Taphonomy of the Late Pleistocene Key Largo Limestone: A Comparison of Modern and Ancient Coral Reef Ecosystems

by

David Weinstein[1]

Advisors:

Dr. Alan J. Kaufman[1]
Associate Professor

Dr. Thomas R. Holtz[1]
Senior Lecturer

Field Advisors:

Dr. Robert N. Ginsburg[2]
Carbonate Sedimentologist

Dr. J. Rodrigo Garza-Perez[3]
Professor/Researcher "C"

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[1]University of Maryland
[2]Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami
[3]UMDI-Sisal, UNAM

ABSTRACT

Understanding the transformation of unconsolidated sediments into their lithified equivalents is an essential concept in geology, and is especially complex for coral reef deposits accumulating at marine and terrestrial interfaces. Because corals are used as paleoclimatic and paleoenvironmental proxies, it is important to identify the extent of alteration to their skeletons. The geographic proximity of ancient limestone reefs and modern reefs in southern Florida provides an ideal location to study coral taphonomy in similar systems separated by over 100,000 years. Linear transects of *in-situ* coral from living Florida Keys patch reefs (representing the once-living reefs of the Key Largo Limestone) and from fossilized patch reefs in the Pleistocene-aged Key Largo Limestone at Windley Key, Florida were compared to gauge the extent of alteration with time. The Key Largo Limestone *in-situ* coral coverage was ~21% while the *in-situ* coral coverage of the modern counterpart was ~33%, suggesting that taphonomic processes reduced coral coverage by ~38%. Ultimately, bioerosion of coral skeletons is most likely the largest cause of alteration and loss of *in-situ* coral coverage. Fine scale X-ray diffraction and carbon and oxygen isotopic analysis of a serially sectioned fossilized coral representative sample were used to demonstrate both biological "vital" effects of coral calcification similar in both modern and ancient examples, and the extent of alteration of the fossilized coral due to interactions between seawater and meteoric fluids, which flushed through the deposit when exposed during sea level regressions. The influence of meteoric water caused the dissolution and re-precipitation of carbonate material, mediating mineralogical and isotopic transformations. The slices of the sample were also used to create a 3-D textural map of primary and secondary phases associated with coral taphonomy. The results of this integrated taphonomic study of an ancient coral reef may be used to help calibrate coral-based paleoenvironmental proxies.

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INTRODUCTION

Coral skeletons are constantly modified – even while the organisms are alive – as they are lithified and ultimately become part of the geological rock record (Stanley, 1966; Greenstein, Curran and Pandolifi, 1998; Holmes et. al., 2000). However, few studies have examined coral taphonomy (fossilization process) by directly comparing living, unconsolidated coral to their preserved limestone counterparts. Southern Florida offers an unparalleled opportunity to examine the taphonomy of coral reef communities. Because living reefs grow in the open ocean adjacent to fossilized ancient reefs exposed on land in the Florida Keys, we can: 1) directly compare the extent of coral coverage in modern and ancient examples; and 2) evaluate the extent of alteration by quantifying the amount of bioerosion while the corals are submerged, and of alteration under the influence of meteoric fluids when corals are exposed.

In general, taphonomy pertains to all processes responsible for the incorporation of a living organism into the fossil record (Brett and Baird, 1986). These processes include physical, chemical, and biological alterations as the organism and surrounding sediments are cemented and lithified into rock. The quality of fossil preservation is primarily dependant on the degree of alteration induced by bioerosion and early diagenesis occurring at, or in close proximity to, the original depositional environment (Brett and Baird, 1986). The study of both living and fossilized coral reefs allows geologists to generate information about present and past environmental conditions, as corals are sensitive gauges of the integrity of reef ecosystems (Greenstein and Pandolfi, 1997). The validity of some coral research, however, depends on whether the fossil reefs studied are representative of ancient living reefs; hence a quantitative understanding of alteration is warranted prior to any paleoenvironmental or paleoclimatic interpretations.

The objective of this research is to evaluate the extent of change in *in-situ* coral coverage between the Pleistocene-aged living reefs represented by the Key Largo Limestone and the coral coverage actually recorded in the preserved limestone record. Using modern Florida Keys patch reefs as a proxy to their once-living Pleistocene counterparts, coral coverage – obtained from the Atlantic and Gulf Rapid Reef Assessment (AGRRA) database (Marks, 2006) − was compared to the preserved Key Largo Limestone coral coverage to ascertain the percent loss of *in-situ* coral coverage. Preserved coral coverage was determined by measured linear transects of the Key Largo Limestone on well-exposed quarry walls at Windley Key, Florida. Textural, X-ray diffraction and stable isotopic analyses were used to formulate interpretations for the large scale loss of coral coverage and to produce a 3-D computer image of sediment accumulation and alteration in a representative fossilized coral sample. The null hypothesis for this research is that bioerosion and secondary alteration has not resulted in statistically significant spatial change in the distribution of recognizable coral.

CORAL FOSSILIZATION

The factors attributed to coral alteration are biological and physical processes, early diagenesis, and chemical interactions. To understand the history of coral fossilization, it is important to detail the processes that occur while the coral is alive,

when it is dead but submerged in seawater and eventually entombed in carbonate sediments, and when it is subsequently exposed above sea level to meteoric fluids.

Biological and Physical Erosion

Even when alive and growing, organisms like echinoderms, tube worms, sponges, bivalves, bryozoans, foraminifera, coralline algae, coelobites (cavity-dwellers, including some types of the organism previously mentioned) and parrot fish bore into or abrade coral carbonate in search of food and shelter (Gischler and Ginsburg, 1996; Greenstein and Pandolfi, 2003; Carriero-Silva, McClanahan and Kiene, 2005). Biological activities create voids and fine-grained sediment that accumulate within and around the coral structures. Coelobites contribute significant amounts of internal sediment to the system because they proliferate in coral rubble (Fig. 1A), the most common deposit of most reefs (Gischler and Ginsburg, 1996). Bioerosion is a major limiting factor in the rate and pattern of coral reef growth (Holmes et al., 2000), and is the most obvious alteration of *in-situ* Key Largo Limestone coral heads (Fig. 1B). The degree and pattern of biological modification is related to the exposed surface area, the duration dead coral remains intact and exposed, the nutrient availability (Holmes et al., 2000; Greenstein and Pandolfi, 2003), and the diversity and abundance of bio-eroding organisms (Brett and Baird, 1986; Greenstein and Pandolfi, 2003).

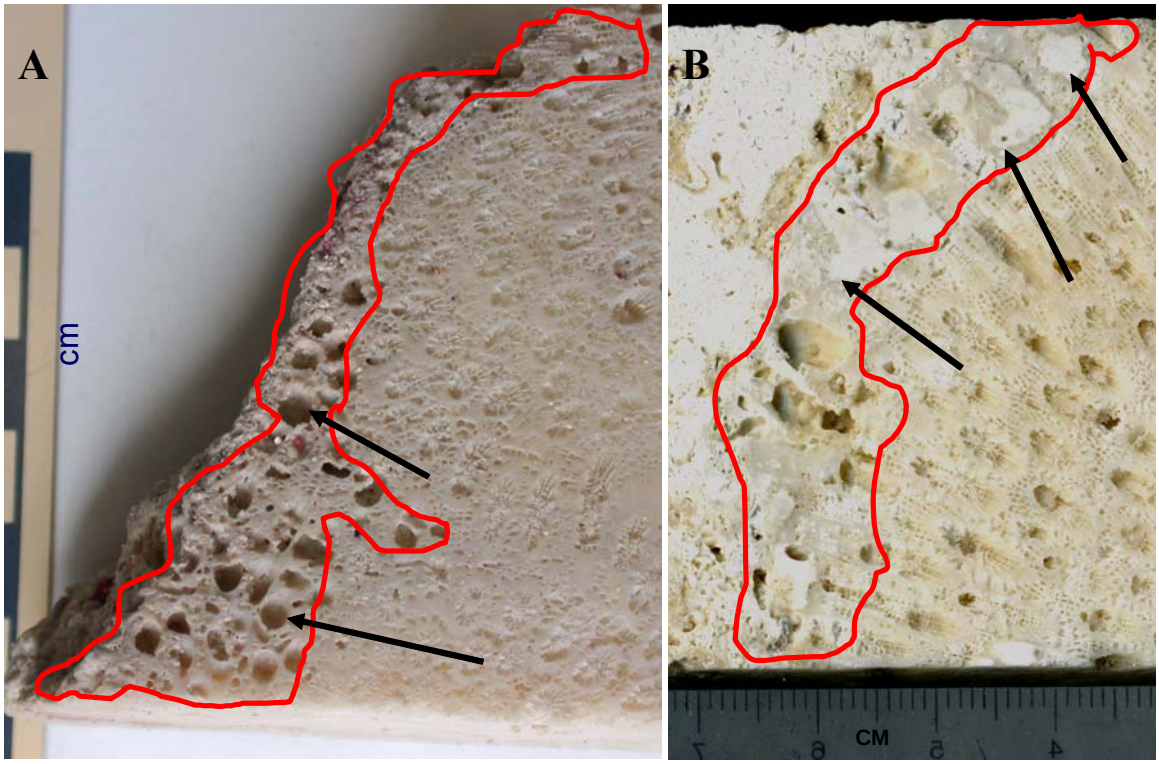

Figure 1: Modern *Montastraea annularis* coral rubble (A) from Biscayne Bay. The circled regions identify bioeroded sections of the coral. The arrows point to bore holes. Evidence of similar bioerosion is preserved in a slice of fossilized Pleistocene *Montastraea annularis* (B) from the Key Largo Limestone. The enclosed area is analogous to that of the coral rubble in A. The arrows indicate bore holes that have been filled in with fine-grained internal sediment.

The degree of bioerosion is often independent of coral growth form. For example, there was no observed growth-form effect on the degradation of the corals in the modern reefs of Florida (Greenstein and Pandolfi, 2003). However, the taxonomic composition actually found in different assemblages may be based on growth form. Massive corals are usually underrepresented in death assemblages (thanatocoenosis; Fig. 2), but are the most common growth form found in fossil assemblages. Branching corals are usually overrepresented in death assemblages (as coral rubble) because they are easily broken up by wave activity. The fragile branch corals are less commonly found in fossil assemblages because they are usually highly exposed to bioerosion (Greenstein and Curran, 1997).

The widespread distribution of well-preserved corals in their original growth position within the Key Largo Limestone is often attributed to a relatively quick burial of the reef (Hoffmeister and Multer, 1968; Greenstein et al., 1998; Greenstein and Pandolfi, 2003). Rapid burial significantly limits the effects of physical processes (such as abrasion, fragmentation, dissolution, corrosion, re-orientation, and transportation); it also prevents certain organisms from boring into coral (Brett and Baird, 1986; Greenstein and Pandolfi, 2003). Ultimately, the standing corals are encased in broken fragments of other corals and carbonate shells, as well as carbonate ooids, grapestones, and sand and silt-sized sediment from calcareous algae (e.g. *Halimeda*; Stanley, 1966). Fossils composed of unstable aragonite may also be preserved by early marine cementation, locking the fossil in place (often in growth position) and protecting the fossil from relocation (Walker and Diehl, 1985). The combination of various eroding processes while still in the ocean cause the most significant alteration to corals.

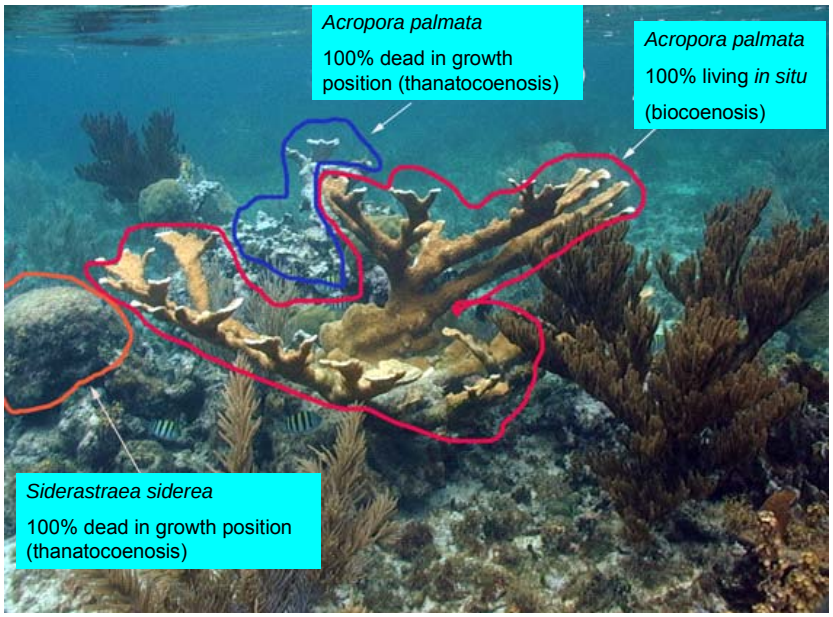

Figure 2: *Acropora palmate* colony, from the Dominican Republic, exhibit branching coral growth from. The colony demonstrates the difference between living assemblages and death assemblages. A common assumption when studying coral alteration is that the incorporation of living coral into the fossilized recorded entails the process of life assemblages (biocoenosis) turning into death assemblages (thanatocoenosis) and death assemblages (dead coral rubble and dead *in-situ* colonies) turning into fossilized assemblages (Pandolfi and Greenstein, 1997). However, this assumption is not often observed in the Pleistocene reef record (Greenstein, Curran and Pandolfi, 1998), implying a complex transitional process. Picture is courtesy of Rodrigo Garza-Perez.

Post-depositional Alteration

As long as the Key Largo Limestone corals remained submerged, marine cements would continue to lithify the compacting sediments as a consequence of calcite super-saturation in the shallow marine environment. However, as sea level fell – due to the buildup of polar sea ice and continental glaciers associated with the ensuing ice age (Fig. 3) – the Key Largo Limestone was exposed. Exposure allowed for meteoric fluids (fresh water under-saturated with respect to calcite and low in magnesium) to have flown through the highly porous, permeable sediments. These fluids would have caused dissolution, erosion, and karstification (Fig. 4), as well the re-precipitation of new carbonate cements (Stanley, 1966; Brett and Baird, 1986).

