a reflection of seasonal growth or sea level fluctuations.

Termination of mound development, according to Bonem (1975), appeared to occur when conditions no longer favored the growth of organisms associated with the mound. Reasons for this change in conditions appears to be sudden influx of clastic sediment, change in water depth, and upward growth of mounds.

Biotic Components

The framework of the Morrowan bioherms consists of several bacterial and algal components. *Ottonosia* is a cyanobacterium occurring in the core of all the studied mounds. It is however, commonly recrystallized in the outermost layers of the mound. A green alga found in the mounds is *Garwoodia.* This alga is found primarily on the tops of mounds indicating shallow water depths. *Archaeolithophyllum lamellosum* is a red calcareous alga that commonly occurs as a crust on the outer layer of *Ottonosia*. Studies of the mounds reveal that this alga encrusts rugose and tabulate corals. This may, however, be a result of the corals sinking into the algal substrate with growth. Another red, encrusting, calcareous algae is *Archaeolithophyllum missouriensis*. This alga has been compared to *Lithophyllum* and *Goniolithon* life habits in modern reefs. It is thought this alga has a preference for higher energy conditions as it is typically found in the complex lime grainstone channel deposits in the Morrowan bioherms. The final alga found in the framework of the Morrowan mounds is a dasycladacean alga occurring in the middle part of the mound core. Its occurrence is relatively limited as it is found in only the southern most mounds in the quarry.

The cement of the mounds consists primarily of encrusting bryozoans. The encrusting forms require a stable base for attachment. Therefore they are confined to mound tops, overhangs, and roofs of cavities. They are usually associated only with the mound as they are rare in the surrounding shales.

The sediments of the mounds are composed of several accessory organisms. One of the most abundant are the fenestrate bryozoans. These bryozoans prefer habitats that are protected, but have agitated water. They are commonly found in pockets and cavities within the mounds, with a few on the upper mound surfaces. The preference for agitated water is seen in their location choice. They are typically found in the channel side of the mounds facing the lime grainstone channel deposits for increased oxygen and nutrient influx. Other sediment contributors are arborescent bryozoans. These bryozoans live away from the mound in the shales either above or below the mound. These too prefer agitated waters found near the channels. Michelinid corals are another source of sediment in the mounds. These tabulate corals are found on the tops, middle surfaces of mounds and within central and intermound shale cavities. They are most abundant on the open marine side of the mounds and prefer to be attached to an algal or bryozoan substrate. Another source of sediment are blastoid and crinoid fragments. These fossils consist of disarticulated fragments that commonly show abrasion, or evidence of transport. These fragments are most abundant on the tops of mounds where they are entrapped by bryozoans. Brachiopods also produce the sediment surrounding the Morrowan mounds. these fragments are typically found on the tops of mounds, under overhangs, on cavity roofs, and in intermound shales. Representatives of these fragments consist of: *Hustedia*, *Composita*, *Puctospirifer*, *Anthracospirifer*, and productids. Bivalves are also found in the mounds. They are rare, but increase in number higher in the shales of the upper mounding interval.

These organisms described appear to show a similar distribution pattern in the mounds that were studied by Bonem (1975). There appears to be a phase of mound initiation by blue-green algae, followed by habitation of the mounds by a variety of organisms during the diversification phase of mound growth. This growth is then terminated by domination of bryozoans or algae.

Association on Mound Surface

During the scope of the study in 1975, possible biotic associations were examined to determine possible communities within the mounds. Three associations were recognized:

1. The Highland Dwellers: echinoderms, spiriferids, *Composita*, and *Hustedia* brachiopods grouped by either life habit or hydrodynamic properties.
2. The Lowlanders: fenestrate and arborescent bryozoans and goniatite cephalopods are restricted in distribution.
3. Cavity Dwellers: michelinid and rugose corals and encrusting bryozoans that dominate the cavity fauna of the bioherms.

In all the mounds studied, the cavity association appears to be the only association representing a true community. This association not only occurs in all mounds, it forms a discrete occurrence that may be readily recognized.

