Extraction and Analysis of Coral Reef Core Samples from Broward County, Florida.

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EXTRACTION AND ANALYSIS OF CORAL REEF CORE SAMPLES FROM BROWARD COUNTY, FLORIDA.

By
Anastasios Stathakopoulos

Submitted to the Faculty of
Nova Southeastern University Oceanographic Center
in partial fulfillment of the requirements for
the degree of Master of Science with a specialty in:

Marine Biology

Nova Southeastern University
December 2009
Master of Science

Marine Biology

Thesis of

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Submitted in Partial Fulfillment of the Requirements for the Degree of

Nova Southeastern University
Oceanographic Center

December 2009

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ABSTRACT

The reefs off Broward County exist as three shore-parallel, sequentially deeper terraces named the “inner”, “middle”, and “outer” reefs and also a shallower, nearshore ridge complex. These structures span the continental coast of southeast Florida from Palm Beach County to southern Miami-Dade County and were characterized as relict, early Holocene shelf-edge and mid-shelf reefs along with limestone ridges. Presently, the reefs are colonized by a fauna characteristic of West Atlantic/Caribbean reef systems. Scleractinian coral cover is low except for a few dense patches of Acropora cervicornis, while Acropora palmata is absent except for a few individual living colonies.

Coral reef core-drilling is a useful analytical tool to extract observable and datable geological samples from within reefs. This technique was employed to retrieve 4 cores from the inner reef off Broward County to better understand its age, composition, and Holocene growth history. Sub-samples from corals in cores provided 7 new radiocarbon ages ranging from 7,860–5,560 cal BP, and reef accumulation rates of 1.7-2.45 m/1,000 yrs were calculated from these ages. In addition, coral species composition and taphonomic characteristics were analyzed to identify former reef environments/reef zonation, and signals for inner reef termination. Reef zonation was detectable but no clear taphonomic signal for inner reef termination was evident.

Current data and radiocarbon ages from all three Broward County reefs suggest that the outer reef accumulated from ~10.6–8 ka cal BP, the middle reef from at least ~5.8–3.7 ka cal BP, and the inner reef from ~7.8–5.5 ka cal BP. A lack of significant age overlaps between the three reefs has led to the assertion that they represent backstepping reefs in response to Holocene sea-level rise. This study has provided the oldest and youngest ages from the inner reef thus far, and confirms that reef backstepping from the outer reef to the inner reef occurred within just a few hundred years after the termination of the outer reef. The middle reef remains poorly understood and thus a definitive Holocene growth history and ultimately an understanding of their formation are still largely unknown.

Keywords: coral reef core, Holocene reef, Acropora palmata, southeast Florida continental reef tract, backstepping, relict reef
ACKNOWLEDGEMENTS

I would like to thank the USGS and NOAA for funding this project and my research. I would like to thank my major professor, Dr. Bernhard Riegl for providing me the opportunity to work on such an interesting and involved research project. It was truly a unique and unforgettable experience. I would also like to thank my thesis committee for all their valuable guidance, input, and suggestions throughout the project.

A special thanks to Captain Lance Robinson and Brian Buskirk for all their help engineering the tripod and barge, as well as their assistance during fieldwork and diving. Their knowledge and expertise have greatly contributed to all aspects of fieldwork. Gwilym Rolands also participated during fieldwork and provided his underwater camera to capture images during reef drilling. Many other people have been involved in various phases of this project. Vladimir Kosmynin of the Florida Department of Environmental Protection aided in identifying coral species in cores. Dr. Ryan P. Moyer of the USGS Center for Coastal and Watershed Studies, St. Petersburg, FL, performed all XRD analyses. Dr. Brian K. Walker provided the most current LIDAR data and invaluable assistance creating the figures. Greg and Kristi Foster provided me with images using their wide-angle camera. Gwilym Rolands and Shana Dunn helped with all things GIS and made working in the lab a great time.

Finally, I would like to thank my family and friends for always providing me the encouragement and support to pursue my ambitions. Without them this thesis would not have been possible.
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1. INTRODUCTION

1.1. Project Location and Overview of Broward County Reefs

The reefs off Broward County exist as a series of three sequentially deeper terraces and a nearshore ridge complex with living corals that crest at ~ 4–16 m below sea level (Banks et al., 2007 and 2008). In a landward to seaward direction, they have been termed the “ridge complex”, “inner”, “middle”, and “outer” reefs by Moyer et al. (2003) based on Lighty (1977) [FIGURE 1]. They were characterized as a “complex of relict, early Holocene shelf-edge and mid-shelf reefs along with limestone ridges” (Banks et al., 2008; Finkl and Andrews, 2008) and are believed to be established on Late...
Pleistocene beach ridges (Shinn et al., 1977; Banks et al., 2008). Relict reefs are coral framework reefs with very low or no net active accretion caused by low cover of reef building corals (Moyer et al., 2003; Banks et al., 2007), and often occur as a result of high sea-level transgressions (Macintyre, 2007). The reefs are part of the larger, mostly continuous ridge/reef structures that span along the continental coast of Florida from offshore Palm Beach County (26°43’N) southward to offshore Miami-Dade County (25°34’N), a distance of ~125 km (Banks et al., 2007 and 2008; Finkl and Andrews, 2008). Collectively, these structures have been referred to as the “Southeast Florida reef tract” after Banks et al. (2007), and are currently distinguished from the Florida Keys reef tract, which is located further south.

The reefs of the SE Florida reef tract are generally positioned linearly and parallel to the trend of the shoreline, and exist in increasing depth (Banks et al., 2007 and 2008; Walker et al., 2008). They are divided landward to seaward by sandy sedimentary deposits of varying thicknesses and overlay Late Pleistocene/Early Holocene erosional hardground surfaces believed to be beach ridges (Duane and Meisburger 1969; Raymond, 1972; Shinn et al., 1977; Banks et al., 2007 and 2008; Walker et al., 2008). The high latitude SE Florida reef tract is near the northern limit for active reef accretion due to natural reductions in light and water temperatures ( Vaughan, 1914; Goldberg, 1973; Lighty et al., 1978; Braithwaite, 1979; Jaap, 1984; Precht and Miller, 2007). The reef tract must also tolerate cold weather fronts, occasional upwelling, and severe wave action and turbidity caused by hurricanes (Goldberg, 1973; Jaap, 1984). Presently, the reefs are not considered to be “framebuilding or accreting but are colonized by a rich tropical fauna otherwise characteristic of the West Atlantic/Caribbean reef systems” (Banks et al.,
2007 and 2008). Possible causes of the termination of reef accretion include: low water temperatures during the early Holocene (Lighty et al., 1978), cold counter-current water from the north, a major influx of sediment-rich water originating from the south during the Holocene transgression (Shinn et al., 1977; Lighty et al., 1978; Macintyre, 1988; Macintyre, 2007), and/or catastrophic sea-level rise events (Braithwaite, 1979; Blanchon and Shaw, 1995; Banks et al., 2007).

1.2. Relevant Coral Reef Research in Southeast Florida

Geological descriptions of southeast Florida coral reefs initiated in the 1960’s and 70’s by researchers including Lidz, Shinn, Ginsburg, Macintyre, Lighty, and others. They provided internal descriptions of the reef frameworks and possible correlations to sea level and environmental conditions. The majority of these studies were conducted in the Florida Keys region, presumably because the extant reefs are more prominent, developed, and well known than the reefs off Broward County further north. More recently, several ecological studies in Broward County have resulted from monitoring programs established in 1997 by the Broward County Environmental Protection Department, and in 2003 by the Florida Fish and Wildlife Conservation Commission (Gilliam et al., 2007; Gilliam, 2009). Other research led to classification schemes and descriptions of the reef landscape (Moyer et al., 2003; Finkl et al., 2005 and 2008; Banks et al., 2007; Walker et al., 2008). The newer research techniques and technologies employed in these studies have provided more detailed data sets and interpretations leading to improved bathymetric maps, geomorphological descriptions, and knowledge of the processes occurring on Broward County reefs in recent geologic time.
1.3. Project Rationale

Despite the numerous and broad-ranging coral reef studies conducted in the SE Florida region, very few geological descriptions of the internal reef frameworks have been performed. These include studies in northern Broward County off Pompano Beach on the outer reef by Lighty et al. (1977) and (1978), in Miami Dade County off Bal Harbor on an intermediate ridge and off Virginia Key on the inner reef by Shinn et al. (1977), and off Ft. Lauderdale and Dania Beach in central/southern Broward County on the inner and middle reefs by Banks et al. (2007). The most recent of these studies (and the most relevant to this study since it was the only reef-coring conducted in the area) came ~40 years after these features were initially described in detail and referred to as “reef-like structures” and “inactive coral reefs” (Duane and Meisburger, 1969; Macintyre and Milliman, 1970).

These 3 studies demonstrate the paucity of geological samples, the lack of scientific knowledge of these reef interiors and ultimately their growth histories, while indicating the need for further research in the area. Much information remains to be discovered from the reefs off Broward County and the SE Florida region regarding descriptions of the internal facies components and thicknesses of the reefs, timing of reef initiation and termination, reef growth and depositional history, as well as the end of Acropora palmata reef dominance. The ages and thicknesses of these reefs may reveal when, how long, and at what rate they were accreting, while comparisons of the reef accumulation rates with those reported from the region may determine if the reefs experienced relatively rapid, average, or slow accretion. Additionally, the ages of the initiation and termination of framework building and the type of framework throughout the life of the reef (i.e. massive corals vs. acroporids) may have implications for sea level,
water quality, and reef backstepping. Environmental conditions during the early and middle Holocene in the region were conducive for significant coral reef accretion (as evidenced by the ages of reef growth from Banks et al., 2007), yet it remains unclear how this relates to the conditions the present day reefs are experiencing with little to no accretion.

Answers to these questions are critical in order to clarify Florida’s coral reef histories, and in particular, their responses to changing sea-levels caused by paleoclimate patterns. The effects of sea-level fluctuations on Holocene reef systems have been extensively studied at many locations in the world, and Florida can be regarded as an ideal location for geologic reef studies due to its multiple reef histories through geologic time (Randazzo, 1997), relatively stable tectonics (Smith and Lord, 1997), and proximity to research institutions. New information gleaned from this type of geological research on regional and global scales could also prove to be vital to management strategies for rising sea-level, climate change, and the decline of local and global coral reefs.

1.4. Study Approach

The study area encompassed specifically chosen sites on the inner reef in Broward County located offshore of Fort Lauderdale, and Dania Beach, Florida [FIGURE 2]. The inner reef was targeted because of its proximity and relatively shallow water depths that permitted simplified drilling and diving protocols. The study focused on the use of geological approaches and employed coral reef core-drilling to characterize the internal facies of the Broward County inner reef during the Holocene period. The core samples were analyzed for: coral species composition, mineralogy of coral samples, \(^{14}\)C ages of reef initiation and termination, calculated reef accumulation rates, characteristics and
Figure 2: LIDAR bathymetric map showing the locations of the core-drilling study sites on the inner reef from offshore Broward County, Florida (inset map shows offshore reef location).
degree of taphonomy, reef thickness, underlying substrates/topography, and reef zonation. The findings were compared to historical published data for SE Florida reef ecology and geology, sea level, and geological history of the region. An attempt to correlate past conditions to the present day was based on a culmination of these and other factors.