Alteration of exposed corals is primarily related to climate and precipitation. The Florida Keys are sub-tropical, with an average rainfall of 150 cm/year (Fruijtier, Elliott and Schlager, 2000). Alternating periods of tropical rainfall, drought, and intense heat affect rates of dissolution and microbial activity in corals (Hoffmeister and Multer, 1968). The rate of dissolution is related to the original mineralogy of the sediments (aragonite for these corals). The transformation of particulate lime muds to crystalline micrite and ultimately coarser grained microspar decreases porosity from 50% to as low at 2%. Successive diagenesis of the lime mud may mask previous diagenetic alteration, highlighting the complexity of the lithification process (Reeder, 1975).

The proportion of primary aragonite relative to secondary calcite, which results in a 7-8% volumetric increase, is one monitor of alteration (Stanley, 1966). When Stanley analyzed a poorly sorted sediment (the most common sediment found at Windley Key) with X-ray diffraction, there was less aragonite (25%) than what the expected original

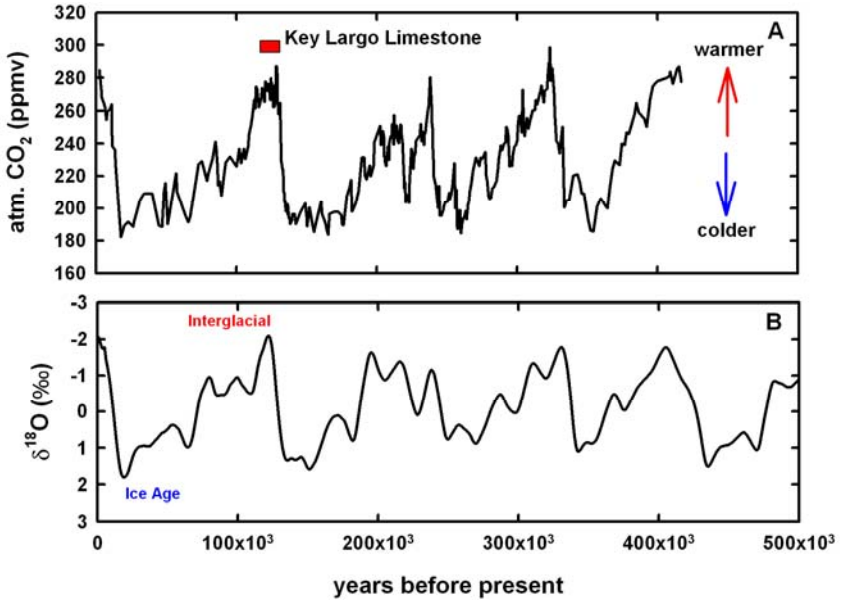

Figure 3: Historical record of atmospheric CO_2 concentration (A) from the Vostok ice core in Antarctica over the past 410,000 years (Petit et al., 1999), with high values related to warmer climate and low values related to ice ages. The history of global ice volume (B) is based on benthic foraminiferal $\delta^{18}O$ values from SPECMAP (Imbrie et al., 1989; McIntyre et al., 1989), which provide an estimate of sea level. During the last glacial maximum about 18,000 years ago (labeled as "Ice Age" in B), sea level may have dropped over 150 meters relative to today. The Key Largo Limestone accumulated during the prior interglacial (see A), where temperatures were similar to today, although sea level was somewhat higher.

Figure 4: Karst breccia exposed in a Windley Key quarry wall of the Key Largo Limestone (approximately 1 meter deep). The interaction of meteoric fluids on the exposed unit led to dissolution of the carbonate and the formation of pits and caves, which were filled in with iron oxides (red coloration) and broken fragments of angular, calcareous solution breccia. Picture courtesy of Alan J. Kaufman.

mineralogy would have been. Carbonates originally composed of aragonite may even completely dissolve, leaving behind a cast of coarse-grained (or sparry) calcite, which would further lithify the unit. The introduction of carbon dioxide from the atmosphere, and the decay of organic matter could also promote dissolution of the exposed carbonate material.

The interaction of corals with meteoric water and carbon dioxide from the atmosphere or from the re-mineralization of organic carbon can also induce changes in the oxygen and carbon isotope compositions of the coral as well as newly-formed cements (Zhou and Zheng, 2005; see **Discussion** for further details on isotopic alteration of corals). In sum, the combination of various biological, physical, and chemical factors associated with the taphonomic process created a complicated post-depositional history of the Key Largo Limestone (Hoffmeister and Multer, 1968).

GEOGRAPHICAL AND STUDY SITE DESCRIPTION

The Pleistocene-aged Key Largo Limestone is geologically young and in close proximity to similar modern patch reefs in the Florida Keys. The formation spans from Miami Beach southwest to the Dry Tortugas (Fig. 5; Stanley, 1966; Hoffmeister and Multer, 1968). Surface exposures extend from Soldier Key to Big Pine Key, where the formation dips below the younger Miami Oolitic Limestone (Stanley, 1966).

The focus of this study is the uppermost section of the Key Largo Limestone (Q5 unit), which formed during the Sangamon Interglacial Stage (Stanley, 1966; Hoffmeister

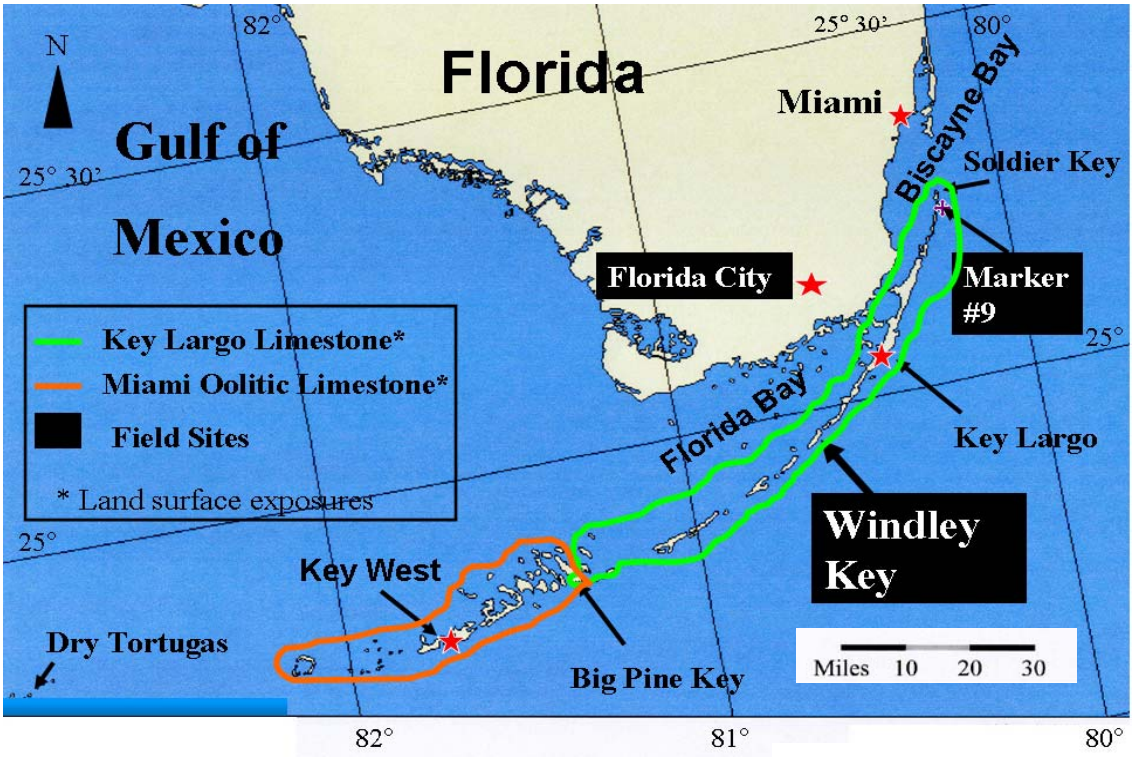

Figure 5: Geographical extent of the Key Largo and Miami Oolitic limestones. Stratigraphic information obtained from Hoffmeister and Multer, 1972.

and Multer, 1968). These coral reefs thrived 120,000-140,000 years ago, based on ^{234}U-^{230}Th radiometric age dating (Broecker and Thurber, 1965). Progressive cooling of the planet 110,000 years ago induced the buildup of continental glaciers and sea ice, causing sea level to drop and exposing the reefs to rainwater percolation and karstification (Lane, 1994; Lidz, 2004). Sea level rose rapidly about 15,000 years ago and again at 7,000 years ago, so that the Key Largo Limestone was inundated in most regions (with the exception of Windley Key and other locations in the Florida Keys), allowing the growth of modern reefs (Lane, 1994; Lidz, 2004).

It is estimated that the coral reefs of the Key Largo Limestone lived at a water depth of 6-8 m (Hoffmeister and Multer, 1968; Harrison and Coniglio, 1985), with a low angle slope dipping to the east (Harrison and Coniglio, 1985). The depositional environment of the formation has been interpreted as either a continuous, crescentric reef growing in open water parallel to the shelf margin (Stanley, 1966), or a shallow coalescing linear series of patch reefs (isolated and often circular) shoreward of a more extensive and continuous reef (i.e., a back reef environment; Hoffmeister and Multer, 1968). Currently, the patch reef hypothesis is most widely accepted (Greenstein, Curran and Pandolfi, 1998).

The Key Largo Limestone consists of framework fossilized corals and coral rubble embedded in a calcareous matrix. The principle frame-building corals are *Montastraea annularis* (>50%)*, Porites astreoides, Diploria strigosa, Diploria clivosa* and *Diploria labryinthiformis* (Stanley, 1966; Hoffmeister and Multer, 1968). About 70% of the limestone matrix consists of a poorly consolidated calcareous sediment

produced from fragmented skeletal remains and sparry cement, with an original mineralogy believed to be >75% aragonite, 20% high-magnesium calcite, and <5% of low-magnesium calcite (Stanley, 1966). The poorly consolidated sediment is separated into two different facies based on reef sub-environments.

The dominant facies is a poorly sorted clastic debris with angular skeletal fragments (mostly *Halimeda*) filling 20-25% of voids in the rock. This facies includes micrite, a brown, homogeneous cryptocrystalline mud with 1-3 µm diameter grains that supports skeletal fragments and has an interlocking texture, implying some degree of recrystallization (Reeder, 1975). The facies also includes recrystallized, interlocking microspar grains, which are usually 5-10 µm in diameter but may be as large as 40 µm. The second, much less dominant facies consists of inorganic, well-sorted clastic carbonate grains, rounded from abrasion. They often accumulated in anastomosing channels between reef buildups (Stanley, 1966).

The field site chosen for a spatial measurement of the Key Largo Limestone was located on Windley Key. Windley Key Fossil Reef Geological State Park (Fig. 6) is located along U.S. Route 1, near mile marker 83 (24°56'46.89"N x 80°35'58.80"W). This site, originally a quarry, was chosen because it offers the best accessible, largest and highest exposure of originally deposited Key Largo Limestone above sea level (~5.5 m; Fruijtier, Elliott and Schlager, 2000).

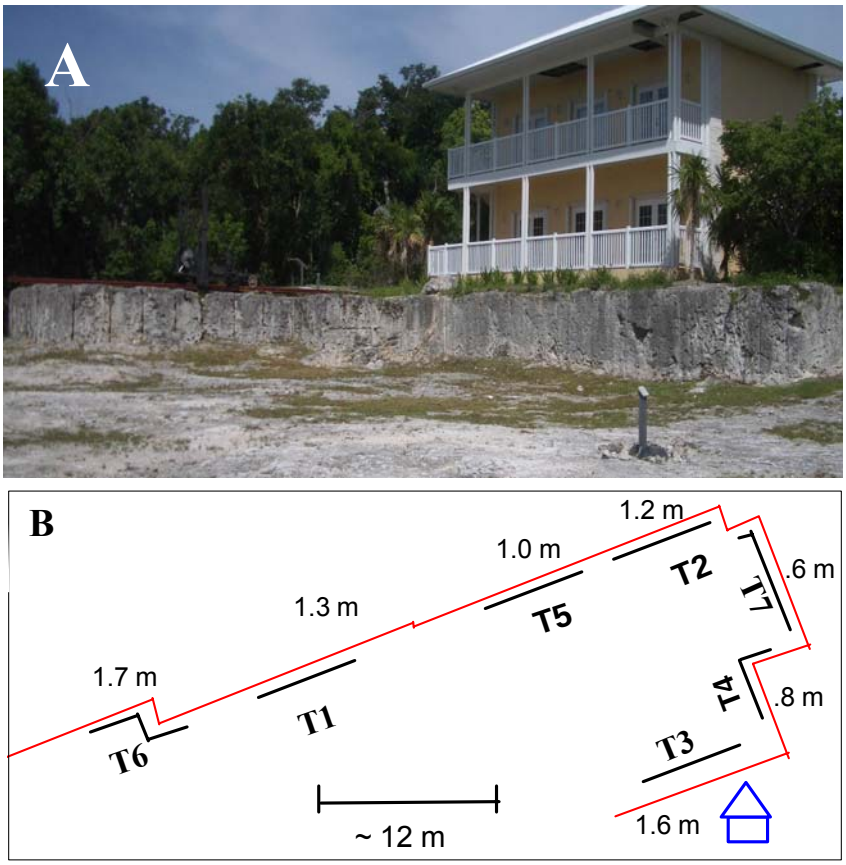

Figure 6: Windley Key Fossil Reef Geological State Park (A). Schematic map (B) approximately to scale, of Windley Key quarry walls. The red lines represent the limestone walls. The solid black lines represent the length of measured linear transects (T1- T7). The indicated markings identify the height of the starting point for the corresponding linear transect. The blue house icon shows the location of the ranger station.

ACADEMIC AND FIELD PREPARATION

Initially, ten trips were taken to the old fire station in Coral Gables, Florida (Fig. 7) to become familiar with all aspects of coral taphonomy for this project, and to photograph and create detailed taphonomic maps (see Appendix A) of the Key Largo Limestone façade of the building. These efforts helped for later recognition of coral types and taphonomic alteration in the Windley Key quarry.