Regional Paleogeography

The mounds in Chisum's Quarry are part of a band of carbonate buildups that trend north-northwest for approximately five miles along the edge of the Morrowan shelf (Sutherland and Henry, 1975). Point counts of biotic components were made by Bonem from slabs cut from the mounding unit at Greenleaf Lake Dam. The biotic composition of the mounds is similar to that observed within the described Chisum Quarry mounds. The core is composed of over 50 percent micrite that probably represents sediments stabilized by cyanobacteria. Echinoderms, bivalves, brachiopods, bryozoans, and michelinid corals form the accessory organisms. Minor percentages of *Arcaeolithophyllum* species, rugose corals, gastropods, and foraminifera also occur in the core. Higher layers are dominated by 80 to 90 percent micrite with sponge spicules and *Cuneiphycus* alga. Shallowing conditions are indicated by ooliths and bird's eye structures similar to those observed in the highest mounding interval in the quarry.

The Morrowan bioherms formed along the edge of the carbonate platform in an area possibly somewhat protected by the presence of the Gore-Braggs Mountain High, approximately six miles east-northeast of the quarry. Even though this feature was being buried, it possibly had sufficient relief to influence currents during Early Morrowan time. Shallow lagoonal and tidal flat deposition occurred to the east and large tidal channels locally deposited coarse pelmatozoan lime grainstones adjacent to the mounds in the quarry. To the west and south are open marine and deeper water deposits of the Arkoma Basin.

Interpretation of Mound Formation

Three recurring groups of carbonate buildups on carbonate shelf margins were discussed by Wilson (1974). These include: down-slope lime mud accumulations, knoll reef ramps, and frame-built reef rims. The Morrowan bioherms appear to be most similar to the knoll ramp reef model (Bonem, 1975). They possess low depositional slopes of three degrees or less and are dominated by encrusting and massive biota. The mound cores are comprised almost exclusively of stromatolitic cyanobacteria, while other organisms occur higher in the bioherms. Many of the mounds contain high percentages of carbonate mud which may have accumulated in cavities and interstices in shallow water.

Comparison of Morrowan Bioherms with Modern Reefs

Comparison of modern reefs with ancient bioherms presents some problems for paleontologic interpretation. The scleractinian corals that currently form a significant portion of the framework of modern reefs no not exist in Paleozoic bioherms. However, the niches that they occupy were inhabited by other organisms. In the Morrowan bioherms, organisms with similar functions and life habits as those in modern reefs are present including: echinoderms, bryozoans, and rugose corals. This does not take into account, however, the large portion of reef biota that is not easily preserved in the fossil record. These organisms include sponges, noncalcareous algae, and bryozoans.

Within the Discovery Bay lagoon, zonation is the result of sediment and light penetration in addition to depth and topography acted upon by currents and salinity. Sediments limit the forms present and reduce light penetration, so that the biotic zones recognized in previous chapters were characterized by biota characteristic of much deeper water on the forereef. Depth must also have exerted some effect on the development of the Morrowan bioherms. The abundant algae in the mounds are photosynthetic restricting their growth to shallow water. In a carbonate mud environment, light penetration is greatly reduced and stromatolitic cyanibacteria may have been confined to the upper 5 or 10 feet rather than the typical 30 feet depth for growth. Thus it is speculated that the bioherms were initiated on shallow areas of the Morrowan platform on areas of slight mud buildup.

Other similarities of the Morrowan bioherms and modern lagoonal patch reefs are the presence of cavities and cryptic biota. Sand and shifting sediments are unsuitable for habitation until they are stabilized by grass or cyanobacteria, although burrowing can occur in some of the more consolidated sediments. Dead or dying coral forms one of the best substrates for development of boring or encrusting organisms. However, living corals are generally one of the least favorable sites because of the toxic reaction to nematocysts. At depths, various biotic assemblages develop under ledges or plates of shingle-shaped corals such as *Agaricia* or *Montastrea*. Sponges, crinoids, ahermatypic corals, and cheilostome bryozoans attach themselves to the lower sides of these shingle-like organisms. These organisms are then protected above the sea floor from sand and mud. Also, calcareous rocks or biolithites form excellent substrates as long as they remain stable. Irregular rocks within the intertidal zone shelter one of the most diverse cavity faunas observed.