1.5. Geological Approaches to Coral Reef Research

It has been stated that the fossil record is the best place to observe the natural variability of coral reefs long before human impacts (Aronson, 2007). “Since coral reefs are both geological and biological entities the logical sequence must be to observe the effects of disturbance in ecological time, detect any historical changes in the paleobiological record, determine whether recent patterns are unprecedented on a relevant scale, and deduce the multiscale processes behind those patterns” (Precht and Aronson, 2006). Stanley (2001) adds that interlocking frameworks of calcifying organisms have become the trademark of reefs and also an essential part of the definition of reefs. Research on modern and ancient reefs has relied largely on the recognition and classification of in-place, interlocking, calcified organisms or framework [FIGURE 3] (Insalaco, 1998; Stanley, 2001; Greenstein, 2007; Macintyre, 2007; Pandolfi and Jackson, 2007). Since reefs usually form on previously existing underwater geomorphologic structures, present day reef locations are determined by antecedent seafloor morphology (Vora et al., 1996). Thus, in order to describe the characteristics of the Broward County reefs, it is essential to understand the locations and morphology of previous features and the environmental conditions of the area in the recent geological past. Additionally, geological approaches to coral reef science can “broaden our understanding of the threats
Figure 3: Fossil Acropora palmata reef facies in outcrop from Curacao. Note the preservation of easily identified in situ coral framework. Researcher for scale.

facing modern coral reefs, and increase our predictive power in a rapidly changing world" (Aronson, 2007), and may aid in formulating effective conservation/management strategies. The Uniformitarian Principle originally proposed by James Hutton, states that the present is the key to the past. According to Balsillie and Donaghue (2004) “the corollary that the past is the key to the present and future is also true and scientists began seeking evidence about past sea levels in order to gain insight as to how sea level could behave in the future”. Employing the Uniformitarian Principle should allow the use of the geological results from the past in a context useful for understanding the processes of present-day coral reefs and their management.
1.6. Core-Drilling as a Scientific Tool for Coral Reef Research

In the 1960's coral reef scientists knew little about the internal structures of modern reefs as most of their knowledge came from observations of topographic features and surface distributions of sediments and biota (Macintyre, 1996). Consequently, the recent history or the factors that influenced the development of western Atlantic/Caribbean reefs were crudely understood (Macintyre, 1996). The predominant view of these reefs previous to drilling operations was that they were “feeble novices” (Davis, 1926) and had been “reestablished only recently with the gradual warming of post-Pleistocene climate to form thin veneers over older relief” (Newell, 1959). They were essentially considered to be immature, thin growths that inherited preexisting topographic relief to grow upon. It was realized shortly thereafter that coral reef geologists were “in need of an inexpensive and portable device” to sample shallow coral reef environments with “minimum logistical support” (Macintyre, 1975). This led Ian Macintyre to construct a submersible hydraulic drill-rig in the early 1970’s and to develop the methods to extract a series of core samples along transects across modern reefs relatively inexpensively by a three-man dive team (Macintyre, 1975 and 1996). Knowledge of underwater substrates in locations accessible to diver-scientists was greatly enhanced by the use of drill-rigs as a tool for marine research as the extracted cores provided valuable clues on the depositional histories of reefs and the postdepositional processes that have occurred within the reef frameworks (Macintyre, 1975 and 1996).

The initial success using coral reef drilling operations for scientific research was “quickly appreciated and researchers in the United States, Australia, Japan, and Germany began assembling their own hydraulic drilling equipment to study Holocene coral reef history” (Macintyre, 2001). Since then, research and analyses of extracted core samples
using drill-rigs was conducted on coral reefs throughout the world. Particular to this study, are the reefs of the western Atlantic/Caribbean region in locations such as: Antigua (Macintyre et al., 1985), Bahamas (Lighty et al., 1980 and 1982), Barbados (Fairbanks, 1989; Rubenstone et al., 1995), Belize (Macintyre et al., 1982; Shinn et al., 1982), Florida (Shinn et al., 1977; and 1991; Toscano and Lundberg, 1998; Banks et al., 2007), Grand Cayman (Blanchon and Jones, 1995; Blanchon et al., 2002), Martinique (Adey and Burke, 1976), Mexico (Macintyre et al., 1977; Blanchon and Perry, 2004), Panama (Macintyre and Glynn, 1976; Macintyre, 1977), Puerto Rico (Macintyre et al., 1983; Rubenstone et al., 1995; Hubbard et al., 1997), and St. Croix (Adey, 1975; Adey et al., 1977; Burke et al., 1989; Rubenstone et al., 1995; Hubbard et al., 2005). Through the use of core-drilling rigs, scientists were able to determine “that many reefs of the western Atlantic have impressive records of Holocene accumulation, in terms of both the amount and duration of deposition” (Macintyre, 1988). These reefs range from a few meters thick to over 30 meters with some growing continuously for thousands of years (Shinn et al., 1977; Macintyre, 2007).

Coral reef core samples are acquired by drilling vertically down through the reef rock using a rotary core-drill and extracting a cylindrical sample of its contents [FIGURE 4]. Drilling units can extract cores “representing a sequence of accumulated reef structure without undue disturbance to the local environment” (Macintyre, 1975). Initial analyses of core samples may be used to identify the compositions of dominant coral species and the antecedent structures that the reefs have formed on (Shinn et al., 1977; Toscano and Lundberg, 1998; Blanchon and Perry, 2004). More in-depth studies may provide insight to previous: reef ecology, ecosystem health, reef growth history, reef community
succession, reef accumulation rates, and responses to climate and sea-level changes (Shinn et al., 1977; Lighty et al., 1982; Buddemeier and Smith, 1988; Blanchon and Shaw, 1995; Bard et al., 1996; Toscano and Lundberg, 1998; Braithwaite et al., 2000; Toscano and Macintyre, 2003; Banks et al., 2007; Macintyre, 2007). In addition, careful

*Figure 4:* Image of a surficial coral reef core sample extracted from the inner reef. This short section displays a *Diploria* sp. on the bottom with a truncation interval that is topped with a *Montastrea* sp. Note the evidence of coral re-colonization after the truncation interval. Scale in cm.

selection of drilling locations and subsequent reef facies interpretations may allow researchers to determine and model past reef types (barrier, fringing, shelf-edge, etc.) and reef zones (fore reef, reef crest, reef flat, back reef, rubble zone, etc.) (Macintyre, 1988; Braithwaite et al., 2000; Blanchon and Perry, 2004; Macintyre, 2007).

Analyses of the location, composition, and geomorphology of extant and extinct (relict) reefs permits comparisons (involving a variety of scientific disciplines) of the present day status to past conditions through geologic time (Lighty, 1977; Shinn et al., 1977; Lighty et al. 1978; Lidz et al., 1991; Shinn et al., 1991; Ginsburg and Shinn, 1993; Lidz et al., 1997; Toscano and Lundberg, 1998; Blanchon and Perry, 2004; Macintyre,
More recently, the application of core sample analyses have been combined with computer models, field data from surveys, sub-bottom profilers, and other remotely sensed data to provide broader and more detailed perspectives of geomorphological coral reef comparisons (Lidz et al., 1997; Walter et al., 2002; Blanchon and Blakeway, 2003; Lidz, 2004; Finkl et al., 2005; Lidz et al. 2006; Banks et al., 2007; Macintyre, 2007; Finkl et al., 2008; Walker et al., 2008).

1.7. Coral Reefs and Acropora palmata as Sea-Level Indicators

It is well documented in the scientific literature that coral reefs are among the best sea-level indicators. Comparisons of the fossil bioconstructions of coral reefs, with their present-day counterparts are often used for the reconstruction of former sea levels (Lighty et al., 1982; Bard et al., 1996; Pirazzoli, 1996; Toscano and Macintyre, 2003). According to Pirazzoli (1991) “The most reliable indications on the elevation and age of former sea levels are probably given by reefal or encrusting marine organisms collected in growth position, such as coral reefs”. From a geological perspective, coral reefs consist of scleractinian corals and crustose coralline algae as the main framework builders and are associated with many other reefal organisms and sediments (generally carbonates) that are trapped in the framework and finally cement it (Pirazzoli, 1991). The uppermost limit of tropical coral reef growth is usually determined by emersion and is close to mean low-water spring tide level (Pirazzoli, 1991), while the accumulation of reef framework is generally limited to water depths less than 30 m (Lighty et al., 1982). Certain morphological features of reefs such as the reef flat and reef/algal crest zones, or microatolls, can be related to sea level with quite narrow uncertainty ranges (Pirazzoli, 1996). This characteristic depth range of tropical reef development has tracked the
Holocene transgression in the geological record which has risen more than 100 m in the last 18,000 years (Lighty et al., 1982; Macintyre, 2007). Among the reef builders (which may be fossilized in situ forming the components of the framework), are some species and associated communities that are typical of shallow-water environments. They have a narrow vertical zonation and live or have lived within even more restricted depths making them useful sea-level indicators. These include encrusting coralline algae, fixed vermetid gastropods, Cliona sp. boring sponges, Lithophaga sp. boring mollusks, and the reef-building coral A. palmata (Lighty et al., 1982; Pirazzoli, 1996).

Examinations of western Atlantic/Caribbean reef sequences have demonstrated that they retain directly datable portions of the sea-level changes in the form of fossil coral species that can track both the positions and rates of sea-level rise (Macintyre 1977; Lighty et al., 1982; Fairbanks, 1989; Bard et al., 1996; Toscano and Lundberg, 1998). The depth ranges and facies assemblages of corals in reef deposits, particularly in association with A. palmata, are well established sea-level elevation indicators (Lighty et al., 1982; Toscano and Macintyre, 2003). Macintyre (1996) adds that the various stages of reef growth can be postulated “by relating the distribution of reef facies and the position of radiocarbon ages to a regional minimum sea-level curve”. Conversely, spatial and temporal gaps within coral reef sequences may indicate periods when the rate of sea-level rise surpassed the rate of coral growth (Blanchon and Shaw, 1995; Toscano and Lundberg, 1998). According to Toscano and Lundberg (1998), the “direct measurement of sea levels from reefal records contributes tangible evidence of the results of global-deglaciation and climate change, and allows for interpretation or identification of forcing factors and mechanisms”. Using fossil coral reefs to determine paleo-sea levels has a
number of difficulties and reservations, yet acknowledgement of these issues can ultimately provide excellent datable material for the establishment of former sea levels (Hopley, 1986).

The coral *A. palmata* is the most prominent shallow-water coral reef framework builder in the western Atlantic/Caribbean, and is commonly dated in geological studies of reefs in this region (Lighty et al., 1982; Macintyre, 2007). It builds a rigid framework particularly in shallow-water reef environments and when identified within a reef facies, can be used as a reliable indicator and reference for reconstructing the history of late Quaternary sea-level history (Lighty et al., 1982). *A. palmata* (and *Acropora cervicornis*) is the only coral to form monospecific reefs in a restricted depth range of waters < 1–5 m deep and forms a distinctive interlocking framework that is easily identifiable [FIGURE 5] (Lighty et al., 1982; Blanchon and Shaw, 1995; Toscano and Lundberg, 1998).

![Figure 5: Shallow-water A. palmata reef displaying the characteristic growth form associated with the reef crest/front zone.](image)

Although live *A. palmata* corals have been reported at depths as great as 17 m, the maximum depths of *A. palmata* framework were reported to range from 3–12 m with an
average of 5.5 m depth (Lighty et al., 1982). When it exists as a monospecific framework, it is believed to be indicative of the reef crest facies, which is theoretically characteristic of western Atlantic/Caribbean reefs (Lighty et al., 1982; Toscano and Lundberg, 1998; Toscano and Macintyre, 2003). According to Lighty et al. (1982), dated samples of *A. palmata* framework should provide a reliable indication of the positions of pre-existing sea levels since the corals probably grew close to sea level and were a part of the structural framework.