Transect measurements made at Windley Key Geological State Park, with seven trips to the locality, required research approval by the Florida Department of Environmental Protection, Division of Recreation and Parks (see Appendix B). No samples were collected from the state park; however, twelve samples (Fig. 8) containing fossilized corals were collected at a rock cutting facility in Florida City, Florida. These samples were used for categorizing taphonomic features and for mineralogical and stable isotopic analyses at the University of Maryland.

Familiarization with modern patch reefs, observations of current taphonomic processes, and collection of coral rubble samples required boat excursions from the Coral Gables marina to three different patch reefs near Biscayne Bay (Fig. 9A and 9B). These reefs included: Bache Shoal (25°N 29.120″ x 80°W 08.958″; Fig. 9C), Bar Bess (25°N 23.324″ x 80°W 09.778″; Fig. 9D), and Marker #9 (25°N 29.761″ x 80°W 08.619″; Fig. 9E). Precise locations were determined with a GPS recorder.

The sample collection from these sites was needed to better understand bioerosion and the earliest stages of alteration, and to have modern samples for X-ray diffraction and isotopic analysis. To this end, a proposal was submitted to Richard Curry, Science/Research coordinator at Biscayne National Park to acquire a collection permit from the United States Department of the Interior, National Park Service, Biscayne National Park (see Appendix C). Approximately 4 kg of coral rubble was collected and

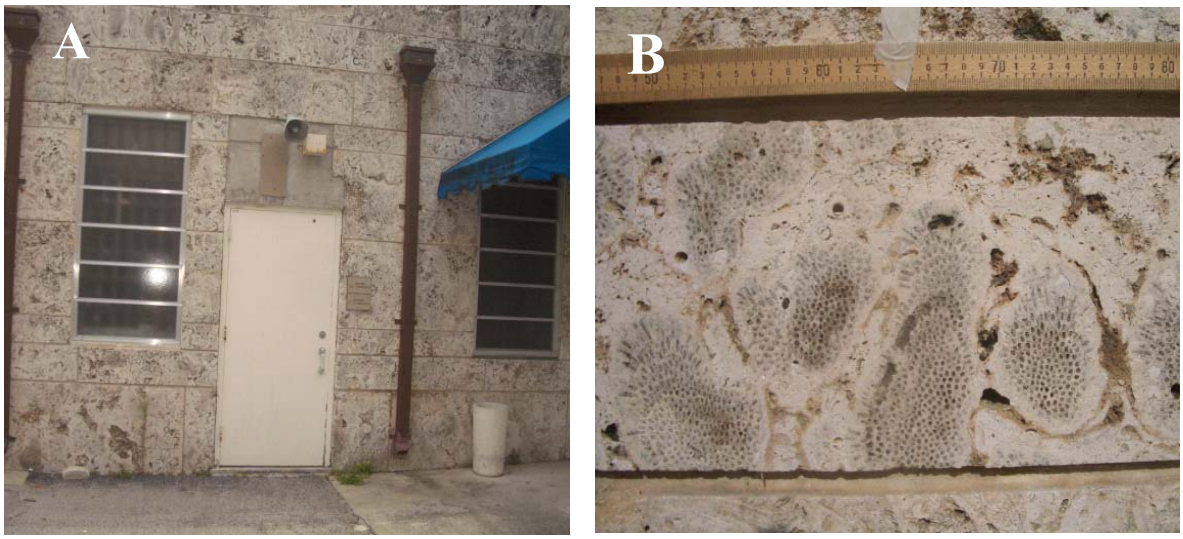

Figure 7: Well preserved blocks (A) of the Pleistocene Key Largo Limestone, located in the outer walls of the old fire station in Coral Gables, FL. Pictures of various blocks were taken to create maps of taphonomic features (see Appendix A). The orientations of each block varied. Coral growth orientation and geopetal structures (e.g. partially sediment-filled voids) must be used to decipher the original vertical position. Block 1 (B) is in a relatively horizontal orientation and contains six *Montastraea annularis* fossils.

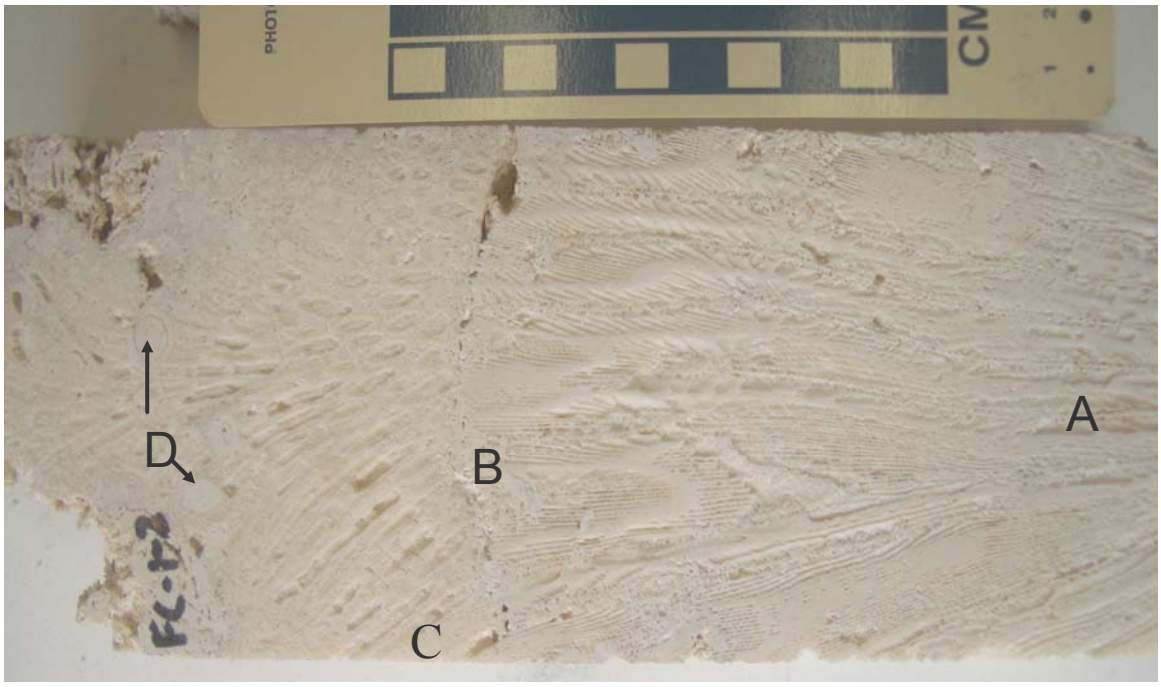

Figure 8: Fossil coral sample collected in Florida City, Florida. Right to left indicates upward growth direction. The lower coral (A) is a cross section of fossilized *Diploria* sp. (brain coral). The coral is truncated at (B) where the surface is lightly bored and covered with a small layer of sediment, creating a hard substrate for new coral growth. The fossil of *Montastraea annularis* (C) grew on top of the bored surface. White elliptical spots (D) represent bivalve borings filled in by fine-grained internal sediment.

identified as *Montastraea annularis*, *Porites* sp., or *Acropora cervicornis.* To clean collected samples, a knife was used to strip off all surface organic matter. The specimens were subsequently soaked in a 30% bleach solution to oxidize trapped organic matter (Fig. 10).

The culmination of these preparations was the creation of a field guide (Appendix D), which provides pictures and identification of dead corals and their living counterparts. The National Coral Reef Institute provided samples to be photographed and used to create the guide.

METHOD OF ANALYSIS

Spatial Distribution of Modern and Ancient Corals

The spatial distribution of modern Florida patch reef corals was obtained from the AGRRA database (Marks, 2006) using a linear transect method (Lang, 2003). For each 10 meter interval, the length of living, partially dead, and standing dead coral was added together. These three components represent what could potentially be preserved as *in-situ* coral in the fossil record. The sum was compared to the total length of all the transects to obtain the overall plan view coverage in the modern patch reef system. Each AGRRA surveyor was proficient in AGRRA protocol (Kramer, 2003), coral species and colony boundary identification and mortality estimates. Surveyors calibrated

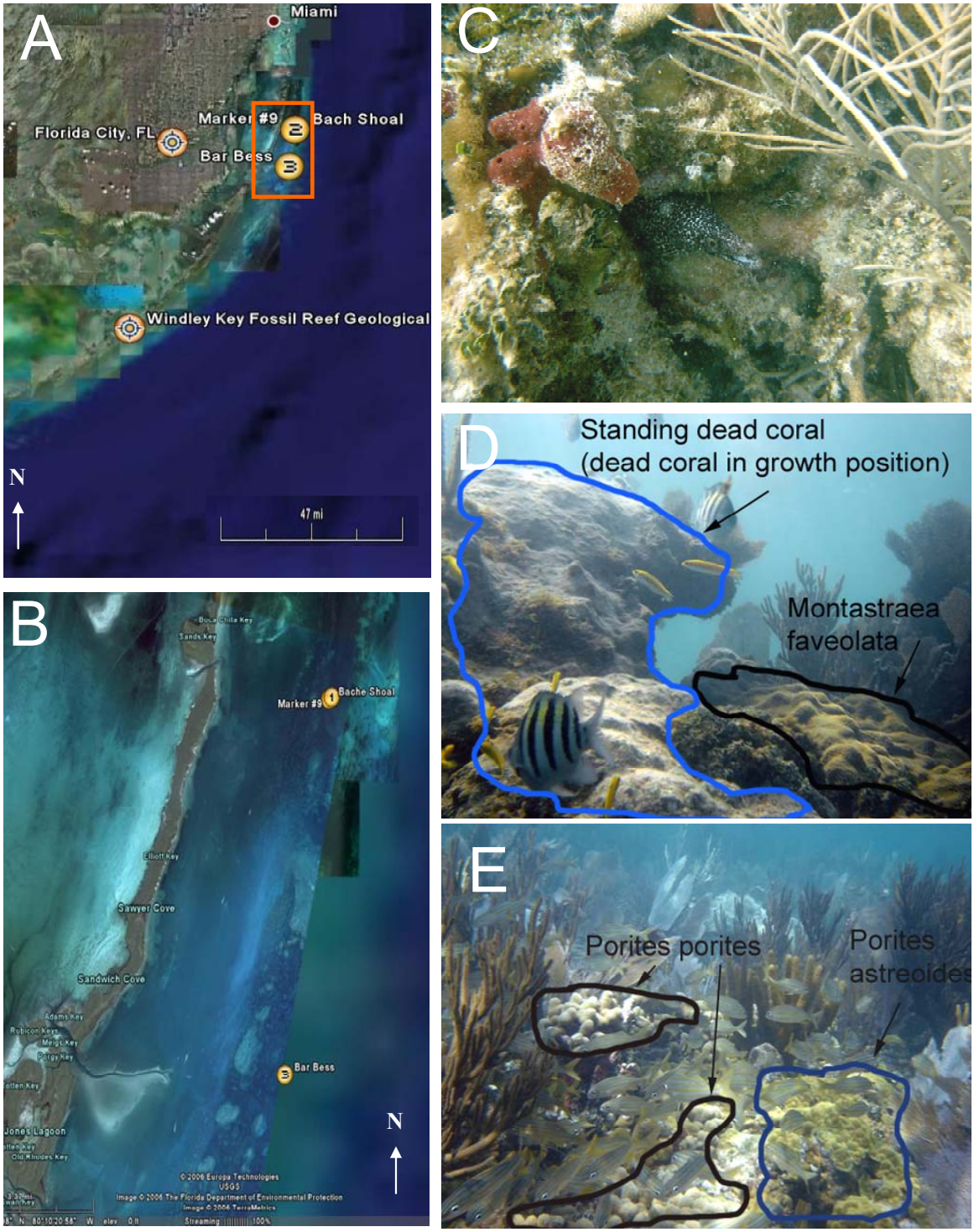

Figure 9: Patch reefs in Biscayne Bay, Florida. The satellite map of Biscayne Bay (A) identifies all field sites. The orange box represents the position of detailed map (B), indicating locations for modern coral collection. The patch reef track is observed clearly in the image to the left of Bar Bess. Modern coral samples were collected from Bache Shoal (C), Bar Bess (D), and Marker #9 (E). Bar Bess contains examples of standing dead coral and live *Monastrea faveolata*. Marker #9 contains examples of *Porites porites*, a branching coral with short "fingers," and *Porites astreoides*, a platy coral. Pictures A and B were obtained from Google Earth and pictures C, D, and E are courtesy of Barbie Bischof.