Both large and small cavities have been observed in the Morrowan bioherms of northeastern Oklahoma. The larger features are formed by irregular biohermal growth and are commonly filled by shale deposited during mound development. These are observed in every mound studied by Bonem (1975). The majority of larger cavities observed in the mounds are internally encrusted by a dense development of encrusting bryozoans on a stromatalitic algal framework. Shales within the cavities may include debris from organisms such as blastoids, crinoids, bryozoans, and brachiopods. Other large shale-filled cavities occur in the bioherms and are considered roll structures. This structure forms a central cavity that is slightly more restricted than areas between the mounds. These cavities are roofed and probably represent and environment similar to the enclosed cavities within the reef located under basal coral knobs.

CHAPTER NINE

Conclusions

A comprehensive model for modern lagoonal patch reef development and biotic distribution for the Red Buoy Patch Reef along the northern coast of Jamaica can be summarized as follow:

A. Sediment distribution on the Red Buoy Patch Reef is directly associated with a specific biotic zonation. As such, each zone can easily be recognized by the compositional and textural sediment distribution on the reef. The poor sorting of the sediment on the reef and the lack of uniform composition and texture indicate the distances of transport across the reef are minimal.

B. The deep zones are associated with highly-skewed, poorly-sorted sediments in the mud-sized fractions, whereas the shallow zones have relatively skewed, relatively well-sorted sediments in the sand and gravel-size fractions. The distribution of faunal growth, and therefore sediment composition, is reflected in the depth and the wave energy present in each of the zones.

C. The greatest change in biotic distribution was noted during periods of intense storms in the area. However, typically within five years of a major storm event, the biotic distribution recovers back to its natural pattern as it was prior to the storm's activity.

D. Factors controlling the distribution and zonation of both modern and ancient reef-like accumulations include depth, light penetration, and sedimentation.

Recommendations for Future Studies

Ideally, continuous surveying and sediment collection would be conducted on an annual basis to construct a more comprehensive model. The methodology has been standard since the preliminary stages of this study and should remain the same for future data collection. The current model produced in this investigation should be applied to actual field localities. Several bioherms in Texas and Oklahoma may fit the developmental pattern of this lagoonal patch reef rather than the fringing/ barrier reef model. Identifying particular storm events in the ancient bioherms and understanding the recovery rates may serve as a comparison with this recently constructed model.

Another investigation should be conducted on a patch reef in a similar lagoonal setting with a hard substrate rather than a muddy substrate. The difference between the model constructed in this study and a model constructed from a hard substrate reef would increase understanding of facies relationships in a carbonate environment.

A third investigation should also be conducted focusing on the forereef environment rather than the lagoonal patch reef. It is suggested that a model constructed for the forereef environment would demonstrate more sensitivity to storm activity increasing the frequency of changes in the biotic distributions. Investigating the forereef environment would also allow correlation of environmental influences on each of the biotic zones given they are composed of similar faunal associations.

APPENDICES

APPENDIX A

Point Count Data from Transects A and B, Red Buoy Patch Reef, Discovery Bay, Jamaica

Table A1. Transect A

Sample	Halimeda	Mollusca	Cnidaria	Annelida	Echinodermata	Arthropoda	Misc.
1	50	27	11	10	7	8	86
2	96	27	22	8	2	9	68
3	50	42	11	13	5	12	76
4	67	40	16	7	1	6	62
5	56	57	18	11	3	12	75
6	80	46	11	6	2	11	50
7	51	72	5	7	6	22	46

Table A2. Transect B

Sample	Halimeda	Mollusca	Cnidaria	Annelida	Echinodermata	Arthropoda	Misc
8	32	60	5	2	2	12	91
9	42	43	7	6	2	6	93
10	85	39	11	17	0	21	30
11	31	43	2	6	1	1	105

APPENDIX B

Statistical Grain Size Parameters of the Red Buoy Patch Reef, Discovery Bay, Jamaica.
All quantities are recorded in phi.