Other cited characteristics that make *A. palmata* an ideal sea-level indicator include: the tendency to maintain themselves at sea level by rapid vertical accretion, minimal postdepositional transport and compaction of the thick branches of framework, it is easily recognized in reef cores and sections, the *in situ* growth position and orientation are readily determined from its distinctive asymmetrical growth form displayed in the skeletal banding, and the ease of obtaining uncontaminated samples and their suitability for radiometric aging (Lighty et al., 1982; Blanchon and Shaw, 1995; Toscano and Lundberg, 1998; Toscano and Macintyre, 2003). Lighty et al. (1982) add that “*A. palmata* samples are particularly suitable for radiocarbon aging because they generally consist of well preserved original skeletons”. Since *A. palmata* reef facies have a high rate of accumulation, submarine diagenesis (in this case, contamination by inclusion of magnesium calcite) is limited to the outer surfaces of these corals, and this material is easily recognized and can be removed prior to aging (Macintyre 1977; Lighty et al., 1982). Sample purity can then be confirmed by X-ray diffraction mineralogy, and if the samples are found to consist of pure aragonite, they are deemed acceptable for radiometric aging (Lighty et al., 1982; Banks et al., 2007).
Lighty et al. (1982) and others urged researchers to exercise caution since *A. palmata* (like any dated sample of an *in situ* coral) is not an absolute indicator of sea-level position, but it is rather only an absolute indicator of submergence conditions (i.e. the coral must have been submerged in order to grow), and may indicate a minimum position of sea level. In addition, knowledge of sample growth position is essential to avoid incorporation of redeposited coral rubble (not *in situ*) into analyses (Pirazzoli, 1996). Blanchon and Shaw (1995) added that these reefs can track rising Holocene sea levels if the “rate of sea-level rise doesn’t exceed its maximum reef-accretion rate of 14 mm/yr and that rises below this threshold rate can be accurately determined by dating the elevation of *A. palmata* reef frameworks”. Minimum sea-level curves of the western Atlantic/Caribbean region were constructed using ages and elevations of reef crest *A. palmata* framework by Lighty et al. (1982) and further refined by Toscano and Macintyre (2003), and are useful for estimating paleo-water depths of Holocene reef history studies in the region.

2. **Study Purpose and Objectives**

2.1. Purpose

This project aimed to further the analyses of Banks et al. (2007) by extracting and analyzing multiple coral reef core samples from the inner reef at different latitudinal locations off Broward County to give a larger and more thorough perspective of the formation, growth history, and composition of Broward County reefs during the Holocene. The core samples were visually and electronically analyzed to determine their inner facies components and the percentages of space the components occupy within cores. Reef thicknesses were determined by measuring the distance from the top of the core to the top of the base contact substrate. Sub-samples were $^{14}$C radiocarbon aged to
determine the onset of reef initiation and termination, and reef accumulation rates. These ages were useful in determining reef responses to sea-level changes as a result of paleoclimate patterns. Results were compared to historical Holocene sea-level and paleoclimate data from the region, and attempted to relate the past conditions to the present. A synopsis of all data was utilized to revise existing diagrammatic models for initiation and termination response patterns of the Broward County reefs in recent geologic time. This project followed the principles and techniques established for coral reef core-drilling by researchers in the western Atlantic/Caribbean region during the past 35–40 years.

2.2. Project Goals

1) Construct and implement a core-drilling system for the extraction of coral reef core samples.
2) Extract and analyze multiple core samples from the inner reef at two sites in Broward County from known locations of reef framework.
3) Describe the coral species, dominating framework (i.e. massive vs. acroporid), and the inner facies of core samples.
4) Analyze and describe the taphonomic characteristics present in cores.
5) Determine the mineralogy of samples using X-Ray Diffraction analysis and confirm if they are suitable for radiometric aging.
6) Determine $^{14}$C ages for the timing of initiation and termination of coral reef framework in cores.
7) Determine reef accumulation rates.
8) Determine reef thickness at cored locations.
9) Determine the underlying substrate(s) that the inner reef is situated on.
10) Correlate the retrieved data with regional sea-level curves and paleoclimate models from the literature.
11) Ensure the entire core-drilling system can be utilized for possible future projects.
2.3. Hypotheses

1) Timing of the initiation and termination of coral framework growth on the inner reef can be determined by $^{14}$C aging and core-analysis.

2) Taphonomic analysis of cores can identify different reef environments.

3) Taphonomic signals for the circumstances of reef termination should exist.

4) The inner reef is ~4 m thick (based on LADS bathymetry profiles and Banks et al. (2007) cores).

5) The accumulation rate of reef framework is measurable by coring and $^{14}$C aging.

6) The inner reef facies consists of mostly acroporid corals in the shallower reef crest zone and massive corals in the back reef and reef front zones throughout the sampled geographic range of this project.

7) The inner reef facies displays a laterally uniform reef zonation over the sampled geographic range of this project.

3. MATERIALS AND METHODS

3.1. Drilling Equipment and Tripod

Core samples were extracted using a tripod-mounted submersible rotary core-drilling rig. The drill equipment consisted of a hydraulic-powered drill with standard drilling barrels, a wire-line core retrieval system, a hydraulic power source at the surface, heavy-duty hydraulic hoses, and a water pump to circulate water around the cutting edge of the drill-bit [FIGURE 6]. This is all commercial-grade heavy-duty equipment routinely employed in exploratory drilling for geotechnical purposes. The core-drill unit was first used in the Banks et al. (2007) study; however, drill stability often limited the penetration depth due to the drill-bit becoming lodged within the reef. This prompted my development of a tripod in order to attach the core-drill and act as a solid stabilizing platform during drilling for this project.
The drill used was a Goelz HBM powered by a Lombardini 12LD 475–2 diesel-powered hydraulic motor capable of running an entire workday on a few gallons of diesel fuel. The core barrels and drill bits were a Christensen HXB–2 double barrel wire-line system, and enabled efficient and simplified removal of core samples <6 cm in diameter.

Wire-line systems streamline the drilling process by allowing recovery of inner core barrels without removing and retrieving the outer core barrels after each core run (Macintyre, 1996). The wire-line system is an improvement on earlier single barrel designs and also provides protection from fragments falling into the core-hole (avoiding misrepresentation of rock structure and $^{14}$C aging) while maintaining minimal loss of
cored material during drilling. It utilizes a steel spring-type core catcher that is dropped into the outer barrel and locks onto the top of the inner barrel containing the cored substrate. Once locked, the inner barrel can be extracted via a tripod-mounted manual cable winch and the core can be removed. The hydraulic fluid used was eco-friendly sunflower oil and minimized any environmental impacts in case of fluid leakage or spills. Sedimentation and turbidity during drilling were reduced to a minimum through the use of the engine-mounted and powered raw-water pump.

I modified the drill-rig to a tripod-type design, resembling a standard folding camera tripod in appearance and function [FIGURE 7]. The tripod and all supporting hardware consist of marine-grade aluminum and stainless steel. It was assembled to

![Figure 7: Image of core-drill tripod with barrels, drill head, and hydraulic hoses attached.](image-url)
desired specifications by welding and simple through-bolting using heavy-duty stainless steel nuts and bolts at its movable joints. Functional features incorporated into the design include: folding legs and support arms to streamline the tripod during transport and field deployment, extendable and adjustable legs to level the tripod prior to coring, and the tripod-mounted hand-operated cable winch for retrieval of the inner barrel using the wire-line system. The vertical stainless steel drill rack is the center piece of the tripod and allowed for the attachment of the drill to the tripod while facilitating the vertical movement of the drill-bit into and out of the substrate during drilling. The tripod weighs roughly 181 kg (400 lbs.) and is approximately 4 m (13') tall with a 1.8 m (6') displacement from its center when unfolded. These properties were critical in determining safe and proper SCUBA dive-planning for fieldwork.

3.2. Work Barge

A 25' Chaparral boat was salvaged from the Nova Southeastern University Oceanographic Center. It was converted into a work barge by the author to serve as a dedicated work platform for core-drilling fieldwork operations [FIGURE 8]. All original boat equipment including the motor, steering assembly, electronics, and most of the deck were initially stripped out and removed. Preexisting minor damage to the fiberglass structure and water drainage/sealing systems were repaired. Modifications and repairs were subsequently made to accommodate the hydraulic power pack in the engine compartment and an electronic Western Mule Fold-Away Crane with an extendable and rotating arm with cable winch on the deck. Once exposed, the wooden stringers were extensively reinforced to handle the load of raising/lowering the tripod by adding additional wood beams and stabilizing the existing ones. This was achieved using
pressure-treated 2x4" and 2x6" wood planks and galvanized heavy-duty outdoor screws and bolts. Additionally, thick gauge and thick diameter aluminum pipes were installed across the back of the barge to stabilize and support the tripod during travel and deployment/retrieval. After installation of the crane, the boat deck was resealed with pressure treated plywood, and painted over with deck paint. Once complete, the work barge was towed to the chosen drill sites with all equipment on-board, and the electronic crane was used to deploy/retrieve the tripod drill-rig, core-barrels, wire-line system, extracted core samples, and all other related equipment [FIGURE 9].
3.3. Site Selection

This project attempted to target two confirmed locations of *A. palmata* framework on the inner reef off Broward County [refer to FIGURE 2]. The first site was the location of a set of mooring balls on the inner reef just south of Hugh Birch State Park off Fort Lauderdale (North site). The second site was near the grounding location of the submarine *USS Memphis* off Dania Beach (South site). It grounded on the inner reef at ~7 m depth in February 1993 and the propwash excavated a trench that exposed ~3 m of mostly *A. palmata* reef framework that also contained some massive coral heads (Banks et al., 1998; R.E. Dodge, pers. comm.). Previous coral reef coring from the Banks et al. (2007) study at these two sites revealed ~1.5 and 1.1 m of surficial *A. palmata* reef framework respectively, both in ~7 m water depth.

Laser Airborne Depth Sounding data (a laser bathymetric surveying system) retrieved in Broward County were used to produce bathymetric and computer generated seafloor topographical maps by Banks et al., (2007) and Walker et al., (2008). These maps allowed careful site selection of drilling locations for specific underwater
geomorphic features and for ease of SCUBA diving/fieldwork procedures. Features were selected for locations assumed to be comprised mostly of *in situ* coral framework indicated by reef structures with high topographic relief in the maps and were assumed to imply accretion of coral reef framework. A GPS was employed to locate and mark the coordinates of the chosen sites when out at sea during drilling operations.

3.4. Field Protocol for Core Sample Extraction

1) Arrive at the chosen site and secure the boat and the barge.
2) Check the substrate conditions by snorkeling and observing the bottom.
3) Once the desired location is confirmed lower the tripod, water and hydraulic hoses, barrels and wire-line, wrenches, and other tools using the barge-mounted crane.
4) Assemble all the equipment underwater, record the water depth from the surface to the substrate, and signal to the surface support (by floating a lift bag to the surface) to start the motor.
5) Begin drilling and record any reef holes by observing the tactile feedback behavior of the drill, and noting the depths of noticeably faster drill penetration using the drill rack-mounted measuring tape.
6) Once the first barrel has fully penetrated the substrate, record the core penetration depth, remove the drill head and extract the inner barrel using the wire-line system and tripod-mounted hand winch.
7) Float the inner barrel to the surface using underwater lift bags and remove the core sample from the inner barrel on the barge.
8) Return with the inner barrel to the core-hole and reinsert the inner barrel into the outer barrel.
9) Add another outer barrel length, and then seal the pipes by reattaching the drill head and resume drilling.
10) Repeat procedures 4–9 until the desired penetration depth has been reached.
3.5. Water and Core Depth Measurements

Submersible SCUBA depth gauges were used to determine the depth from the water surface to the substrate. Observed depths were calibrated for tidal changes and are reported herein as elevations in the NAVD88 datum using tide charts and tidal datums for Port Everglades provided online by NOAA (http://tidesandcurrents.noaa.gov/). The protocol used during drilling is presumed to ensure relatively accurate recovered core sample length and core recovery at the target sites. A centimeter divided measuring tape attached to the drill rack allowed determination of the depth of penetration into the substratum and reef porosity during drilling [FIGURE 10]. Initial contact of the drill bit with the substratum was taken as the zero-mark, and achieved depths reached down-core were recorded and measured from this reference. A hand crank that lowers and raises the drill string provided tactile feedback to the operator, who also recorded changes in drilling speed and penetration and noted the depths using the scale on the drill rack (Burke et al., 1989; Hubbard et al., 1997 and 2005). When drilling was complete, core recovery was calculated by expressing recovered core length as a percentage of the total barrel length that penetrated the substratum (Banks et al., 2007).