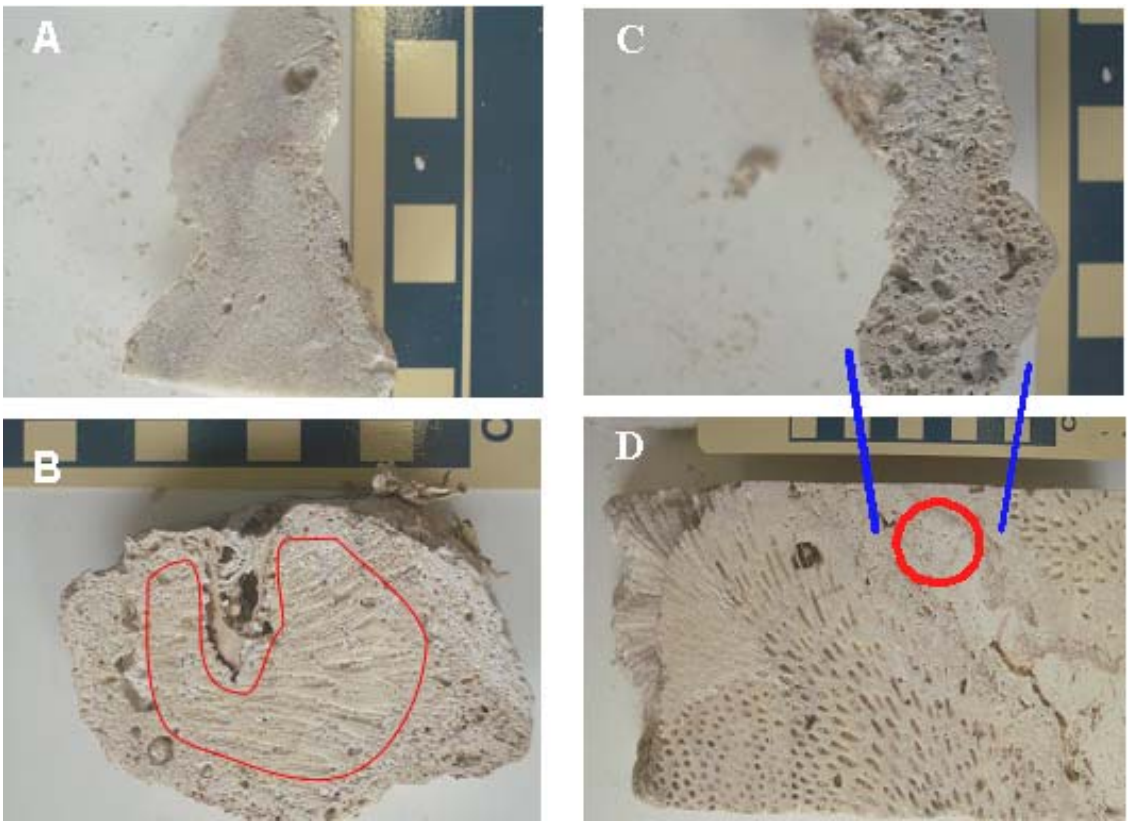

Figure 10: Collected samples of recently dead coral in the modern Florida patch reef system. A *Porites* sp. sample (A), collected at Bache Shoal, exhibits little biological alteration. A *Montastraea annularis* sample (B), collected at Marker #9, shows moderate levels of alteration (outside of the red enclosed unaltered section). The cluster of material on the top right of the sample are fragments of the green algae *Halimeda,* a large contributor to the carbonate sediment in Florida reefs. There are also faint trances of algal lamination on some of the outside boarders. Extremely altered coral rubble (C) collected at Marker #9 is often beyond visually identified. The sample is an example of how highly altered coral rubble could be mistaken for coarse sediment in a sample of Pleistocene limestone (D).

their techniques every other day of a survey to guarantee a >90% level of confidence. Using 135 linear transects, an error of 3.4% ($2\sigma_M$) was calculated.

Pleistocene Key Largo limestone coral coverage measurements at Windley Key were obtained through the use of a linear transect method modeled after the AGRRA method (Lang, 2003), except the transects at Windley Key were done on wall cross sections (Fig. 11). A ten meter tape measure was adhered to a quarry wall roughly parallel to the ground. The height of the tape measure was randomly selected for each transect, and seven locations in the quarry were measured (Fig. 6B; see Appendix E for example of measurements and calculations for one transect). For each textural feature along the transect, the intersection points between the feature and the transect were used to measure the length of the feature along a linear path (Fig. 12).

Major reef features were separated into eleven categories including: *Diploria* sp.; small polyp corals; *Montastraea* sp.; branch coral; coral rubble; coarse sediment; fine sediment; coralline algae; breccias; weathered sections; and unidentified. These categories were grouped into: 1) *in-situ* coral; 2) coral rubble; 3) coarse sediment; 4) fine sediment; and 5) other (see Appendix F for exact classification scheme).

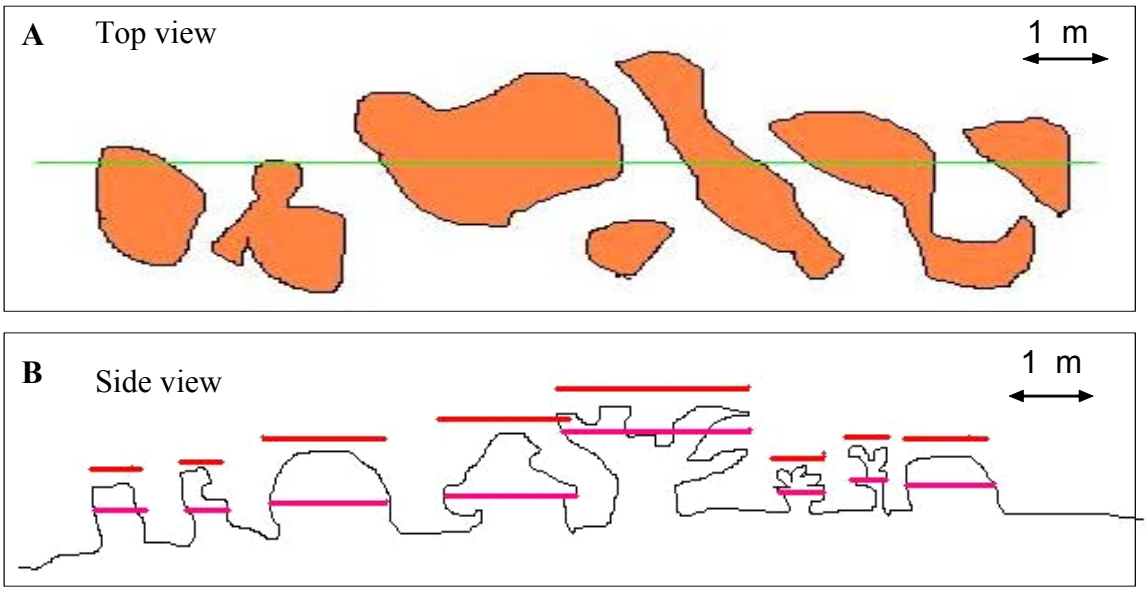

Figure 11: Schematic map view (A) of a theoretical reef, with the orange shapes representing corals and the green line representing a linear transect. The modern AGRRA sea measurements consist of whatever portion of the orange shapes is crossed by the green line. The map view schematic could also represent the top view of a fossilized reef. A schematic cross-section of a map view (B) shows coral shapes. A transect measure of what is seen from map view (red line) is the same as what would be measured with a transect alone the cross sectional (pink line). The red lines represent what is measured in modern sea techniques and the pink line represents what is measured in the quarry walls.

The identification of coral in growth position is subjective. The most important feature was that polyps grow upward and outward, depending on where the coral is sectioned in the quarry wall. An *in-situ* coral primarily has a generalized genus-dependent shape and does not look like a random fragment. Coral in growth position are usually large (at least 10 cm) and grow near other corals. A small piece of isolated coral is less likely to be in growth position. Notably, *in-situ* corals tend to be less altered.

Errors in the measurements at Windley Key are related to visual identifications, the placement of the tape measure parallel to the ground, and the deviation of the quarry wall from a flat surface. To calculate reproducibility of the measurements, three marker points on a rock face were measured ten times. Each set of measurements were made by pulling the tape measure off the wall, closing eyes for thirty seconds, and remounting the transect. Using this technique, error for each measurement was found to be $\pm 9.1 * 10^{-3}$ m ($\pm 2\sigma_M$). The error for the total length of each category was calculated using an equation for propagation of indeterminate errors (see Appendix G for table, error equations and formula for σ_M).

The other measuring error was the deviation of a linear transect from a flat surface. Small divots and bulges (Fig. 13) in the generally flat quarry walls existed. The divots were of no consequence because the linear transect remained on a flat horizontal plane. The linear transect bridged the divot, and the measurement of a feature was based on where the visual horizontal line intersected the feature. When the tape measure traversed a bulge, however, the measured feature was longer than if the surface were flat. It was estimated that every meter of wall could have an average deviation (from a flat surface) of no more than 0.05 m. In this case, there would be a total

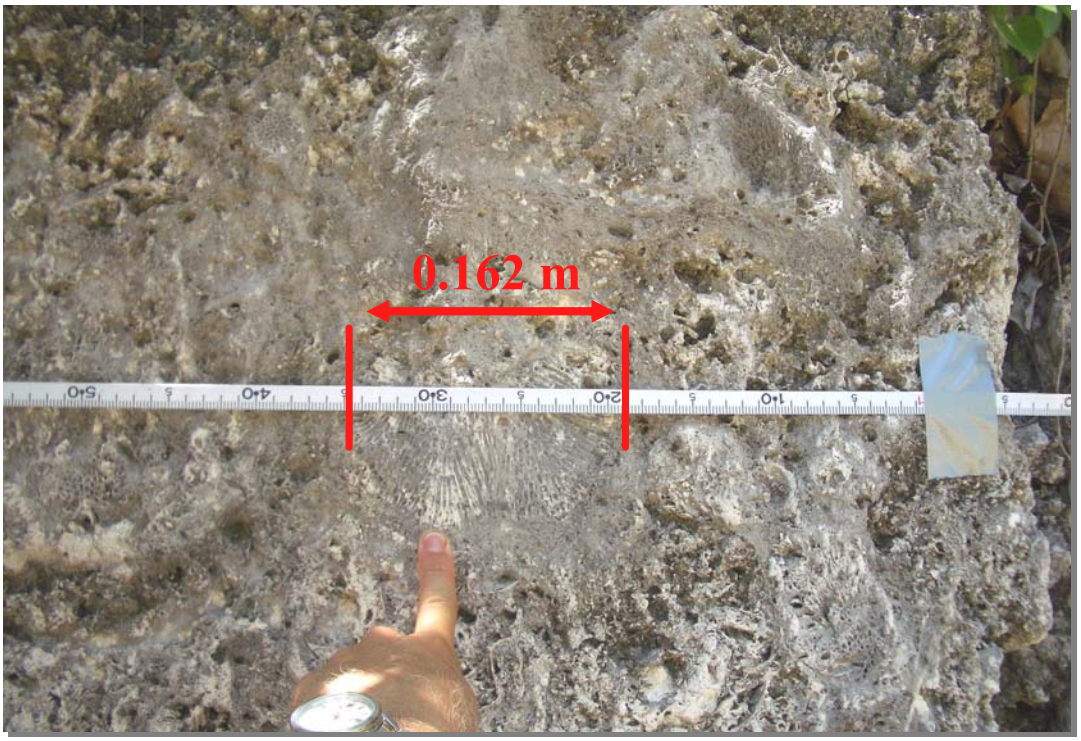

Figure 12: Transect #6 at Windley Key Fossil Reef Geological State Park (see Fig. 6B). This picture demonstrates the technique used to measure textural components. For example, the red vertical lines indicate the intersection of coral rubble not in growth position (identified as *Montastraea annularis*) with the tape measure. The distance between the intersections is 0.162 m.

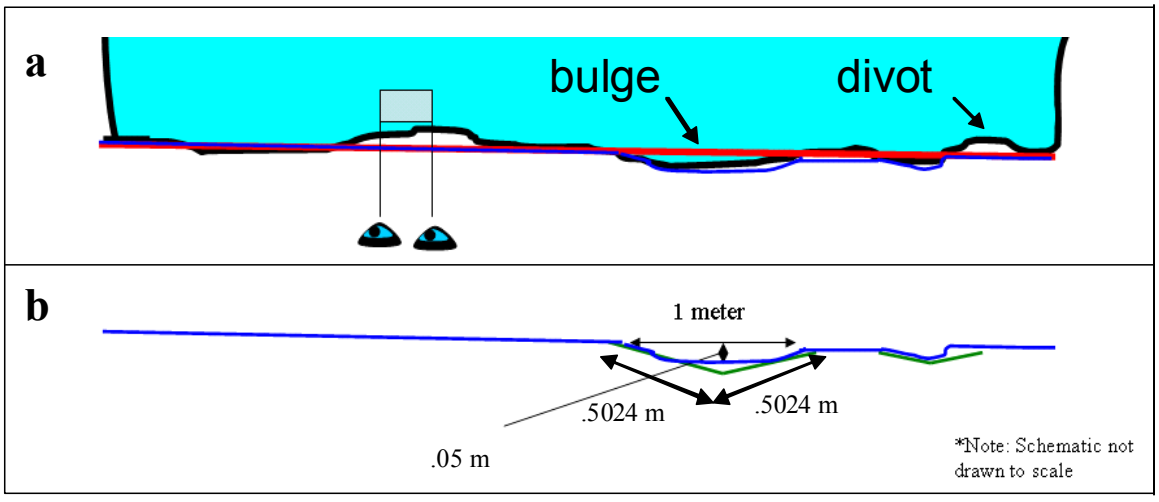

Figure 13: Schematic map view (A) representation of the linear transect method used at Windley Key. The bottom of the light blue object represents a wall in the quarry. The red line is the length of a line on a vertical, flat plane parallel to the transect, with the same starting and ending points as the transect. The dark blue line represents the transect, which must curve around bulges in the wall face but stays flat when bridging a divot. The eyes show how a feature, like the grey box, in a divot is measured as the intersection of a visually horizontal line with the transect. Using trigonometry (B), the green lines are used to calculate the estimated amount of departure from a straight line.

deviation of 1.005 m for a one meter horizontal increment of the wall with a bulge, resulting in a difference of 0.005 m. This deviation results in a 0.5% systematic determinate error.

Fine-Scale Assessment

Volume.− To acquire a better understanding of volumetric distribution of diagenetic elements and possible changes and textural variations in stable isotopic composition of the Key Largo Limestone, a single rectangular representative sample of the Key Largo Limestone was analyzed. The Florida City sample (Fig. 14) contained well preserved fossils of the dominant coral, *Montastraea annularis*, and various other textures.

The sample was serially sectioned using a circular rock saw. Each side of every slice was polished with a Struers Labopol-21 two-wheel grinding apparatus. The polished slices were then placed on a computer scanner to produce digitalized images. Twelve major features were identified including: two discrete corals; a bioerosion zone (Fig. 1); coarse internal sediment; altered brown coarse sediment; fine-grained internal sediment; skeletal sediment; altered skeletal sediment; altered white "bleached" coral; meteoric internal sediment; meteoric meniscus cement; and coralline algae (Fig. 15). Adobe Photoshop was used to outline the various textural features and the area of each textural feature was calculated using the Image J program (developed by Wayne Rasband, National Institute of Mental Health). Using a form of the trapezoid rule for integration, an equation was developed to calculate the volume of each textural feature [volume = (thickness of slice or distance between slices)*(Area of texture on one face + area of same texture on next face)/2]. A 1.3% error was determined by comparing the sum of the volumes for each texture (635.4 cm^3) with the maximum volume of the block 643.5 cm^3).