Table B1. Transect A

Sample	Mean Size	Std. Dev.	Skewness	Kurtosis
1	1.60	4.17	-0.01	-0.39
2	0.16	1.49	0.25	0.64
3	1.12	1.62	0.20	0.65
4	2.12	1.72	-0.09	0.48
5	1.28	1.29	-0.05	0.71
6	2.62	1.74	-0.49	6.47
7	3.08	1.57	-0.79	0.50

Table B2. Transect B

Sample	Mean Size	Std. Dev.	Skewness	Kurtosis
8	1.42	1.48	-0.02	0.54
9	1.58	1.55	0.15	0.69
10	2.83	1.68	-0.70	0.47
11	1.53	1.53	0.03	0.62

APPENDIX C

Weight Percentages of Gravel, Sand, and Mud of the Red Buoy Patch Reef, Discovery Bay, Jamaica

Table C1. Transect A

Sample	% Gravel	% Sand	% Mud
1	40.01	53.07	6.92
2	39.85	55.26	4.89
3	31.43	49.77	18.80
4	59.13	39.18	1.69
5	53.46	39.14	7.40
6	29.18	29.55	41.27
7	17.22	23.98	58.80

Table C2. Transect B

Sample	% Gravel	% Sand	% Mud
8	44.18	48.23	7.59
9	41.32	57.83	0.85
10	41.22	43.08	15.70
11	38.68	10.16	1.61

APPENDIX D

Table D. Bathymetric Data for the Red Buoy Patch Reef in Discovery Bay, Jamaica from 2006

Radii	Angle (degree)	Depth (ft)	Biotic Zone
100 ft. Radius	0	57	*Agaricia*
	10	58	*Agaricia*
	20	60	Massive Coral
	30	60	Massive Coral
	40	66	Massive Coral
	50	70	Mixed Sponge
	60	67	Massive Coral
	70	67	Massive Coral
	80	63	Massive Coral
	90	63	Mixed Sponge
	100	71	Massive Coral
	110	68	Massive Coral
	120	76	Massive Coral
	130	69	Massive Coral
	140	68	Massive Coral
	150	65	Massive Coral
	160	63	Massive Coral
	170	62	Massive Coral
	180	60	Massive Coral
	190	52	Massive Coral
	200	43	Massive Coral
	210	40	Massive Coral
	220	38	Massive Coral
	230	36	Mixed Sponge
	240	29	*Porites*
	250	23	*Porites*
	260	21	*Porites*
	270	28	*Porites*
	280	31	*Porites*
	290	34	Massive Coral
	300	38	*Madracis*
	310	43	Massive Coral
	320	46	Massive Coral
	330	55	Massive Coral
	340	52	Massive Coral
	350	58	Massive Coral
75 ft. Radius	0	53	Massive Coral
	20	53	Mixed Sponge
	40	61	Massive Coral
	60	59	Massive Coral

Table D. Bathymetric Data for the Red Buoy Patch Reef in Discovery Bay, Jamaica from 2006--Continued

Radii	Angle (degree)	Depth (ft)	Biotic Zone
75 ft. Radius	80	63	Mixed Sponge
	100	63	Mixed Sponge
	120	64	Massive Coral
	140	59	Massive Coral
	160	57	Massive Coral
	180	44	*Madracis*
	200	43	*Madracis*
	220	40	Mixed Sponge
	240	26	*Porites*
	260	28	*Porites*
	280	30	*Porites*
	300	37	Massive Coral
	320	41	Massive Coral
	340	47	Massive Coral
50 ft. Radius	0	47	Mixed Sponge
	30	50	Mixed Sponge
	60	55	Mixed Sponge
	90	58	Mixed Sponge
	100	60	Mixed Sponge
	120	60	Massive Coral
	150	53	*Madracis*
	180	40	*Madracis*
	210	44	*Madracis*
	240	39	*Madracis*
	270	32	*Porites*
	300	35	*Porites*
	330	40	Massive Coral
25 ft. Radius	0	48	Mixed Sponge
	90	50	Mixed Sponge
	180	48	Mixed Sponge
	270	47	Mixed Sponge

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