Figure 10: A section of the central drill rack. The hand crank facilitates vertical movement of the drill string (not pictured) and also provides tactile feedback of drilling character. The white measuring tape attached directly to the drill rack (arrow) allows measurement of the penetration depth, and the length of voids, sand/rubble, or coral framework intervals. 
3.6. Core Sample Analyses and Descriptions

The extracted cores were initially aligned in core-boxes to take digital picture core logs of each sample. The core samples were then slabbed (sliced in half) longitudinally using a diamond blade circular saw in order to photograph and document the inner facies of the cores. A macroscopic visual examination of the inner facies of the slabbed cores was used to identify the coral species encountered in cores (later confirmed by V. Kosmynin). The individual core fragments were then electronically scanned with a flatbed scanner to produce digital images that were entered into Canvas X for image analysis and qualitative interpretation [FIGURE 11]. Further examinations were performed to

Figure 11: A view of a slabbed core before and after Canvas image analysis for selected features.
determine the presence of borings and boring organisms, organismal encrustations, the presence of cements, and other indications of taphonomic processes. Taphonomic descriptions and interpretations used in this study follow the summary and guidelines of Perry and Hepburn (2008) and descriptions of *A. palmata* recovered from cores are based on the observations of Blanchon and Perry (2004). In addition, the studies by Martindale (1992), Perry (1998; 1999; 2000; 2001), and Scoffin and Hendry (1984) were useful in ichnospecies identification and other taphonomic framework characteristics. For core descriptions, all grain sizes were based on a modified Wentworth-Udden Grain Size Scale from Flugel (2004, fig. 6.1). The software tools of Canvas X were used to digitally observe and manipulate the core sample images and aided in the qualitative analysis of the inner facies components, and taphonomic indicators. The images were analyzed to locate: coral material; cements; boring sponges, bivalves, and worms; vermetid gastropods; serpulid worms; coralline crusts; and the foraminifer *Homotrema rubrum*. The "smooth polygon" and "fill" tools of Canvas X were used to digitally trace and isolate core features. New digital images were produced with the selected features highlighted in various colors and segregated from one another [refer to FIGURE 11]. These images also permitted more efficient identification and placement of core features for descriptive and visual presentation purposes. Finally, the highlighted images were quantitatively processed in Matlab 7.0 (using a written program code) to determine the percentages of the space cover (in pixels) of each feature in-core.

3.7. X-Ray Diffraction Analysis

Following the descriptive analyses, the cores were sub-sampled to determine the mineralogy of coral samples by X-Ray Diffraction analysis and for suitability of
radiometric aging. Sub-samples were taken from areas as close to the top and bottom of cores as possible (essential for determining the timing of reef initiation and death described below). The fragments were cut from the core samples using the large circular saw and then broken to smaller pieces weighing ~5 g. Only unaltered coral was selected for X-Ray Diffraction analysis to provide the most accurate results and to ensure that the samples were suitable for $^{14}$C aging analysis. All X-Ray Diffraction analyses were conducted by R.P. Moyer at the USGS Center for Coastal & Watershed Studies, St. Petersburg, Florida.

3.8. $^{14}$C Radiocarbon Aging

After obtaining the results from X-Ray Diffraction analyses and confirming the samples consist of pure aragonite, they were again sub-sampled for $^{14}$C radiocarbon aging to determine their age with respect to the present day. These sub-samples weighed ~30-50 g and were taken from the same locations in cores tested for X-Ray Diffraction analysis. These ages were used to determine the timing of coral reef framework initiation and termination and reef accumulation rates. According to Pirazzoli (1996), “recrystallization and isotopic exchanges between the sample material and the environment will modify the apparent age of a sample and give misleading results. Samples that may have been contaminated by older or younger organic material, or carbonate, should also be carefully avoided”. Thus a careful choice of samples from only unaltered sections of coral that were free of borings, encrustation, and submarine cementation were selected for aging in order to obtain reliable age estimates. Standard radiocarbon aging was performed and calibrated by Beta Analytic Inc. located in Miami, Florida. The $^{14}$C radiocarbon calibration was performed using the INTCAL 04
Radiocarbon Age Calibration (Calibration issue of Radiocarbon: vol. 46 nr. 3, 2004) and the MARINE 04 Database (Darden Hood of Beta Analytic Inc., pers. comm.). The $^{14}$C ages were corrected for the $^{14}$C/$^{12}$C difference between atmospheric CO$_2$ and the ΔCO$_2$ of the surface-ocean mixed layer using the calibrated data provided by Beta Analytic Inc. Calibrated ages (cal BP) are based on the intercepts of the radiocarbon age with the calibration curve (Beta Analytic Inc.). The CALIB 5.1 freeware computer program was used to calibrate the ages from the literature and also to confirm the reported calibrated ages from this study.
4. RESULTS

4.1. X-Ray Diffraction Analysis and $^{14}$C Radiocarbon Aging

Mineralogy of the inner reef coral samples was determined by X-Ray Diffraction analysis and all samples except the upper sample from Core #4 were found to consist of aragonite. All pure aragonite samples were then prepared and processed for $^{14}$C radiocarbon aging.

Table 1: Radiocarbon ages of corals sampled within cores from the inner reef offshore Broward County, Florida. The Conventional Radiocarbon Age is the Measured Radiocarbon Age corrected for isotopic fractionation using the $\delta^{13}$C. The ages were also calibrated to calendar years (Cal BP ages) using the Conventional Radiocarbon Age (BETA Analytic).

<table>
<thead>
<tr>
<th>Name of Core</th>
<th>Coral Species Sampled</th>
<th>GPS Coordinates of Drilling Locations</th>
<th>Sample Elevation (NAVD88)</th>
<th>Measured Radiocarbon Age (years BP and range)</th>
<th>Conventional Radiocarbon Age [cor.] (years BP and range)</th>
<th>Cal BP (Calendar years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core #1 [Top]</td>
<td><em>M. annularis</em></td>
<td>26°07.482′N 80°05.515′W</td>
<td>-7.3 m</td>
<td>4,890 ± 70</td>
<td>5,290 ± 70</td>
<td>5,640</td>
</tr>
<tr>
<td>Core #2 [Top]</td>
<td><em>M. annularis</em></td>
<td>26°07.482′N 80°05.515′W</td>
<td>-6.6 m</td>
<td>5,530 ± 60</td>
<td>5,920 ± 60</td>
<td>6,330</td>
</tr>
<tr>
<td>Core #2 [Bottom]</td>
<td><em>Diploria</em> sp.</td>
<td>26°07.482′N 80°05.515′W</td>
<td>-8.0 m</td>
<td>6,190 ± 50</td>
<td>6,610 ± 50</td>
<td>7,160</td>
</tr>
<tr>
<td>Core #3 [Top]</td>
<td><em>A. palmata</em></td>
<td>26°07.546′N 80°05.519′W</td>
<td>-7.6 m</td>
<td>5,520 ± 50</td>
<td>5,930 ± 50</td>
<td>6,350</td>
</tr>
<tr>
<td>Core #3 [Middle]</td>
<td><em>A. palmata</em></td>
<td>26°07.546′N 80°05.519′W</td>
<td>-8.1 m</td>
<td>5,420 ± 60</td>
<td>5,820 ± 60</td>
<td>6,260</td>
</tr>
<tr>
<td>Core #3 [Bottom]</td>
<td><em>Diploria</em> sp.</td>
<td>26°07.546′N 80°05.519′W</td>
<td>-11.1 m</td>
<td>6,930 ± 50</td>
<td>7,290 ± 50</td>
<td>7,760</td>
</tr>
<tr>
<td>Core #4 [Bottom]</td>
<td><em>A. palmata</em></td>
<td>26°03.290′N 80°05.870′W</td>
<td>-12.4 m</td>
<td>7,130 ± 80</td>
<td>7,560 ± 90</td>
<td>8,010</td>
</tr>
</tbody>
</table>
4.2. Core #1

- Location: North site. Inner reef off Fort Lauderdale Beach just south of Birch Park on the southernmost [1st] buoy (26°07.482′N 80°05.515′W)
- Elevation: -7.2 m
- Coral species: *Montastraea annularis*, *Siderastrea* sp., *Diploria* sp.
- Dominating framework: Rubble from massive coral species (~0.35 m *M. annularis*, 0.10 m *Siderastrea* sp.)
- Length of total framework retrieved in cores: ~0.45 m coral material
- Core recovery (by percentage of total barrel length that penetrated the substratum and length of recovered material): [0.45 m/0.75 m] = 60%
- Base contact substrate: None (no base penetration due to bent core barrel)
- Age of initiation: Indeterminable (no bottom sample)
- Age of termination: 5,640 cal BP (*M. annularis*, ~0.10 m down-core)
- Interval between samples: Indeterminable (no bottom sample)
- Age difference between samples: Indeterminable (no bottom sample)
- Reef Accumulation Rate: Indeterminable (no bottom sample)
- Reef-framework thickness: Indeterminable but at least >0.50 m
- Interpreted Reef Facies Zonation: Possibly back reef massive coral rubble zone but difficult to interpret due to minimal penetration and insufficient sample

**Figure 12:** Reef profile and morphology at the drill site of Core #1 using the LIDAR bathymetric data. Light blue shading indicates massive coral framework.
Taphonomic Description: Core #1 was composed of coral rubble most of which was *M. annularis*. A small *M. annularis* colony marked the top of the core and was the largest fragment. It was followed by more *M. annularis* rubble and a short section of mixed coral rubble down-core. The lower section of this core was composed of small *Siderastrea* sp. coral fragments that were larger than the overlying mixed rubble. The core sequence contained ~37% coral material and ~63% cement observed in slabbed sections (excluding all other framework constituents; Core recovery = 60%).

Borings observed in cores are the result of sponges (*Entobia* ispp.), bivalves (*Gastrochaena* ispp.) and worms (*Trypanites* ispp.).
Top – 0.25 m unconsolidated *M. annularis* rubble. The section began as small cobble fragments -6 φ and changed to very coarse pebbles -5 φ, and ended as small cobble fragments -6 φ again.

- Upper coral clasts were the largest and had reddish/brown intraskeletal cements on the upper, lower, and outer surfaces. These cements penetrated a few cm within the coral clasts as observed in slabbed sections. The clasts were bored mostly by sponges with some worms and even fewer bivalves on internal surfaces. The outer surfaces were heavily bored and extensively altered with encrusting serpulids, vermetids, and *Homotrema rubrum*. The reddish/brown cements covered more outer-surface space than unaltered coral material.

- The lower clast of this section was completely altered and cemented. No remaining coral material could be detected, and half of the clast’s outer surface was covered by very dark reddish cement (the darkest encountered in all cores). This surface appeared to be encrusted by serpulid and vermetid calcareous tubes and globose and branching forms of *H. rubrum* (likely indicating a low-illumination, cryptic habitat setting). The slabbed section showed a fully cemented and altered material with some traces of sponge boring and *H. rubrum*.

**Middle**: Sand/Rubble – 0.10 m unconsolidated *M. annularis* and other unidentified coral rubble. Rubble fragments ranged from very coarse pebbles -5 φ to coarse pebbles -4 φ.

- Rubble fragments were both rounded and angular.

- A few small rubble clasts had coatings of the reddish/brown stained cement and there was evidence of sponge and possibly worm borings and some *H. rubrum*. 
- A small bivalve shell was completely coated by dark grey cement with some *H. rubrum*.
- The remaining few rubble clasts appeared to be *M. annularis* and had partial coatings of grey cement with some sponge borings and *H. rubrum*. One fragment had some mm thin coralline crusts.

**Bottom** - 0.10 m unconsolidated *Siderastrea* sp. rubble. Coral fragments were very coarse pebble size -5 φ.

- The upper clast had thin coating of coralline crust on upper surface. It had dark grey intraskeletal and intergranular cements with two truncation surfaces and a half cm thick coralline crust in between with some vermetids. The highly altered fragment appeared to be bored externally by sponges and possibly worms and bivalves. The internal surface was bored by sponges, worms, and possibly bivalves. *H. rubrum* formed within and on the outer surfaces. There were also encrusting serpulids on the outer surfaces. This clast appeared to be composed of more cement than remaining unaltered coral material.
- The lower clast of this section also displayed truncation surfaces but had no crusts at these areas. The transition at the truncation surface was from a *Siderastrea* sp. to a *Diploria* sp. coral. Some thin crusts appeared to be present on the lower surface with intergrown, low-relief *H. rubrum*. It was extensively bored both internally and externally by bivalves, sponges, and worms and was highly altered. There was more cement than unaltered coral material. In cryptic microhabitats within the clast, there were branched *H. rubrum* and serpulids. This clast
contained some reddish/brown stained cement, but was composed of mostly grey intraskeletal and intergranular cements.