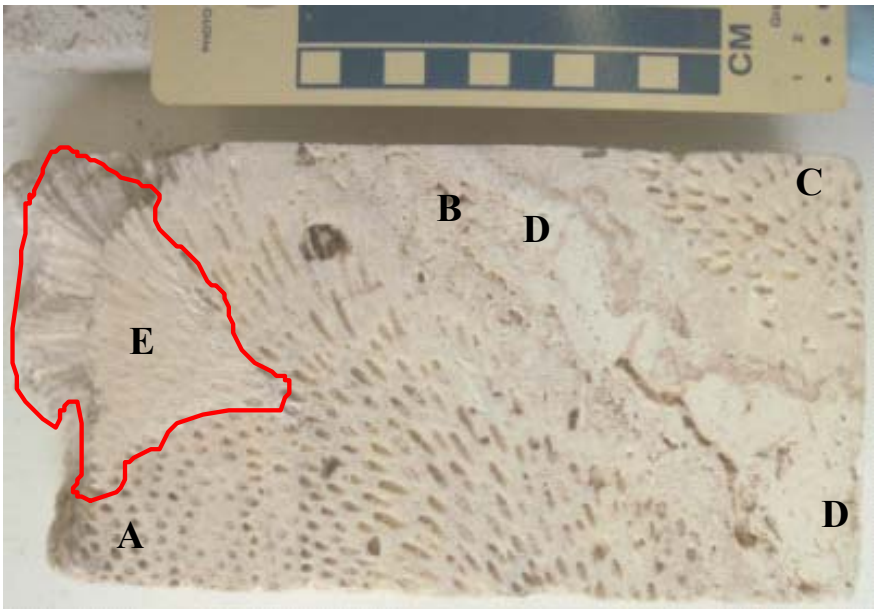

Figure 14: Representative Florida City sample used for fine-scale analysis. Two different fossils of *Montastraea annularis* (A, C) were determined to be 100% calcite. One of the fossils (A) is bounded by a bioerosion zone (B). Both corals are separated by calcareous sediment (D). The "bleached zone" of the left-hand coral enclosed in red (E) was determined by XRD to be 100% aragonite, which was contrary to expectations.

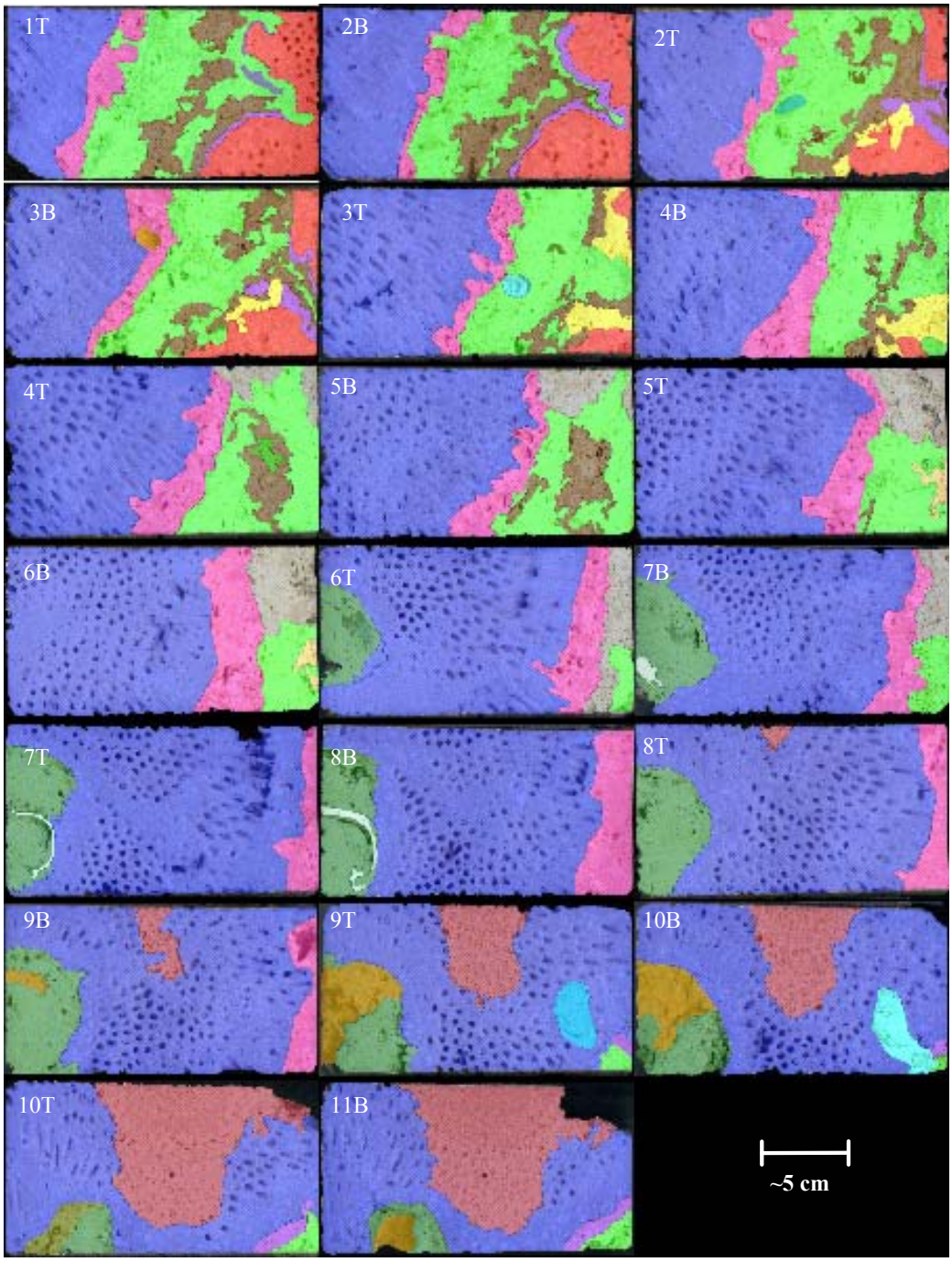

Figure 15: Serial sectional slices of the representative sample used for X-ray diffraction, isotopic and volumetric analysis. Colors indicate various textural features. T= Upper side, B= Lower side. Distance between the bottoms of each slice to the top of the next slice is 0.2 cm (amount cut from rock saw). Slices were of slightly different thicknesses.

X-Ray Diffraction (XRD) Analysis.– Mineralogical data for the Key Largo Limestone was obtained by quantifying the abundances of aragonite and calcite by X-ray diffraction. Four drilled samples from the Key Largo Limestone, one drilled sample from a recently dead piece of coral rubble and a mixed powder containing 50% each of pure aragonite and calcite were prepared for powder analysis. Also, one sectional slice was used to scan two coral textures ("bleached" and "pristine" *Montastraea annularis)* directly from the limestone block. The analysis was performed by Dr. Peter Zavalij, director of the University of Maryland Chemistry Department X-ray Crystallographic Center. A Bruker D8 Discover Advance Powder diffractometer equipped with HiStar area detector and Göbel mirror monochromator using Cu$K\alpha$ radiation with a sealed X-ray tube was used (see http://www-chem.umd.edu/facility/xray/XCC_facilities.htm).

X-rays were created by applying a voltage of 20 kV to a copper source, which resulted in characteristic excitation of the atoms and production of X-rays. The incident $K\alpha$ X-ray beam (λ = 1.54Å) passed through a Ni filter and then hit a sample. The beam was diffracted by the symmetrical atomic planes of the mineral onto a rotating detector (1^{o}/minute; Fig. 16). The angle of diffraction (2Θ) was measured and relates to the distances between the planes of atoms in the mineral by Bragg's Law:

$$n\lambda = 2d\sin\Theta$$

where the integer n is the order of the diffracted beam, λ is the wavelength of the incident X-ray beam, d is the distance between adjacent planes of atoms (the d-spacing), and Θ is the angle of incidence of the X-ray beam. The d-spacing generated in a typical X-ray scan provides a unique "fingerprint" of the mineral or minerals in the sample (Cullity, 1978). For these analyses, X-rays were detected over a 2Θ range of 20º to 45º to capture the three major peaks for aragonite [3.396(1); 1.977(0.65); 3.273(0.52)] and calcite [3.035(1); 2.095(0.18); 2.285(0.18)]. The relative peak heights (intensities) were used to quantify the abundance of the minerals in each sample.

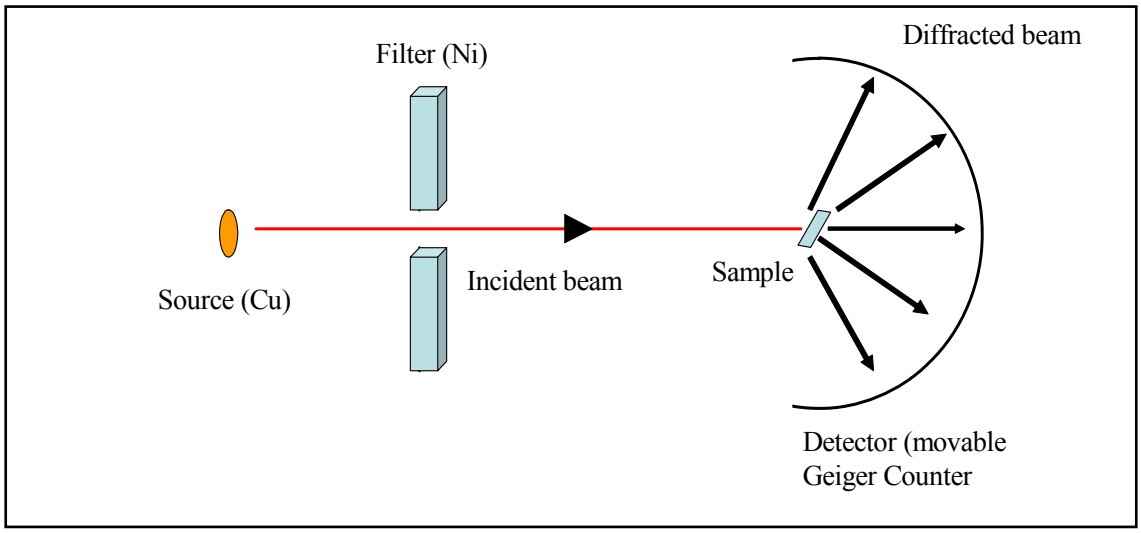

Figure 16: Schematic of X-ray diffraction pathway from the Cu source through a Ni filter and the diffraction (scattering) of incident X-rays onto a rotating detector.

Isotopic Composition.− Following the identification of textures, the slices were sub-sampled for later isotope determinations. A Servo Products Drill Press and 1 mm diamond encrusted drill bits were used to collect samples of each textural feature from both sides of every block. Care was taken when drilling so samples were collected away from other textures or weathered surfaces. A total of 57 samples were collected. For each sub-sample: 1) ~100 μg of carbonate powder was placed into a Wheaton V-vial; 2) the vial was capped with a blue septa and a Kel-F Teflon disc; 3) the sealed vial was placed into a Multiprep carbonate rxn device in-line with a dual inlet Isoprime gas source mass spectrometer; 4) the sample was evacuated from the vial with a double needle and subsequently acidified with phosphoric acid (H_3PO_4 ; anhydrous ρ~1.90 g/cc) at 90º C; 5) released carbon dioxide (CO_2) from the reaction was trapped for 10 minutes; and 6) the gas was introduced to the dual inlet mass spectrometer for isotopic measurement. Abundances of carbon and oxygen isotopes were calculated using the standard δ notation (using known delta values of VPDB as the standard) where, for example:

$$\delta\ ^{13}C = [(^{13}C\ /^{12}C)_{sample}/(^{13}C\ /^{12}C)_{standard} - 1] * 1000.$$

Error was calculated by taking multiple measurements (n = 10) of standard carbonate material (NBS 19) between measurements of the samples (n = 30). The error for the isotopic measurements was calculated using the standard, NBS19. Four analyzed sessions with the mass spectrometer took place, resulting in maximum errors of ±0.200‰ (1σ) for $\delta^{18}O$ and ±0.066‰ (1σ) for $\delta^{13}C$.

RESULTS

Field Observations

A generalized inventory of organisms such as sponges, worms, and algae was taken to gain a qualitative understanding of the organisms that induce bioerosion. This led to the observation that the longer a piece of dead coral lies unburied on the sea floor, the more altered it becomes from this biological process. Observations of many cavities filled by various organisms in the collected samples were made. Some of the sectioned samples were infested with bore holes (Fig. 10C), and would likely have been misidentified. For example, some textures in a Pleistocene Key Largo Limestone rock have intervals identified as coarse sediment, however, some of these could have been highly altered, unrecognizable coral fragments (Fig. 10D).

Modern Florida Patch Reefs

In 2006, the AGRRA program compiled data obtained from trained professionals who took linear transect measurements along coral reefs in the Caribbean (Marks, 2006). Utilizing the AGRRA data from the Florida Patch reefs (Table 1), the coverage of *in-situ* coral that could potentially be fossilized in growth position was calculated to be 33 ± 3.4% ($2\sigma_M$). The total coverage of *in-situ* coral material (living and dead) was 438.2 m, averaging 3.25 m per transect and 19.1 m per reef.

Site	Reef	Date	Lat.	Long.	Depth	NT	NC	NSD	TPM	CC	TC	PTC
BB	Anniversary Reef	6/12/03	25.38887	-80.16457	1.9	6	121	1	2.39	15.40	17.79	29.65
BB	Bache Shoal	6/12/03	25.48498	-80.14915	1.7	6	90	0	1.70	13.65	15.35	25.59
BB	Marker 14 Reef	6/12/03	25.46418	-80.16843	2.2	6	111	0	2.90	20.80	23.70	39.51
LK	Boca Chica Patch	6/03/03	24.55193	-81.70160	2.2	6	81	0	4.16	27.40	31.56	52.59
LK	Looe Cay Patch	6/05/03	24.56460	-81.39308	7.7	6	106	0	2.99	20.85	23.84	39.73
LK	Mystery Reef	6/04/03	24.58535	-81.58100	2.3	6	78	0	6.88	24.90	31.78	52.96
LK	Newfound Harbor Patch	6/05/03	24.61655	-81.39110	1.7	6	128	5	9.00	20.50	29.50	49.17
LK	Offshore Sand Key Patch	6/02/03	24.47568	-81.88741	7.3	6	64	0	1.15	7.85	9.00	15.00
LK	West Washerwoman Patch	6/04/03	24.55145	-81.58800	4.3	6	104	0	2.44	16.25	18.69	31.16
LK	Western Sambo ER Patch	6/03/03	24.49938	-81.70232	5.6	6	73	0	2.57	12.15	14.72	24.54
MK	11 ft. mound	7/28/03	24.72355	-80.85995	6.1	6	63	0	0.88	6.93	7.81	13.01
MK	Coffins Patch	7/28/03	24.68558	-80.96443	3.2	6	61	0	0.94	9.09	10.03	16.72
MK	Coral Gardens	7/29/03	24.83753	-80.72842	3.1	6	80	0	4.94	21.70	26.64	44.40
MK	East Marker 49	7/28/03	24.69337	-81.02029	4.9	6	97	0	4.85	34.40	39.25	65.42
UK	Aggregated Patches	5/21/03	25.03537	-80.36380	7.1	6	39	0	0.63	5.32	5.95	9.92
UK	Basin and Hills-4	5/19/03	25.23587	-80.25920	2.2	6	74	0	7.32	21.60	28.92	48.20
UK	Cheeca Spa	7/29/03	24.90448	-80.61658	3.3	6	87	1	3.49	20.30	23.79	39.66
UK	Hens and Chickens	5/22/03	24.93167	-80.54833	4.6	4	68	0	3.87	16.80	20.67	51.67
UK	Memorial Reef	5/23/03	25.01328	-80.41360	3.4	6	60	1	1.26	7.47	8.73	14.56
UK	North North Dry Rocks	5/20/03	25.13632	-80.28962	4.0	6	55	1	1.22	11.28	12.50	20.83
UK	NW Davis Reef	5/22/03	24.94990	-80.50142	4.3	5	40	0	0.64	3.88	4.52	9.03
UK	Watson Patch	5/20/03	25.16805	-80.25750	4.6	6	46	0	1.99	9.28	11.27	18.79
UK	White Banks Dry Rocks	5/21/03	25.04493	-80.36987	2.0	6	59	0	4.02	18.20	22.22	37.03
Total					89.4	135	1785	9	72.2	366.0	438.2	32.57

Table 1: Coral Coverage in Modern Florida patch reefs. Data provided by AGRRA. * Filtering restriction: corals with diameters less than 10 cm were ignored.

Key:
Site - General geographic location, **Reef** – Patch reef name, **Date** – When measurements were taken, **Lat**. – Latitude (in decimal degrees), **Long**. – Longitude (in decimal degrees), **Depth** – Average depth of transect (meters), **NT** – Number of transects for reef, **NC** – Total number of corals, **NSD** – Total number of standing dead corals, **PM** –Total partial mortality and standing dead (meters), **CC** – Total live stony coral coverage (meters), **TC** – Total sum of total coverage of living stony coral, total partial mortality and total standing dead coral, **PTC** – Percent of TC per reef.

Site Classification:
BB – Biscayne Bay, **LK** – Lower Keys, **MK** – Middle Keys, **UK** – Upper Keys

Pleistocene Key Largo Limestone at Windley Key

Seven linear transects, each 9.870 m long, were adhered to the Windley Key Quarry walls to obtain a quantified representative textural composition of the Pleistocene Key Largo Limestone, specifically addressing *in-situ* corals. Overall, 69.1 m of the limestone walls were measured (Fig. 17A). After normalizing the data by factoring out unidentifiable textures (Fig. 17B), the formation consisted of 20.5 ± 0.5% *in-situ* coral. Of the 69.1 m of quarry wall measured, 45 *in-situ* fossilized coral skeletons were intersected by one of the transects. Almost half of the *in-situ* coral was identified as *Montastraea* sp. (Fig. 17C, D).

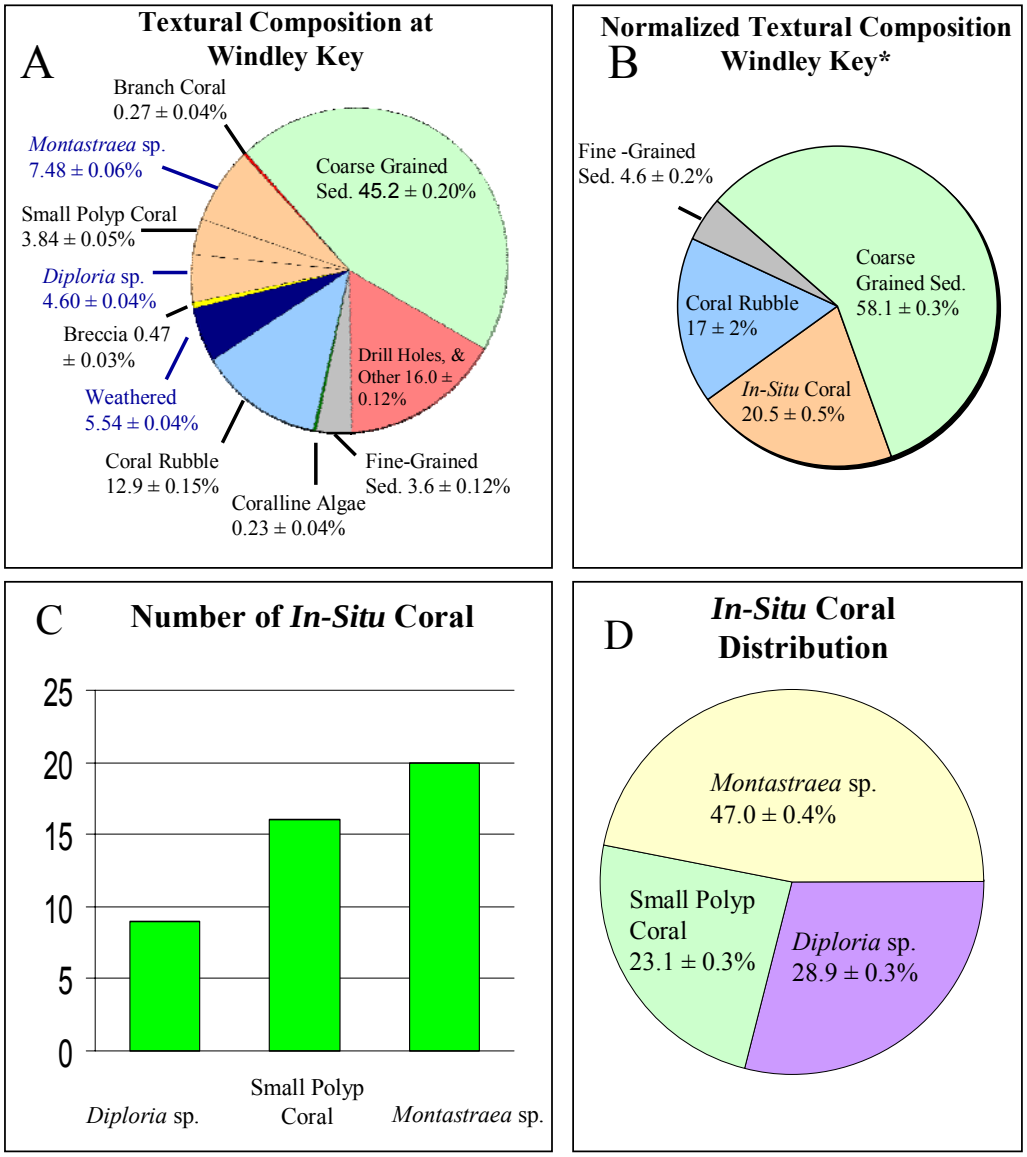

Figure 17: Textural composition (A) measuremented at Windley Key. Tan colors represent *in-situ* coral. Some textural categories (weathered, breccia, coralline algae and drill holes and other) were scaled out of the overall composition to obtain a normalized depiction of the composition at Windley Key (B). There was a total of 45 *in-situ* corals intersected by the seven transects (C). The distribution of *in-situ* coral species in the transects (D) at Windley Key indicate that *Montastraea* sp. is the dominant coral in the formation.

Fine-Scale Assessment

Volume.− The first quantitative measurement for the fine-scale analysis was to calculate the volumes of each texture visually identified in the representative Pleistocene coral sample used for analysis. The measurements indicate that coral 1 is the dominant feature, encompassing 61% of the block (Fig. 18). The volume of the sample before sectioning was 643.5 cm^3. The sum of the volumes of all textures was 635.4 cm^3. Therefore, a 1.3% error was estimated for each volumetric determination (A visual 3-D projection of these volumes is presented online in a power point format).

X-ray Diffraction (XRD) Analysis.− X-ray maps were created for one sample of modern *Montastraea annularis* rubble (Fig. 10B), and four sub-samples from the representative sample (one Pleistocene Key Largo Limestone fossilized *Montastraea annularis sub-sample*, two coarse grained sediment sub-samples (Fig. 14D) and one sub-sample of a "bleached" zone of *Montastraea annularis* (Fig. 14E) to evaluate the relative percent of aragonite and calcite. The high intensity peak for aragonite was found at $2\Theta = 26^o$, and the major peak for calcite was at $2\Theta = 29.4^o$, as expected (Downs and Hall-Wallace, 2003). X-ray diffraction indicated that the modern coral sample was 99% aragonite and the ancient coral was 100% calcite. However, the bleached portion of the same coral (originally assumed to be more altered) was 94% aragonite. Both internal micrite sediments were100% calcite (Fig. 19). These measurements have <1% uncertainty.

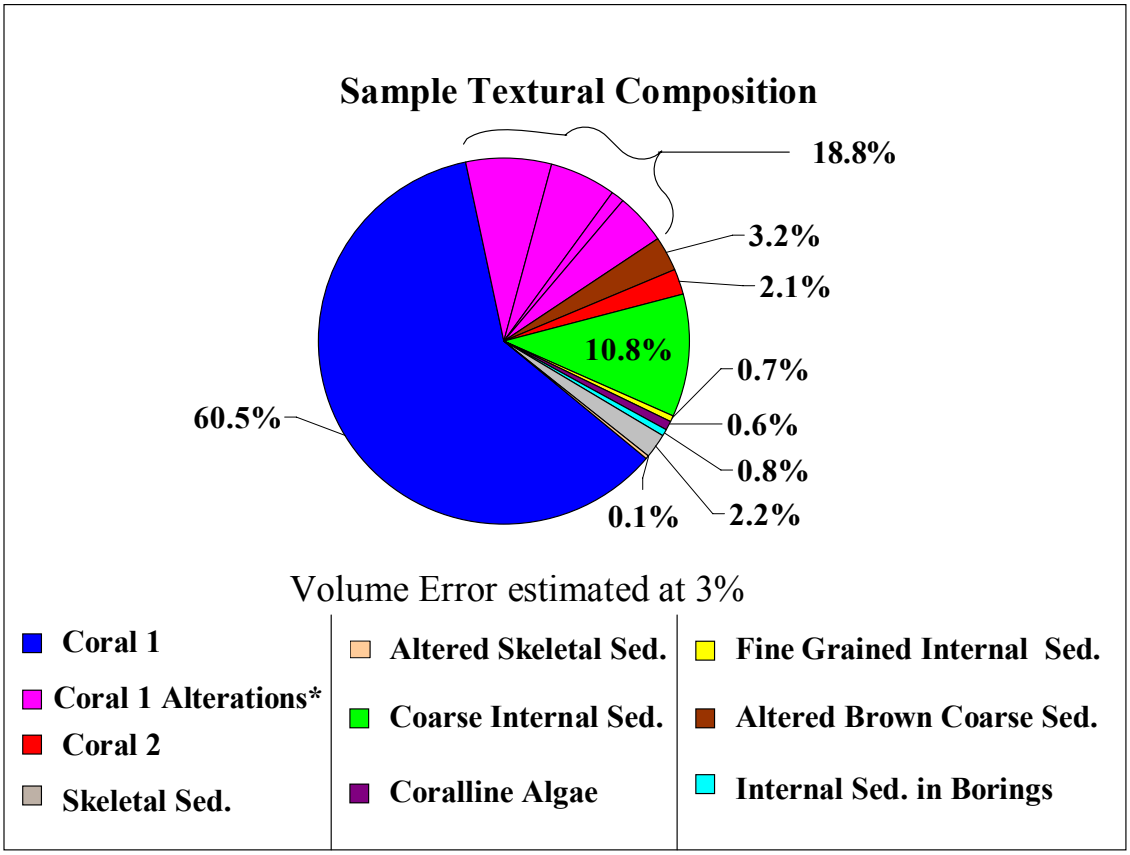

Figure 18: Volumetric distribution of textural features in Florida City sample. *Alterations to coral 1 include bioerosion, internal sedimentation, and new cement.