![Pie chart showing composition of Core #1](chart.png)

**Core #1**

- Serpulid Worms: 1%
- Vermatid Gastropods: 1%
- Boring Spines: 14%
- Coral Material: 29%
- Boring Worms: 1%
- Boring Bivalves: 1%
- Crusts: 1%
- Cements: 53%
- H. rubrum: 1%

Figure 14: Contribution of the different components to the recovered material of Core #1 in slabbed sections. Core recovery = 60%.

4.3. Core #2

- Location: North site. Inner reef off Fort Lauderdale Beach just south of Birch Park on the southernmost [1st] buoy (26°07.482’N 80°05.515’W)
- Elevation: -6.5 m
- Coral species: *M. annularis, Diploria* sp., *Porites porites*
- Dominating framework: Massive coral species (~0.65 m *M. annularis*, ~0.25 m *Diploria* sp.)
- Length of total framework retrieved in cores: 1.95 m (~0.90 m massive coral species, ~0.25 m of mixed coral rubble, ~0.80 m lithified, consolidated sand)
- Core recovery (by percentage of total barrel length that penetrated the substratum and length of recovered material) : [1.95 m/3.75 m] = 52%
- Base contact substrate: Lithified, consolidated carbonate/quartz mixed sand. 
  ~0.80 m total: ~0.55 m of brown/reddish/tan lithified sand that is brittle and fine 
  grained and ~0.25 m of greyish/tan lithified sand that is denser with coarser grains 
- Age of initiation: 7,160 cal BP (Diploria sp., ~1.50 m down-core) 
- Age of termination: 6,330 cal BP (M. annularis, ~0.10 m down-core) 
- Interval between samples: ~1.40 m 
- Age difference between samples: 830 years 
- Reef Accumulation Rate: ~1.70 m/1,000 years 
- Reef-framework thickness: < 3.00 m 
- Interpreted Reef Facies Zonation: Massive coral patch reef

![Fig 15](image)

**Figure 15:** Reef profile and morphology at the drill site of Core #2 using the LIDAR bathymetric data. Light blue shading indicates massive coral framework. Patterned lines at the bottom of the core represent the pre-Holocene foundation.
Figure 16: A view of Core #2 in the core-box. Detailed description of the core is in the text body.
**Taphonomic Description:** Core #2 initiated with mixed coral rubble and fragments on a pre-Holocene surface, and changed to small colonies of *Diploria* sp. up-core. These colonies were then topped by larger *M. annularis* colonies. The core was composed of mostly *M. annularis*, then *Diploria* sp. colonies, with very little mixed coral rubble. The core sequence contained ~83% coral material and ~17% cement observed in slabbed sections (excluding all other framework constituents; Core recovery = 52%).

**Top** = 0.65 m unconsolidated *M. annularis* colonies. Uppermost colony was small boulder size -8 φ and lower colonies were large cobble size -7 φ.

- Uppermost colony was almost all unaltered coral material internally and externally except at the top and bottom of the colony. These areas had a small amount of reddish/brown stained and grey intraskeletal cements. They were bored by sponges and worms only, and had a few vermetids and *H. rubrum*.
- The middle colony had a very small and thin coralline crust near its upper surface. It had cm thick grey intraskeletal cement on the upper and lower surfaces and a high degree of boring and cementation.
- The lower colony was almost all unaltered coral except at the lower surface which had some grey intraskeletal cement and *H. rubrum*, and was bored by bivalves, sponges, and worms.
- The outer surfaces of the most altered clasts were heavily bored by bivalves, sponges, and worms, and had flat and globose forms of *H. rubrum*.

**Middle** = 0.25 m unconsolidated *Diploria* sp. colonies. The section was composed of large and small cobbles -7 φ and -6 φ.
- The upper colony was mostly all unaltered coral but was very lightly bored by 2 bivalves and a sponge. Grey intraskeletal cement was present on the lower surface and within the slabbed section.

- The lower colony was heavily bored by sponges and bivalves and had some traces of *H. rubrum*, a worm, and some serpulids in slabbed sections. Grey intraskeletal cement was abundant and ~1/3 unaltered coral material remained. The outer surfaces were heavily bored by large bivalves and some sponges and worms. It was also extensively altered with little coral material remaining.

**Bottom:** Sand/Rubble – 0.25 m unconsolidated mixed coral rubble. Fragments ranged from very coarse pebbles -5 φ to fine pebbles -2 φ.

- Consisted of angular fragments. Larger rubble fragments had partial coatings of grey intraskeletal cements.

- Small rubble fragments were almost entirely coated by grey intraskeletal cements.
4.4. Core #3

- Location: North site. Inner reef off Fort Lauderdale Beach just south of Birch Park on the 3rd southernmost buoy (26°07.546'N 80°05.519'W)
- Elevation: -7.4 m
- Coral species: *A. palmata*, *M. annularis*, *Montastrea cavernosa*, *Diploria* sp., *Siderastrea* sp., *Dichocenia* sp.
- Dominating framework: *A. palmata* (~0.90 m) and massive coral species (~1.00 m *Diploria* sp., ~0.30 m mixed coral rubble)
- Length of total framework retrieved in cores: ~2.20 m (~0.90 m *A. palmata*, ~1.30 m massive coral species)
- Core recovery (by percentage of total barrel length that penetrated the substratum and length of recovered material): [2.20 m/3.75 m] = 59%
- Base contact substrate: None (corals still present at bottom of core)
- Age of initiation: 7,760 cal BP (*Diploria* sp., ~3.65 m down-core)
- Middle age: 6,260 cal BP (*A. palmata*, ~0.70 m down-core)
- Age of termination: 6,350 cal BP (*A. palmata*, ~0.20 m down-core)
- Interval between top and middle samples: ~0.50 m
- Age difference between top and middle samples: Indeterminable, age reversal
- Reef Accumulation Rate of top and middle samples: Indeterminable, age reversal
- Interval between middle and bottom samples: ~3.15 m
- Age difference between middle and bottom samples: 1,500 years
- Reef Accumulation Rate of middle and bottom samples: ~2.10 m/1,000 years
- Interval between top and bottom samples: ~3.45 m
- Age difference between top and bottom samples: 1,410 years
- Reef Accumulation Rate of top and bottom samples: ~2.45 m/1,000 years
- Reef-framework thickness: >3.75 m
- Interpreted Reef Facies Zonation: Reef crest

*Figure 18:* Reef profile and morphology at the drill site of Core #3 using the LIDAR bathymetric data. Yellow shading indicates *A. palmata* framework and light blue shading indicates massive coral framework.
Figure 19: A view of Core #3 in the core-box. Detailed description of the core is in the text body.
Taphonomic Description: Core #3 initiated with a long section of Diploria sp. colonies. It was topped by a short section of mixed coral rubble and then A. palmata rubble up-core. The upper section of this core was composed of an ~1.00 m section of large A. palmata colonies and stumps up-core. The core sequence contained ~79% coral material and ~21% cement observed in slabbed sections (excluding all other framework constituents; Core recovery = 59%).

Top = 0.90 m unconsolidated A. palmata stumps and branches. The section began as large cobbles -7 φ and increased to small boulders -8 φ. Lower rubble fragments were very coarse pebble size -5 φ and were angular.

- The A. palmata clasts were variably bored by bivalves, sponges, and worms and the outer surfaces of the uppermost clasts were heavily bored by bivalves, sponges, and worms, and contained H. rubrum, vermetids and serpulids. The clasts contained small amounts of mostly intraskeletal but also some intergranular grey cement. The uppermost clasts down to ~30 cm contained small outer coatings of reddish/brown stained cements.

- Taphonomic alteration was most significant in the surface clast and reduced in intensity in the middle of this section before increasing again at the lower rubble interval of the A. palmata section.

- The uppermost clast had what appeared to be multiple truncation surfaces with colony reinitiation, similar to the dense bioerosion bands as described by Blanchon and Perry (2004). The clast also had a thick (cm) coralline crust with intergrown vermetids and flattened H. rubrum that became thinner (mm) down-core.
• The middle stump was large cobble-sized -7 φ, and had a high degree of
taphonomic alteration and a diverse infauna of bioeroders. These included various
boring sponges, numerous vermetids, and some bivalves. The clast also contained
the encrusting foram *Carpenteria utricularis* in conical form on its outer surface.
It is common on cryptic surfaces to ~10 m depth and on exposed surfaces at
deeper depths according to Perry and Hepburn (2008). This stump contained
numerous inverted geopetals.

• The lowermost stump was small boulder-sized -8 φ, had very low taphonomic
alteration, and was virtually all unaltered coral material except on its lower
surface (possibly a lower basal stump). This stump contained a normal-oriented
geopetal.

• The bottom of this section contained small *A. palmata* rubble fragments (very
coarse pebble size -4 φ) that were either partially or completely coated by grey
intraskeletal cements, some of which were intergranular. Taphonomic alteration
varied between these rubble clasts as some were bored by sponges and/or
contained vermetids, *H. rubrum*, and serpulids.

**Middle:** Sand/Rubble – 0.30 m unconsolidated massive coral rubble fragments. The
fragments were all angular. This section was composed of rubble clasts ranging from
coarse pebbles -4 φ to small cobbles -6 φ.

• The rubble fragments had partial grey cement coatings that were mostly
intraskeletal with some intergranular cement. Some fragments had thin coralline
crusts and were lightly bored by sponges, worms, and bivalves and also had
flattened and globose *H. rubrum*, vermetids, and serpulids. Taphonomic alteration was uniform between the rubble clasts.

**Bottom** – 1.00 m of mostly unconsolidated *Diploria sp.* colonies and massive coral rubble fragments that were all angular. This section began with a coral colony that was large cobble size -7 φ. It was followed by a short section of rubble ranging from very coarse pebbles -5 φ to coarse pebbles -4 φ. The last section was composed of small cobble sized -6 φ *Diploria* sp. colonies that graded down-core to very coarse pebbles -5 φ and ended in small cobble size -6 φ.

- The larger fragments and colonies had some intraskeletal grey cements and a small degree of boring by sponges, bivalves, and worms on both external and slabbed surfaces. Overall taphonomic alteration in these larger clasts increased down-core.
- Some clasts had both thick and thin coralline crusts with *H. rubrum* and vermetids intergrown.
- Rubble fragments varied from relatively unaltered to mostly altered with light boring and flattened *H. rubrum*, serpulids, and vermetids. One small rubble fragment possibly contained grey intergranular cement at a truncation surface.
4.5. Core #4

- Location: South site. Inner reef off Dania Beach just south of Dania Pier near the USS Memphis grounding site (26°03.290'N 80°05.870'W)
- Elevation: -8.8 m
- Coral species: *A. palmata, M. annularis, Diploria* sp., *P. porites, Millepora* sp.
- Dominating framework: *A. palmata* stumps and rubble (~0.60 m) topped with pebble to cobble-sized rubble from massive coral species (~0.50 m)
- Length of total framework retrieved in cores: ~1.85 m (~0.60 m *A. palmata*, ~0.50 m massive coral species [*M. annularis*], and ~0.60 m pebble-sized fragments of *M. annularis, Diploria* sp., *P. porites*, and *A. palmata*. Rubble grades from massive corals to *A. palmata* down-core.) ~1.70 m total coral, ~0.15 m lithified, consolidated sand

*Figure 20:* Contribution of the different components to the recovered material of Core #3 in slabbled sections. Core recovery = 59%.
- Core recovery (by percentage of total barrel length that penetrated the substratum and length of recovered material): \[1.85 \text{ m}/3.75 \text{ m}] = 50\%
- Base contact substrate: Lithified, consolidated carbonate/quartz mixed sand. 
  ~0.15 \text{ m} of greyish lithified, consolidated sand that is dense with coarse grains
- Age of initiation: 8,010 cal BP (\textit{A. palmata} ~3.60 \text{ m} down-core)
- Age of termination: Indeterminable (undatable coral material at top of core)
- Interval between samples: Indeterminable (no top sample)
- Age difference between samples: Indeterminable (no top sample)
- Reef Accumulation Rate: Indeterminable (no top sample)
- Reef-framework thickness: <3.60 \text{ m}
- Interpreted Reef Facies Zonation: Deeper reef front rubble zone

\textbf{Figure 21:} Reef profile and morphology at the drill site of Core #4 using the LIDAR bathymetric data. Yellow shading indicates \textit{A. palmata} framework, light blue shading indicates massive coral framework, and white shading indicates an interval of no recovery. Patterned lines at the bottom of the core represent the pre-Holocene foundation.
Figure 22: A view of Core #4 in the core-box. Detailed description of the core is in the text body.
Taphonomic Description: Core #4 initiated as *A. palmata* rubble on a pre-Holocene surface and graded to larger stumps and again as rubble up-core. The *A. palmata* section was topped by a sand/rubble section with mostly all massive coral rubble fragments. This core was topped with a section of *M. annularis* rubble fragments and possibly small colonies. The core sequence contained ~57% coral material and ~43% cement observed in slabbed sections (excluding all other framework constituents; Core recovery = 50%).

**Top** - 0.50 m unconsolidated *M. annularis* rubble and possibly small colonies. The section began as small cobbles -6 φ and graded to coarse pebbles -4 φ.

- Clasts were moderately bored by sponges, bivalves, and some worms on internal slabbed surfaces, and heavily bored on external surfaces. There were also some vermetids, serpulids, and *H. rubrum* on external and internal surfaces.
- The uppermost clast contained thick coralline crusts with some intergrown vermetids, while clasts further down-core in this section contained thinner crusts.
- Unaltered coral material was roughly equal to cements in this section. The cements were intraskeletal, reddish/brown in color, and partially coated the outer and some inner surfaces.

**Middle**: Sand/Rubble - 0.60 m unconsolidated mixed coral rubble fragments that were mostly angular with some rounded. This section contained fragments that ranged from fine pebbles -2 φ to very coarse pebbles -5 φ.

- The rubble clasts were the smallest encountered in all cores with some completely, partially, or not at all coated by either grey or reddish/brown stained cements. They were variably encrusted by flattened *H. rubrum*, with some globose forms in a few clasts.
Some coral rubble clasts had little to no taphonomic alteration enabling coral identification, while others were completely altered and indistinguishable. There was evidence of boring by sponges, bivalves and worms.

**Bottom** – 0.60 m unconsolidated *A. palmata* rubble that was both rounded and angular, followed down-core by larger stumps and again rubble on a pre-Holocene surface. The section began as rubble that was very coarse pebble size -5 φ and transitioned to large cobbles -7 φ and ended with very coarse pebbles -5 φ again.

- The upper rubble clasts were mostly unaltered with little cement and some boring by sponges and worms mostly on external surfaces.
- The stumps down-core were extensively altered and encrusted and were bored heavily by sponges and bivalves and lightly by worms both internally and externally. They also contained encruster sequences of corallines that directly coated the coral material which themselves were then coated by thin layers of flattened *H. rubrum* in some locations. This clast also appeared to demonstrate a potential repair growth of *A. palmata* as indicated by a truncation surface that was reinitiated by coral growth in a different orientation.
- The stumps were approximately equal in amounts of coral material to cement. Intraskletal cements were grey (a change from the reddish/brown stained cements up-core) and partially coated the outer surfaces of the stumps. They also penetrated a few cm within the stumps as observed in slabbbed sections. The side opposite of the cement coatings was relatively unaltered but lightly bored in some areas. The cements present in these clasts were the most pervasive of all *A. palmata* clasts encountered in cores.
The least altered *A. palmata* rubble clasts unexpectedly occurred at the bottom of the core before the pre-Holocene surface. It is unclear whether this was transported material down-slope from the inner reef or originated further seaward from the outer reef, which is possible due to the proximity in age.

**Figure 23:** Contribution of the different components to the recovered material of Core #4 in slabbed sections. Core recovery = 50%.
Figure 24: Core logs detailing the composition of all inner reef core samples extracted from Broward County, Florida. From left to right cores are oriented in a North to South direction. Graph includes data from this study [Core #’s 1-4], Banks et al. (2007) [Cores KB 1-2], and the descriptions of the USS Memphis trench by R.E. Dodge (unpublished) [*not in-core]. Figure drawn approximately to scale.
Table 2: Compilation of all inner reef radiocarbon ages from Broward County, Florida. Note: water depths and sample depths reported in the literature are in their original formats.

<table>
<thead>
<tr>
<th>Name of Core</th>
<th>Location and Elevation</th>
<th>Position in Core and Sample Species</th>
<th>Sample Elevation (NAVD88)</th>
<th>Conventional Radiocarbon Age [cor.] (years BP and range)</th>
<th>Cal BP (Calendar years)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core #1</td>
<td>Location: 1st Buoy (North Site) Elevation: -7.2 m</td>
<td>TOP: <em>M. annularis</em></td>
<td>-7.3 m</td>
<td>5,290 ± 70</td>
<td>5,640</td>
<td>Youngest inner reef age.</td>
</tr>
<tr>
<td>Core #2</td>
<td>Location: 1st Buoy (North Site) Elevation: -6.5 m</td>
<td>TOP: <em>M. annularis</em></td>
<td>-6.6 m</td>
<td>5,920 ± 60</td>
<td>6,330</td>
<td></td>
</tr>
<tr>
<td>Core #3</td>
<td>Location: 2nd Buoy (North Site)</td>
<td>MIDDLE: <em>A. palmata</em></td>
<td>*Sample Depth: 8.3 m below MSL</td>
<td>6,003 ± 17</td>
<td>*TIMS U/Th Age</td>
<td>6,003</td>
</tr>
<tr>
<td>Core #4</td>
<td>Location: 3rd Buoy (North Site) Elevation: -7.4 m</td>
<td>TOP: <em>A. palmata</em></td>
<td>-7.6 m</td>
<td>5,930 ± 50</td>
<td>6,350</td>
<td>2nd youngest <em>A. palmata</em> age.</td>
</tr>
<tr>
<td>Core #4</td>
<td>Location: USS Memphis Site (South Site) Elevation: -8.8 m</td>
<td>BOTTOM: <em>A. palmata</em></td>
<td>-12.4 m</td>
<td>7,560 ± 90</td>
<td>8,010</td>
<td>Oldest inner reef age. Oldest <em>A. palmata</em> age.</td>
</tr>
<tr>
<td>*Not in core</td>
<td>USS Memphis Trench (descriptions from R.E. Dodge, unpublished data) Location: USS Memphis Site (South Site) *Water depth: 7 m</td>
<td>*Not in core</td>
<td>*Sample Depth:</td>
<td>7.8 m</td>
<td>5,950 ± 90</td>
<td>6,800</td>
</tr>
<tr>
<td>Banks et al. (2007) Core</td>
<td>*Not in core</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*Not in core</td>
<td>Location: Fore reef north of Port Everglades *Water depth: 10.4 m below MSL</td>
<td>*Not in core</td>
<td>*Sample Depth: 10.4 m below MSL</td>
<td>6,010 ± 80</td>
<td>6,430</td>
<td>Surficial coral from fore reef exposure section.</td>
</tr>
</tbody>
</table>
5. DISCUSSION

5.1. Limitations of Coral Reef Core Sample Studies

A lack of knowledge of reef interiors is the result of the technical difficulties inherent in drilling through reefs, since good recovery is often restricted to framework or rubble lithosomes that are poorly characterized (Braithwaite et al., 2000). Based on 74 cores in different areas of the Caribbean, Hubbard et al. (1998) suggested that Holocene reef interiors are comprised of less than 30% of corals, and that less than half of that volume is in situ. As a comparison, estimates of reef structure in northern Queensland contain ~5% of in situ coral (Hopley, 1986 SLR; Pirazzoli, 1996). It is important to note that cores obtained using drill-rigs “represent only a partial section of the penetrated substrate”, and that unconsolidated material is often lost potentially causing any core to lack some sections of the sequence (Macintyre, 1975).

Previous drilling research demonstrates that core recovery is almost always less than 100% except in well lithified pavements, while recovery from the open framework of A. palmata is usually around 30% (Macintyre, 1996). Hubbard et al. (1997) reported recoveries ranging from ~10–46% with a mean of ~26%, Burke et al. (1989) reported total recoveries of less than 30%, and Macintyre (1975) reported recoveries of 33% or less. Banks et al. (2007) achieved core recoveries of <30% and 80% from the SE Florida inner reef. Core recoveries from this study are as follows: Core #1 = 60%; Core #2 = 31%; Core #3 = 59%; Core #4 = 45%. As a comparison for A. palmata facies, Blanchon and Perry (2004) attained recoveries of 60–100% off the Yucatan Peninsula, however they only extracted shallow (~2 m) cores from the uppermost sequences of the framework. The upper meter of Core #3 contained a comparable dense in situ A. palmata framework that allowed 80–90% recovery.
It is essential to keep a detailed record during drilling for subsequent interpretations. This is accomplished by measuring the penetration depths of core barrels into the substrate and recording intervals of smooth coring versus rapid drops by noting the tactile response of the drill. Rapid drops of the drill stem are often the only indications of voids within the reef structure or of unconsolidated sections such as intervals of sand and small coral rubble that are only recovered in traces (Macintyre, 1996; Hubbard et al., 2005). Without such records, penetration depths, reef accumulation rates, and substrate thickness and character are indeterminable.

Coral reef core samples have done much to clarify the Holocene pattern of sea-level rise but do not provide a complete understanding of reef structure. This is likely caused by low core recovery, sparse drilling locations, and the lack of a lateral perspective in cores (Braithwaite et al., 2000). According to Braithwaite et al. (2000) reef growth history is only partly reflected in facies distribution, while radiometrically defined timelines provide the only evidence of changes in rates of deposition, and without these, wide variations in interpretation are possible. Pirazzoli (1996) added that “some reservations and difficulties arise in environmental reconstruction when using cores, owing to doubts on the growth position because reef debris may be removed by wave action and deposited as rubble in other reef zones” (Pirazzoli, 1996). Braithwaite et al. (2000) also noted that the narrow perspective of cores may make it impossible to “differentiate algally encrusted in-place coral from encrusted coral debris unless in situ skeletal remains with clear basal contacts are demonstrably oriented” within cores. All of these factors and findings emphasize the importance of extracting core samples along the trend of the reef and in transects across the reef zones to attain the most complete
perspectives for interpretation of cores (Burke et al., 1989). Additionally, submerged reef substrates and facies are often optimally studied by using a combination of marine geophysical surveys and coring (Pirazzoli, 1991).

According to Perry and Hepburn (2008), examinations of “taphonomic processes are important because they exert a strong influence on the composition of coral material entering the fossil record”. Paleoecological interpretations can be impeded by the effects of taphonomic alteration since skeletal material is effectively lost from the fossil record by bioeroders and mechanical processes. Many of these processes however, leave traces of their activity and presence on and in coral skeletons and these have significant potential as indicators of the depositional environment, and also the history of framework accumulation (Perry and Hepburn, 2008). Thorough taphonomical examinations are believed to help reduce some of the aforementioned limitations of core-sample studies.

5.2. Outer Reef

The outer reef is a relict acroporid-framework reef that crests at -16 m below sea-level and is >10 m thick (Macintyre and Milliman, 1970; Lighty, 1977; Lighty et al., 1978; Banks et al., 2008). It displays a mature windward reef morphology with a spur and groove system that is essentially absent on the other, younger, reefs (Banks et al., 2007; Walker et al., 2008). Lighty (1977) examined the outer reef from a wastewater-pipe trench off Hillsboro Inlet in northern Broward County and found five distinct facies including: the back reef coral head, back reef A. cervicornis, A. palmata, fore reef coral head, and fore reef rubble facies. The outer reef has a similar geomorphologic zonation to the present day Florida Keys reefs (Shinn, 1963; Enos, 1977; Shinn et al., 1981; Lidz et al., 2006) and from “a landward to seaward direction contains a rubble apron (talus), back
reef, reef crest, a first (17m deep) and second (23m deep) terrace with spur-and-groove zones, and a fore reef slope that extends to 28 m bsl” (Banks et al., 2007). Because of their depths however, these features no longer function the same.