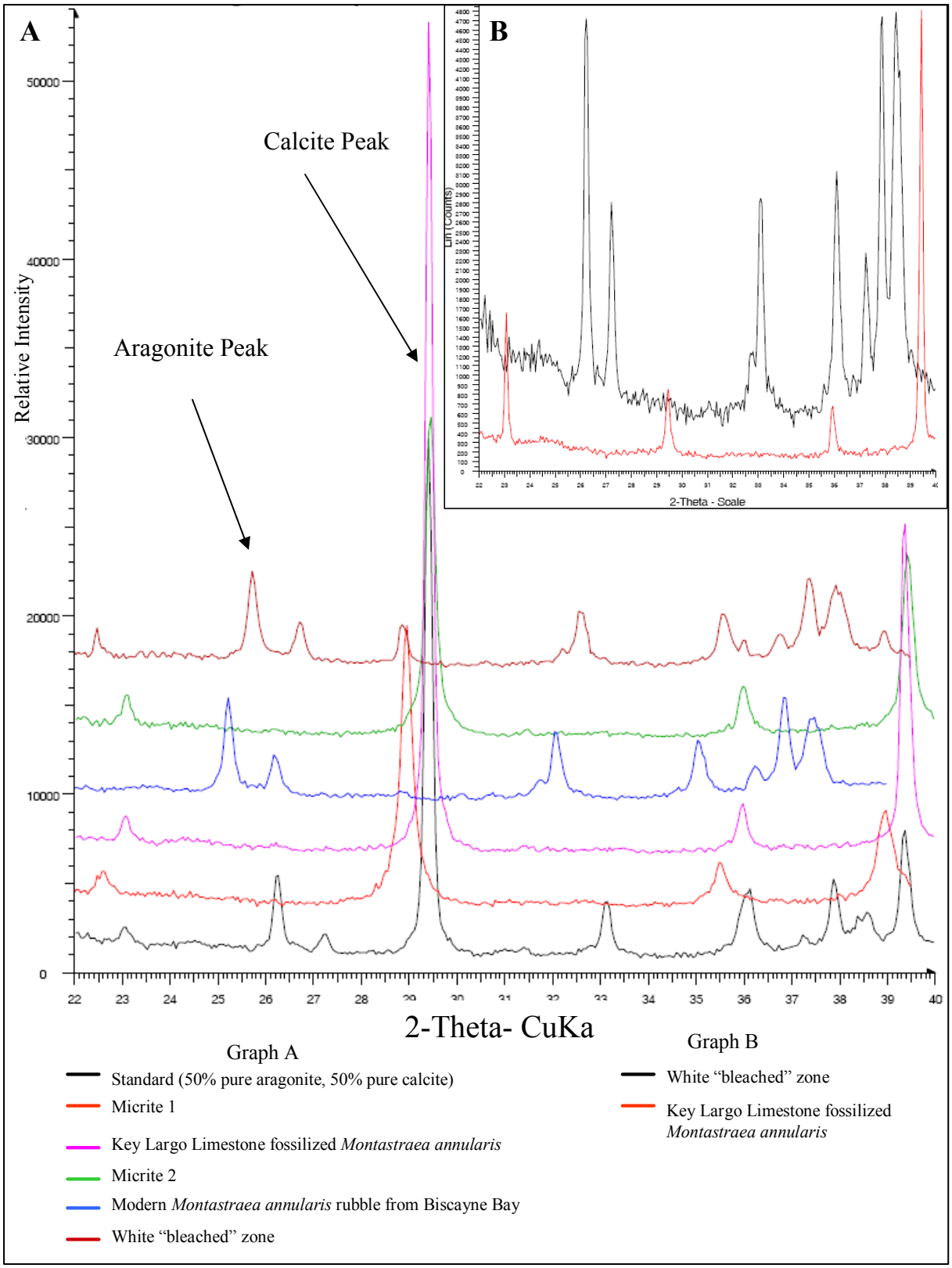

Figure 19: X-ray diffraction results from powder (A) and intact (B) carbonate samples. The y-axes indicate relative intensities. Both show give the same results for the white "bleached" zone and the fossilized coral, which are aragonite and calcite, respectively.

Stable Isotopic Analysis.− Stable isotopic composition uncertainties were determined using the NBS19 carbonate standard. The isotopic measurements for 11 samples of coral 1 in the test sample yielded $\delta^{13}C$ values between -5.06 ‰ and -1.76‰ with an average of -3.72 ± 1.37‰. Coral 1 also had $\delta^{18}O$ values between -5.20‰ and -4.33‰ with an average of -4.96 ± 0.29‰. Additionally, 4 samples of coral 2 yielded $\delta^{13}C$ values ranging between -3.50‰ and -1.95‰ with an average of -2.75 ± 0.63‰. Coral 2 had $\delta^{18}O$ values between -5.73‰ and -5.26‰ with an average of -5.4 ± 0.22‰ (Fig. 20A). The isotopic compositions of the other primary and secondary textural components are displayed in figure 20B and figure 20C, respectively.

DISCUSSION

Pleistocene and Modern Reef Equivalence

Initially, it is important to assume that an accumulating assemblage of dead coral deposited close to living coral and dead sections of a living colony represent a logical proxy for the limestone that may potentially become fossilized (Greenstein and Pandolfi, 1997). Specifically, this study assumes that the Pleistocene Key Largo Limestone was a series of patch reefs that are ecologically, volumetrically, and spatially analogous to present-day Florida patch reefs. The assumption is validated by climatic, biologic, and morphologic similarities between the modern and ancient counterparts.

Climatically, the reefs associated with the Key Largo Limestone formed during an interglacial period, when climate and ocean conditions were similar to today (Fig. 3; Stanley, 1966; Reeder, 1975). Biologically, the taxonomic composition and diversity represented in the Pleistocene Key Largo Limestone reef system is almost identical to what is recognized in the modern Florida patch reefs (Stanley, 1966; Hoffmeister and Multer, 1968; Reeder, 1975; Greenstein, Curran and Pandolfi, 1998). However, in this study, virtually no *in-situ* fossilized branch coral were observed at Windley Key, while *Porites furcata* and *Porites porites* were both identified in the AGRRA study (Marks, 2006). Morphologically, the zonation of the fossil assemblages closely matches the zonation observed in the modern patch reef assemblages (Greenstein and Curran, 1997). Because the two patch reef systems are taxonomically similar and because the Quaternary fossil reef record of Florida reliably preserves long term responses of coral communities to environmental change (Greenstein and Curran, 1997), it can be assumed that the reefs are constructed in the same fashion.

Also, the Florida Keys living patch reefs, which have experienced less anthropogenic destruction than all other Florida reefs, are representative of patch reefs that flourished before the influence of humans (Greenstein, Curran and Pandolfi, 1998). We assume that modern Florida patch reef conditions are in their worst condition ever and the only major difference between modern patch reefs and their Pleistocene equivalents is attributable to anthropogenic influences. Therefore, the comparison between the Key Largo Limestone reefs and its modern counterpart represents the minimal difference in coverage induced by taphonomy. A comparison would offer a conservative approximation of alteration.

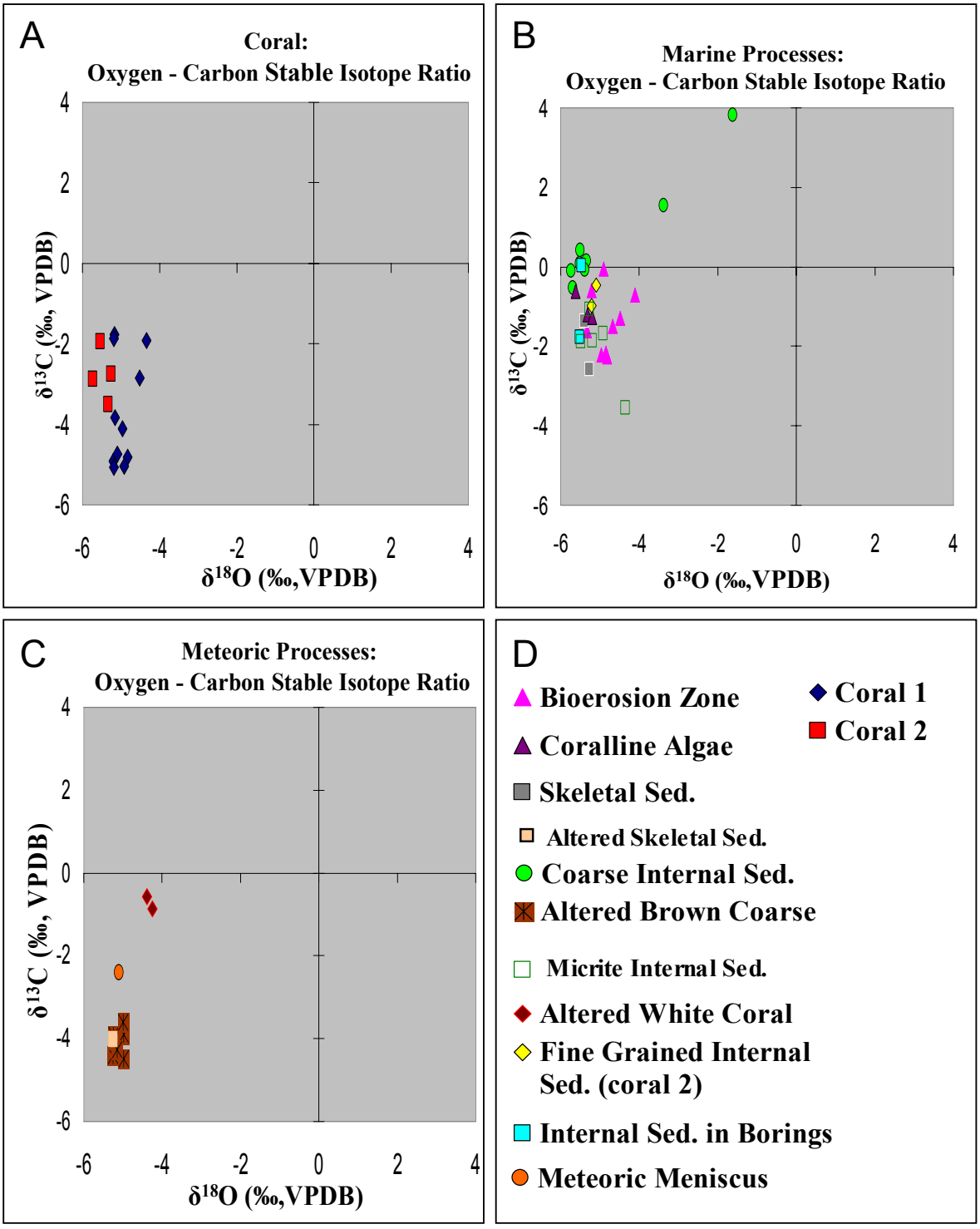

Figure 20: Plot of $\delta^{18}O$ and $\delta^{13}C$ values for Key Largo Limestone corals (A), other marine sediments (B), and secondary textures (C). Key (D) shows symbols for the various textural features. The scales for the graphs were chosen for later discussion, in comparison with the isotopic composition of modern seawater and modern corals.

Horizontal and Vertical Linear Transects

A key assumption in this research is that the plan view modern reef linear transects are comparable to the fossilized reef cross sectional linear transects (Fig 11). Because these linear transects are one dimensional, they represent the same relative measurement; the amount of coral under transect. The assumption is acceptable when using a robust sample and when using a random placement of linear transects (Greenstein, personal communication, 2007).

Linear transects are used to infer a good approximation of coral coverage. The AGRRA program mathematically determined that six linear transects are the minimum number needed to get a good estimate of coral coverage in a 600 m^2 site (Kramer, 2003). Because this study used seven linear transects at Windley Key, the data obtained can be used to calculate a reasonable approximation of the coral coverage preserved in a 600 m^2 area of the Pleistocene Key Largo Limestone reefs.

Loss in Coral Coverage

To evaluate the change in coral coverage due to taphonomy, the difference between the modern *in-situ* coral (living and standing dead) coverage and the Pleistocene *in-situ* coral coverage was quantified. Insofar as the coral coverage was 33.0 ± 3.4% in the modern Florida patch reefs and 20.5 ± 0.5% in the Pleistocene Key Largo Limestone reefs, we estimate a 38% total loss of *in-situ* coral, due to taphonomy (Fig. 21) where:

% Loss = (% modern – % Pleistocene) / (% modern).

Over one third of coral material is removed from the original coral reef by biological, physical and chemical alteration.

The modern reef measurements are not as accurate as the Windley Key measurements because there is more error involved and less measurable detail in scuba linear transects. Features such as edge alteration, infilling of bore holes and small *in-situ* coralline algae were not recorded by AGRRA. Boarder alterations (often hard to identify in the field) were included with the surrounding matrix of the fossilized coral.

The reasons for more than one third loss of coral coverage are complex, probably associated with a variety of biological, chemical and physical elements. A major fact to consider is that many corals do not remain intact before burial. The AGRRA transects contain 1785 corals for 1350 linear meters of patch reefs. Proportionally, 54 linear meters of rock measured at Windley Key should have 71 corals. However, the combined number of corals found intersecting the Windley Key transects (accounting for 54 meters of once living patch reefs) was only 45. Therefore, less then two thirds of the number of the original corals were preserved. Clearly, alteration occurred before the corals were buried.

One reason for the presence of less coral could be because no *in-situ* branch coral were recorded in any of the Windley Key linear transects, yet *Porites furcata* and *Porites porites* were both incorporated into the AGGRA calculation as *in-situ* corals that could potentially be preserved. This suggests that a major reason for the loss of coral in the taphonomic process is because branch corals do not preserve well.

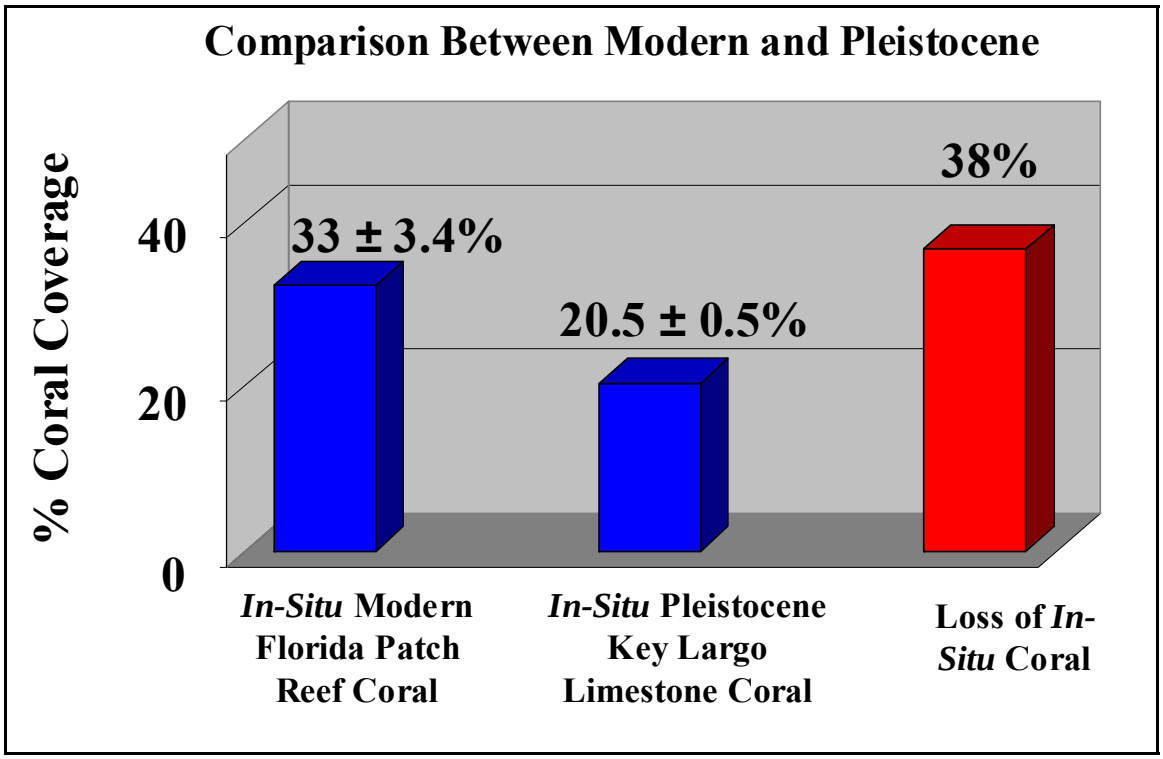

Figure 21: The results of theWindley Key study compared to AGRRA data indicate over a one-third loss of *in-situ* coral.