Lighty et al. (1978 and 1982) obtained 10 $^{14}$C ages of $A. \text{palmata}$ outer reef samples that ranged from 9,440–7,145 yr BP. Lighty et al. (1978) calculated reef accumulation rates ranging from 3.6–10.7 m/1,000 years with a mean rate of 6.6 m/1,000 years. Calibration of the original ages was conducted by Toscano and Macintyre (2003) who provided an updated range of 10,610–8,000 cal BP, demonstrating the phenomenon of uncalibrated $^{14}$C ages being younger as documented by Pirazzoli (1996) and many others. Accumulation rates were recalculated in this study using the calibrated ages (from Toscano and Macintyre, 2003) and these new rates range from 3.85–7.65 m/1,000 years with a mean rate of 5.71 m/1,000 years.

5.3. Middle Reef

The middle reef remains the least understood of the three reefs in terms of structure, composition, thickness, and age. According to Banks et al. (2008) the middle reef is a mostly continuous structure where it exists and crests at ~15 m bsl. It is linear but does not display a detectable zonation and reef framework is variably continuous in development. Frameworks are mostly dominated by massive corals and only a few patches of $A. \text{palmata}$ framework (off Palm Beach County) have been discovered to date (Banks et al., 2007 and 2008). Any frameworks that do exist are developed on or drape a well-defined antecedent slope or ridge that was interpreted as the shoreline (based on its elevation and cross section morphology) at the time when the outer reef initiated and began to accrete (Banks et al., 2007 and 2008). It is uncertain however, whether the locus
of the middle reef was in fact a shoreline or an antecedent indurated subtidal sand bar (Banks et al., 2007) since no core to date has penetrated to the base contact substrate.

Two shallow cores (1.62 and 0.62 m core length) were taken from the middle reef off Fort Lauderdale Beach (just north of the North Site) by Banks et al. (2007) and consisted of massive coral framework. Based on the reported ages of 3,730 and 5,815 cal BP from the upper 1.62 m of the reef, an accumulation rate of <1.00 m/1,000 yrs is calculated. This rate is slower than all other accumulation rates calculated for the inner reef from this study as would be expected from massive coral framework. It is important to note however that a complete core sequence through the middle reef framework and into the underlying base substrate has yet to be retrieved. It remains uncertain why the middle reef continued to grow albeit at a reduced accumulation rate, after the termination of the inner reef.

5.4. Inner Reef

According to Walker et al. (2008), the inner reef is an immature reef, most of which is patchy growth on top of an inshore ridge with no clear evidence of reef zonation. Banks et al. (2008) add that the morphology of the inner reef resembles a "complicated amalgamation of patch reefs that can be fused to form longer structures, with identifiable and frequent individual patch reefs". It is the most variable and discontinuous of the three reefs, crests at ~8 m bsl, and is believed to be ~4 m thick. The inner reef generally consists of A. palmata framework that is sometimes mixed with massive corals, but also occurs as framework and/or patch reefs consisting exclusively of massive corals. Four cores taken from the inner reef in this study and one by Banks et al. (2007) yielded ages ranging from ~8,000–5,600 cal BP.
Banks et al. (2007) reported the inner reef to be ~3.15 m thick based on a core through the reef framework off Fort Lauderdale Beach (the North Site) [refer to FIGURE 2]. It consisted almost entirely of *A. palmata* with the upper 1.50 m containing *in situ* stumps and the lower 1.50 m consisting of taphonomically altered fragments and rubble. It is the longest recovered section of *A. palmata* inner reef framework to date. An age of 6,003 ± 17 years BP [TIMS U/Th] was retrieved 1.50 m down-core.

Core #'s 1-3 of the present study were taken from the North Site, where a set of mooring buoys attached directly to the reef substrate along the trend of the reef provided relatively easy drilling access. Core #1 consists of small rubble fragments and only penetrated 0.75 m into the substrate due to a bent core-barrel. This short sequence was interpreted as representing a back reef rubble zone based on the bathymetry and taphonomy. Core #2 penetrated 3.75 m and consisted of ~2.50 m of larger massive corals and coral rubble situated on ~1.25 m of lithified sand. It was interpreted as massive coral patch reef with a calculated reef accumulation rate of 1.70 m/1,000 yrs. Core #3 contained 3.75 m of framework and represents the thickest section of the inner reef described thus far. The pre-Holocene foundation was not encountered in this core, thus evidencing a reef framework >3.75 m at this particular site. Two reef accumulation rates of 2.10 and 2.45 m/1,000 yrs were calculated from this mixed massive coral and *A. palmata* facies. The observed taphonomy from the uppermost meter of framework displayed an *A. palmata* reef crest facies with a 'catch-up' or shallowing upward signal in both observed taphonomy and fossil reef biota before the eventual reef demise (Perry and Hepburn, 2008). The remainder of the core consisted of massive corals and rubble. The two ages from the upper *A. palmata* section at 0.20 m and 0.70 m depth in-core
displayed a potential age reversal, however the age ranges overlap (the upper clast is 6,450–6,270 cal BP and the lower clast is 6,370–6,160 cal BP). The upper clast displayed evidence of inverted geopetals while the lower clast displayed a normal geopetal, potentially making them even closer in age and possibly even representing the same original growing colony. It might suggest however, that the upper clast is not in situ.

At the South site near the USS Memphis trench, 10 coral samples (6 A. palmata, 4 M. annularis) were collected in outcrop by R.E. Dodge [FIGURE 25] and had $^{14}$C ages ranging from 7,420–6,800 cal BP (depths, ages and calibrations published in Toscano and Macintyre, 2003 as Precht et al., unpublished data). No clear reef zonation was evident however, and the trench revealed a facies that consisted mostly of A. palmata with some scattered massive coral heads (R.E. Dodge, pers. comm.). A second core by Banks et al.

**Figure 25:** Image of the trench created by propwash from the USS Memphis submarine. SCUBA diver for scale.
slightly south of the trench contained ~1.10 m of thick branches of *A. palmata* in a dense framework and was interpreted as a reef crest facies. Fragments were “lined by dense, grey to reddish peloidal micritic cements with encrustations of *H. rubrum*, coralline algae, were moderately bored by bivalves and sponges and taphonomic alteration was highest in the top 10 cm of the core, after which the alteration decreased, then increased again toward the bottom” (Banks et al., 2007).

Similar sequences of framework and taphonomic alteration were observed from the upper meter of the present study’s Core #3 which was taken from the North Site and was also interpreted as a reef crest facies. Core #4 was taken near the trench from what appeared to be a slightly deeper reef front zone. The *A. palmata* section of Core #4 began 1.50 m down-core as small rubble clasts that were slightly altered and changed to larger clasts that were highly altered by borings, encrustations, and abundant skeletal pore-filling cements. Judging by their observed taphonomy, it is also possible that these clasts may have originated from a reef crest zone before they were deposited. The lowest section unexpectedly consisted of the least altered *A. palmata* rubble clasts that occurred at the bottom of the core before the Pre-Holocene surface. Based on the stark differences between the clasts of the *A. palmata* section and the amount of rubble throughout the entire core, this core may have sampled a reef area that experienced storm-induced accumulation (Perry, 2001). It is unclear whether the ^14^C aged *A. palmata* coral (8,200–7,860 cal BP) retrieved from the bottom of the core was in situ, transported material from somewhere on the inner reef, or if it originated further seaward from the outer reef.

From a wastewater-pipe trench, Shinn et al. (1977) described the inner reef off Virginia Key (just south of South Beach, Miami) as initiating around 5,580–5,770 cal BP
He found the reef to be ~3.70 m thick and to consist exclusively of massive corals. It is unclear why this particular reef area initiated much later than the inner reef off Broward County given that the water depths are comparable. One possible explanation is its proximity to Biscayne Bay. The Holocene transgression would have flooded the area and likely produced deleterious waters for sensitive reef corals in the surrounding area (Lidz and Shinn, 1991). This delayed reef initiation (in comparison to the SE Florida reef tract) may have only begun once turbidity and water clarity were ameliorated. According to Wanless (1969), Biscayne Bay began flooding around 5,400 BP while Lidz and Shinn (1991) stated that most of the Bay was flooded by 4,000 BP.

5.5. Intermediate Ridges

Structures morphologically similar to the middle reef occur in the sandy areas between the inner and middle and between middle and outer reefs (Banks et al., 2007). Shinn et al. (1977) described an intermediate ridge from a dredge site exposure off Bal Harbour in Miami-Dade County between the inner and middle reefs. He found the reef to contain 2.40 m of massive coral framework and initiated around 7,430–6,930 cal BP (calibrated in this study using CALIB 5.1). Based on sub-bottom profiles in central Broward County, the intermediate ridge between the middle and outer reefs appears to be a series of patch reefs, some of which have a high vertical relief (Banks et al., 2007). According to Banks et al. (2007) the intermediate ridges are “low ridge-like structures that are mostly covered with sediment and are not observed on all sub-bottom profiles. It is unclear which of these structures are framework ridges or lithified sand ridges, since evidence for both exists”.
5.6. Pre-Holocene Foundation

Several nearshore ridges in Broward County consist of coquina and carbonate/quartz mixed sand (Banks et al. 2007). Shinn et al. (1977) described two reef outcrop locations off Miami that are interpreted as being from the inner reef and an intermediate ridge (between the inner and middle reefs). The inner reef site was 3.70 m thick and established on a laminated soilstone crust on a semi-lithified lightly cemented quartz and carbonate sand. The intermediate ridge site was 2.40 m thick and established on a laminated soilstone crust on lightly cemented cross-bedded quartz and carbonate sand. Patches of terrestrial plant root systems and land snails were observed in both underlying sand deposits and suggested the features were of “eolian origin, likely as parallel coastal dunes similar to those existing on the coast today” (Shinn et al., 1977). Banks et al. (2007) also found an underlying lithified sand deposit in one of their inner reef cores in Broward County. Cores on the inner reef from the present study (Core #2 and Core #4) indicate that the reef is situated on lithified consolidated carbonate/quartz mixed sand that sometimes contains ooids. The longest section of this substrate retrieved in cores was ~1.25 m from Core #2. This base contact substrate was recovered from 2 of the 4 cores and was either tan/reddish or grey. This is in agreement with the notions that the SE Florida reef tract is controlled by underlying dune/ridge topography as the reefs were established on Late Pleistocene beach ridges (Shinn et al., 1977; Lidz, 2004; Banks et al., 2007 and 2008).

5.7. Coral Reef Growth and Responses to Holocene Sea-Level Rise

The stages of coral reef development are primarily controlled by the depth and topography of the structures on which the reefs were established and by the position and history of local postglacial relative sea-level (Lighty et al., 1982; Pirazzoli, 1996).
Tectonic activity is also a very important control however the SE Florida platform has been tectonically stable throughout the Holocene, since the Cretaceous period (Smith and Lord, 1997). The pantropical establishment of present-day coral reefs began in the Holocene as the rate of sea-level rise was decelerating in what are now ~10–30 m water depths (Pirazzoli, 1996; Braithwaite et al., 2000). According to Pirazzoli (1996), reef growth in the study region was dominated by a shallow-water framework situated on the shelf-edge platform ~20–30 m deep in the early Holocene.

The rate, coral species composition, and mode of coral reef accretion (aggrade, prograde, retrograde, backstep) are influenced by the interplay between severe storm events (i.e. hurricanes and tropical cyclones) and fairweather hydrodynamic conditions (Braithwaite et al., 2000, fig. 7), with the effects of changing sea level superimposed. Moderate hydrodynamic energy levels without severe storm events allow a continuous primary reef growth frame to form, while in high-energy settings influenced by severe storms, the net rate of accretion is reduced because growth is truncated by catastrophic events that require time for the reef biota to reestablish. Severe storms destroy the continuity of reef structures and also produce large amounts of coarse rubble that can subsequently be deposited in other areas (Braithwaite et al., 2000; Kennedy and Woodroffe, 2002; Blanchon and Perry, 2004). The resulting accumulation is a secondary framework that consists almost entirely of encrusted coral debris that may be colonized by corals, and is shifted landwards of the growing margin that may or may not be preserved (Braithwaite et al., 2000). The effects of storms on the sequences and taphonomic character of the SE Florida reef tract has not been examined by others and is
not obviously detectable from the observations thus far except for the previously mentioned rubble sequence of Core #4.

Hubbard et al. (1997) stated that “from a geologic perspective, the geometric relationship between reefs and their surrounding facies reflects a dynamic interplay between the average rate of sea-level rise and the long-term production of carbonate along the margin that is being affected”. The effects of sea-level rise on the patterns of reef development are well documented in the internal frameworks of western Atlantic/Caribbean reefs and can generally result in three growth styles termed Keep Up, Catch Up, and Give Up reefs (Neumann and Macintyre, 1985; Macintyre, 2007). Keep Up reefs are characterized by reefs that accrete at a rate approximately equal to the rate of sea-level rise or if sea level is stationary and the reefs are shallow enough to keep pace. During a slow sea-level rise barrier reefs may retrograde (accumulate landwards), while fringing reefs may prograde (accumulate seawards) and can eventually become barrier reefs offshore (Pirazzoli, 1996). Catch Up reefs occur during rising sea-level intervals, and aggrade (accumulate upwards) at a rate greater than the rate of sea-level rise and can eventually become Keep Up reefs if conditions are favorable. Give Up reefs result from a rapid rise in sea level that cannot be matched by the rate of reef accretion and eventually accumulation of the reef system terminates. Many fossil reef systems have remained submerged and have been preserved underwater on continental shelves (Pirazzoli, 1996; Macintyre, 2007). In addition, during a sea-level rise that is too fast for coral reefs to keep pace, reef backstepping may occur where the demise of one reef will be followed by the landward establishment of a new reef trend on a shallower substrate (Hubbard et al., 1997; Braithwaite et al., 2000; Blanchon et al., 2009). The Holocene transgression caused
the SE Florida outer reef to backstep to the present-day location of the inner reef and eventually they ceased vertical accumulation and became Give Up reefs in response to sea-level rise (Walker et al., 2004; Banks et al. 2007 and 2008).

Habitat maps compiled by Moyer et al. (2003) have described the present-day biogeographical community structure of BC reefs, revealing dominance by mixtures of algae, soft corals, zoanthids, and sponge reef-occupying communities throughout Broward County. Moyer et al. (2003) reported that scleractinian coral cover was low in all areas and *M. cavernosa* dominates as the major hermatypic scleractinian and *A. palmata* was largely absent. There are presently 6 total living colonies of *A. palmata* in Broward County (K.W. Banks, pers. comm.). Several dense patches of *A. cervicornis* communities do thrive however on the nearshore ridge complex (Vargas-Angel et al., 2003). The modern SE Florida reef tract communities pale in comparison to the once flourishing reef ecosystem.

The Holocene transgression dynamically altered the overall history of western Atlantic/Caribbean coral reefs. According to Macintyre (2007), it involved Give Up reefs on the outer slopes drowned by rapid meltwater pulses, or on the shelf edges terminated by stress conditions caused by shelf-flooding, and finally Catch Up and Keep Up reefs on the shelves, but also Give Up reefs caused by exposure to deleterious waters originating in their shallow lagoons (but see Hubbard et al., 2008 and Hubbard, 2009). These internal reef frameworks provide exceptional examples of the patterns of reef development in response to sea-level rise that occasionally rose in rapid jumps (Blanchon and Shaw, 1995). The reefs did not always survive but the zooxantellate corals were able to
reinitiate reef building, and ultimately demonstrated that coral reef communities possess an impressive ability to survive conditions of rapidly rising sea level (Macintyre, 2007).

Evidence for the effects of Holocene sea-level rise on coral reefs is readily observed from the geological record of the SE Florida reef tract. During the early Holocene, the outer reef (which initiated as a fringing reef) developed into a classical Caribbean barrier reef system, complete with spur-and-groove zones and a distinct reef zonation. The available 14C ages indicate it initiated >10,610 cal BP and terminated at ~8,000 cal BP. Inner reef 14C ages obtained from the lowest sections of the cores from this study [refer to FIGURE 24 and Table 2] have age ranges of 7,860–7,660 cal BP from a Diploria sp. sample and 8,200–7,860 cal BP from an A. palmata. The A. palmata sample may have been transported material based on its taphonomic characteristics. Using the more reliable age from the Diploria sp. sample reveals the initiation of the inner reef as a massive coral species community within a few hundred years after the termination of the outer reef. This backstep sequence in response to early Holocene sea-level rise was originally proposed by Banks et al. (2007), but they lacked the lower initiation dates that this study has provided. The backstep resulted in inner reef growth from 7,860–5,560 cal BP, but not the full development of a complete fringing reef system. Rather these were patch reefs with a clear biotic zonation of massive coral patch reefs that were fused together in some areas (likely the result of antecedent topography), and A. palmata dominated patch reefs, forming on topographic highs containing up to ~4 m of coral framework. These observations suggest that A. palmata communities were relatively dense in some areas, but scattered and short-lived. This is confirmed by the available ages and by plotting the known locations of A. palmata from core samples and
outcrops on the LIDAR bathymetry and observing the more developed reef framework [FIGURE 26]. It appears that *A. palmata* framework locations were controlled by the height and morphology of their bases, whether pre-Holocene foundation or Holocene massive coral patch reefs, as evidence for both exists.

*Figure 26:* Close-up view of the LIDAR bathymetry at the North [a] and South [b] sites. *A. palmata* framework was found in cores at the locations of Core #3 and Core KB1 in [a] and Core #4 and Core KB2 in [b]. Note the more prominent and developed reef structures at those particular locations. Red dots in [a] indicate locations of mooring buoys.
6. SUMMARY AND CONCLUSIONS

This study has yielded the youngest (5,850–5,560 cal BP) and the oldest (7,860–7,660 cal BP) ages obtained from the inner reef of the SE Florida reef tract thus far. An age range of 8,200–7,860 cal BP was obtained from an A. palmata sample in Core #4, but it is unclear whether the sample was transported rubble or if it originated there. Excluding that particular sample, this study establishes the age range for reef accumulation of the SE Florida inner reef from ~7,860–5,560 cal BP.

The ages obtained from A. palmata corals in this study ranged from 6,450–6,160 cal BP. Ages from A. palmata corals at the USS Memphis site ranged from 7,250–6,800 cal BP (Toscano and Macintyre, 2003) while the youngest reported age is 6,003 +/- 17 years BP [TIMS U/Th] (Banks et al., 2007). The ages demonstrate that A. palmata existed as a framebuilder on the SE Florida inner reef from ~7,250–6,000 cal BP.

Even though A. palmata framework construction was short-lived on the inner reef (~7.2–6 ka cal BP), it was able to contribute to the relatively significant reef structure that accumulated from ~7.8–5.5 ka cal BP. In comparison, accumulation of A. palmata framework on the outer reef occurred from >10.6–8 ka cal BP (twice as long as the inner reef), and was reported as being >10 m (Lighty, 1977), making it ~3 times as thick overall as the inner reef. In addition, the outer reef attained accumulation rates (recalculated in this study) ranging from 3.85–7.65 m/1,000 years (mean = 5.71 m/1,000 years), while the inner reef had rates ranging from 1.70–2.45 m/1,000 years (mean = 2.08 m/1,000 years) from cores and a rate of 4.25 m/1,000 years from the USS Memphis trench samples collected in outcrop. The enhanced accretion rate at this location further demonstrates the patchy distribution of A. palmata framework on the inner reef. This draws the conclusion that the dominance of A. palmata and its effects on the overall
development and thickness of the inner reef was never as significant as it was on the outer reef. This was likely a result of the early termination and shorter growth interval of the inner reef for which the causes are still unknown.

The inner reef is almost certainly a constructional feature and not merely depositional (i.e. a storm-ridge rubble accumulation) as it has been suggested (Blanchon, 2005). This is based on the observed taphonomy and because the available $^{14}$C ages for the timing of the initiation and termination of the outer reef (~10.6–8 ka cal BP) and the inner reef (~7.8–5.5 ka cal BP) do not overlap. They represent two different episodes of reef growth at two different locations; one at the shelf edge and the other landward, on the inner shelf. These locations are >1 km apart and illustrate a backstepped reef system similar to backstepped reef sequences described in the fossil record from other locations such as Mexico (Blanchon et al., 2009), St. Croix (Hubbard et al., 2005), and Puerto Rico (Hubbard et al., 1997) for example.

Examinations of the taphonomic characteristics of cores permitted the distinction between reef zones. This was evident by the differences in taphonomy and the proportion of coral material to cements between Core #’s 1 and 4 to Core #’s 2 and 3 [refer to FIGURES 13, 15, 17, and 19]. A greater proportion of coral material distinguishes the reef zones that facilitated greater and faster active reef accumulation (i.e. reef crest).

This study also supports the notions of Pandolfi and Jackson (2007) that the ecological continuity that existed throughout the Pleistocene and Holocene has recently been lost. That pattern was a consistent Caribbean reef zonation that involved $A.\ palmata$ dominating the shallow reef crest and reef front zones while massive type corals dominated the peripheral and deeper zones (Lighty, 1977, fig. 1 and Gladfelter et al.,
1978, fig. 2). The zonation and ecological pattern of the inner reef during reef growth (~7.8-5.5 ka cal BP) was comparable to that observed on most modern Caribbean reefs up to the 1970’s, but that is no longer visible in many areas (Precht and Miller, 2007). Thus the present loss of A. palmata in many areas in the Caribbean is indeed unsettling, since such a loss on the Broward County inner reef (and outer reef) resulted in the termination of rapid reef-building.
7. REFERENCES


Rutzler, I.G. Macintyre (eds.), The Atlantic Barrier Reef Ecosystem at Carrie Bow Cay, Belize, I, Smithsonian Contributions to Marine Science. 12: 63-75


### REPORT OF RADIOCARBON DATING ANALYSES

**Dr. Anthony S. Santekopulos**  
Report Date: 2/17/2009

**Material Received:** 1/26/2009

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*Data and reported as RTRC carbon/Carbon dates before present present “present” = AD 1950s. by international convention the marine reference standard is the 1950 sea level and the terrestrial reference standard is the marine 1950 sea level. All dates are presented in 2σ error terms (68% confidence limits). Uncertainties for the marine 1950 sea level are based on the marine isotope stratigraphic time scale (MIS) and the terrestrial reference standard is the marine 1950 sea level. All dates are presented in 2σ error terms (68% confidence limits). Uncertainties for the terrestrial 1950 sea level are based on the marine 1950 sea level.*

The **Conventional Radiocarbon Age** represents the mean of the Radiocarbon measurements for marine samples. **Calibrated** using the sea level 13°C correction equation since the Conventional Radiocarbon Age and calibrated using an assumed climate 13°C correction and radiocarbon age for initial use. **The Calibrated Radiocarbon Age is age that corrects the calibrated age and is based on the marine 13°C calibration dataset for both samples.**
### REPORT OF RADIOCARBON DATING ANALYSES

**Dr. Antonius Salaheldin**

North Southem University

Material Received: 3/21/2000

### Sample Data

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**Notes:**

- Radiocarbon dates are reported in years before present (BP) as of 1950. By International convention 14C dates are reported in the 20th century using the scale BP. For example, the 20th century is from 1901 to 2000 BP.
- Elemental and fractionation correction and 2σ calibration ranges are based on the international calibration standards. Measured 14C/12C ratios were calculated relative to the PDB standard.

The Conventional Radiocarbon Age represents the Measured Radiocarbon Age corrected for isotopic fractionation. Nominal ages are calculated using the delta 14C. On rare occasions when the Conventional Radiocarbon Age is calculated using an unknown delta 14C value, and the Conventional Radiocarbon Age will not be displayed. The Conventional Radiocarbon Age is not reliable calculated.

- The 2σ (95%) calibrated range is calculated from the Measured Radiocarbon Age and is listed at the Two Sigma Calibrated range for each sample.