Branching coral are more likely to break and disperse because they are thinner and smaller, making them transform into rubble at much higher rates than other coral types.

Another major reason for the differences in observed coral coverage is bioerosion. From preserved samples of the ancient Pleistocene reefs, it is evident that the types of bioeroding organisms critical to the breakdown of coral in the modern reefs were present in the Pleistocene reefs. The corals are often so bored out and encrusted when they die, they become unrecognizable (Fig. 10C). Because we observe this trend in modern coral rubble, this undoubtedly was the case in the Pleistocene example as well.

Mineralogical Transformations

Mineralogical analyses by X-ray diffraction were conducted to evaluate the relative amounts of aragonite and calcite in the sub-samples of *Montastraea annularis* coral and internal sediment from the representative Pleistocene Key Largo Limestone block and from a piece of modern *Montastraea annularis* coral rubble (Fig. 10B). For the ancient corals, which were originally 100% aragonite, the analysis additionally provides a measure of the aragonite to calcite transformation that has occurred over ~120,000 years. While both minerals are composed of calcium carbonate, aragonite (which has an orthorhombic crystal structure and is meta-stable) will convert to the hexagonal crystal structure of calcite over time. The conversion usually occurs under the influence of meteoric waters that cause the more soluble aragonite ($k_{sp} = 10^{-8.33}$) to dissolve, allowing for the less soluble calcite ($k_{sp} = 10^{-8.48}$) to precipitate. The timing of

aragonite-to-calcite transformation is related to the salinity of pore waters relative to seawater. For example, in fresh water lenses, aragonite transforms rapidly to calcite in 4,700 to 15,600 years; in brackish pore water (a mixture of meteoric fresh water and seawater) the transformation takes between 8,700 to 60,000 years (Budd, 1988).

In a previous investigation of the Key Largo Limestone, Stanley (1966) stated that 75% of the original poorly sorted sediment was composed of aragonite. This makes intuitive sense based on the original mineralogy of the internal sediments, which are primarily composed of particulate and broken fragments of green algae like *Halimeda* and *Pennicillus* (aragonite), as well as foraminifera (calcite), sponges (calcite), bryozoa (calcite), mollusks (both aragonite and calcite), annelids (both aragonite and calcite), arthropods (calcite) and echinoderms (calcite).

Results from X-ray diffraction for this study indicate that the poorly sorted sediment is now primarily composed of calcite. This suggests that most of the exposed formation sat above the meteoric water table and that water flowed quickly through the porous rocks, causing some mineralogical transformation.

Similarly, the coral mineralogy was also found to consist primarily of calcite, suggesting that the aragonite – to – calcite transformation was complete. Although the coral fabrics are well preserved to the naked eye, this carbonate has undergone a mineralogical metamorphosis. On the other hand, the "bleached" coral, which appears to be more altered to the eye, is primarily composed of aragonite. This result was very surprising. Figure 15 (panel 8T to 11B, labeled as "altered white coral") shows that the majority of this texture occurs in the interior of the *Montastraea annularis* coral. The position of the "bleached" coral may explain the enhanced preservation of aragonite, if this zone was more protected from meteoric fluids.

Isotope Composition of Coral Skeletons

Stable oxygen and carbon isotope compositions of variably preserved Pleistocene coral, fine and coarse grained internal sediment, and secondary cements and textures were determined to evaluate the degree of alteration associated with mineralogical transformations and exposure to fresh water during sea level regression.

To place stable isotopic measurements in context, however, the isotopic composition of modern seawater and carbonate skeletons from live coral in the present-day Florida Keys should be considered (Fig. 22A). The field of data for modern coral carbonate is significantly offset from that of seawater, which reflects the redistribution of the isotopes by biological "vital" effects related to the relative rates of calcification and of photosynthesis (McConnaughey and Whelan, 1997; McConnaughey, 1989; Jabo, 2001; and references therein). A full explanation of these complicated processes is beyond the scope of this study, but the range of present-day coral skeleton values and the significant offset from seawater can be used for comparison of the Pleistocene coral data.

Isotopic data from the Pleistocene corals shows that the carbon isotope compositions are more variable than the oxygen isotope compositions (Fig. 22B). Notably, carbon isotope variation in the Pleistocene coral samples matches variations seen in modern corals of similar species, but the oxygen isotope is offset by ~1.4‰.

The oxygen isotope contrast might reflect a difference in interglacial seawater $\delta^{18}O$ composition ~100,000 to 120,000 years ago (Figs. 3B and 22C) or that temperatures

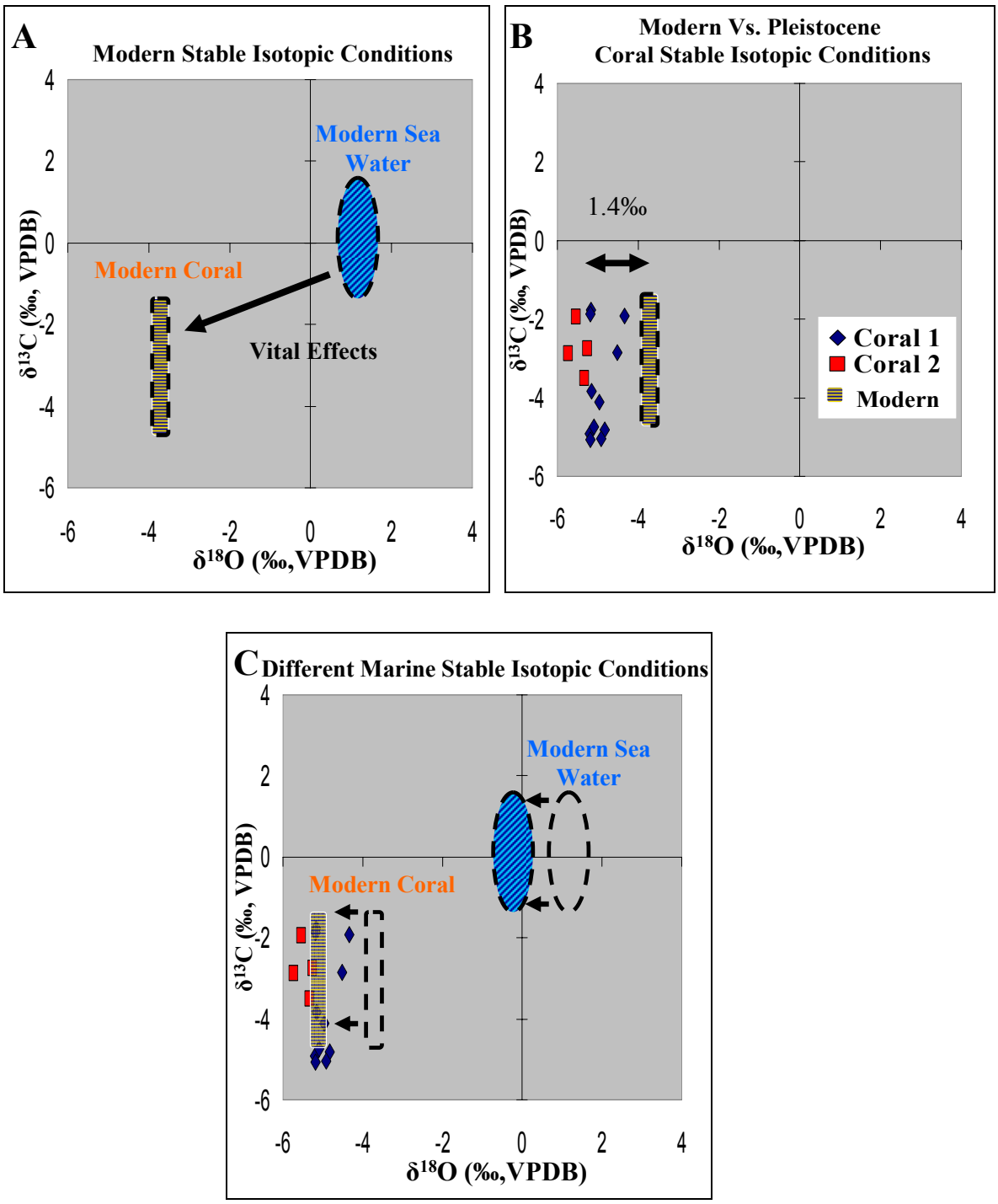

Figure 22: Carbon and oxygen isotopic compositions of modern sea water and modern *Montastraea annularis* (A; Swart et al., 1996; Leder et al., 1996). The difference between the isotopic compositions reflects "vital" effects induced by complex biological processes. Carbon isotopic compositions of Key Largo Limestone fossilized *Montastraea annularis* and its modern counterpart are comparable (B), but there is an ~1.4‰ offset in the oxygen composition. If the isotopic composition of the ocean was different than today (C), the corals that developed in the Pleistocene would also have different isotopic compositions. This offset could explain the difference between the oxygen isotopic composition of the modern corals and the Pleistocene corals.

were warmer. Seawater oxygen isotopes are sensitive to both salinity (Craig, 1965) and the global volume of water trapped as sea ice and continental glaciers at high latitudes. This is because evaporation of seawater causes water vapor in clouds to be depleted in $\delta^{18}O$. Therefore, later precipitation (as rain or snow) at high latitudes has more negative $\delta^{18}O$ values than seawater. Thus if continental glaciers and sea ice melt during an interglacial, the oceans would trend to more negative oxygen isotope compositions.

The oxygen isotope composition of coral carbonate formed in equilibrium with seawater is also temperature sensitive (Craig, 1965). If seawater temperatures were warmer during the past interglacial, one would predict that the resulting $\delta^{18}O$ of the carbonate would also be more negative. Insofar as sea level was apparently higher during the last interglacial relative to today – based on the observation that the Pleistocene Key Largo Limestone is at least partially exposed, and there is no evidence for tectonic uplift in the Florida Keys – then either decreased ice volume or higher temperature could result in the observed oxygen isotope offset. In fact, historical records of oxygen isotope variations (Fig. 3) indicate that seawater during the Sagamonian interglacial was slightly less enriched in oxygen isotopes. Thus the observed offset may have a paleoclimatic significance. However, clear evidence of mineralogical alterations suggestion other possible explanations.

Meteoric Alteration

A more likely reason for the isotopic difference between modern and Pleistocene *Montastraea annularis* would be the interaction of meteoric water with the carbonate material. Coral material is very porous, from both the dissolution of calcium carbonate by meteoric solutions, and from bioerosion. These processes create a porous and permeable network for rain water to percolate through the limestone once exposed above sea level. Swart (1981) noted isotope exchange effects between dead coral skeletons and sea water. Dissolution and re-deposition of calcium carbonate may alter oxygen isotope equilibrium between the meteoric water and the newly precipitated calcite, eliminating the isotopic information that the aragonite originally possessed (Zhou and Zheng, 2005). This isotopic change would be dependent on the residence time of water in the system, the state of the system (open or closed), and the temperature.

The monthly averaged oxygen isotopic composition of Southern Florida meteoric water between January 17, 1989 and December 27, 1994 was -1.82 ± 0.41‰ ($2\sigma_x$) in terms of standard mean ocean water (SMOW) (Welker and White, 2007). Samples were taken at Everglades National Park, Florida at 25.39° latitude and 80.68° longitude. Using the equation:

$$\delta^{18}O_{SMOW} = 30.92 + 1.03092 * \delta^{18}_{VPDB},$$

the average value was recalculated in terms of VPDB (the carbonate oxygen isotope standard) to yield -31.76‰.

For further evaluation of the Florida City test block, it was important to consider the equilibrium isotope fractionation of the oxygen isotope composition of rain (meteoric) water in equilibrium with newly-formed carbonate. For temperatures at approximately 25ºC, the fractionation of meteoric water and newly-formed carbonate, is

~ 28.6‰, which results in a pore water isotope composition of -3.58‰ (Fig. 23; Kim and O'Neil, 1997; Zhou and Zheng, 2005).

Insofar as the calculated value for this pore water overlaps with the modern Florida Keys coral carbonate, it is conceivable that alteration under the influence of meteoric solutions could result in the 1.4‰ difference between the modern and ancient examples. The source of the oxygen isotope offset observed is likely related to the transformation from original aragonite to calcite by dissolution and re-precipitation, which depends on the oxygen isotope composition of water in isotopic equilibrium with the newly-formed carbonate (Zhou and Zheng, 2005). These generally occur under the influence of meteoric solutions. It is know that the conversion from meta-stable aragonite to calcite causes a 7-8% volumetric increase (Stanley, 1966). Therefore, because this study found that the limestone block sampled had coral consisting of calcite, a change in at least some of the coral skeletons is definite, providing proof of meteoric alterations.

Field observation of karst breccia on the outcrop (Fig. 4) and the general presence of brown-stained coarse sediment between the corals in the Florida City sample (Fig. 15) further indicate that meteoric fluids have influenced the coral carbonate after exposure. The brown sediment was specifically sampled along with meniscus void-filling cement and unusually bleached portions of the coral (Fig. 14E) as these are believed to have formed in the meteoric environment. Notably, these textures are not isotopically distinct from the corals (Figure 20C); everything is essentially in equilibrium, independent of the material. Because these textures were altered or precipitated in the meteoric

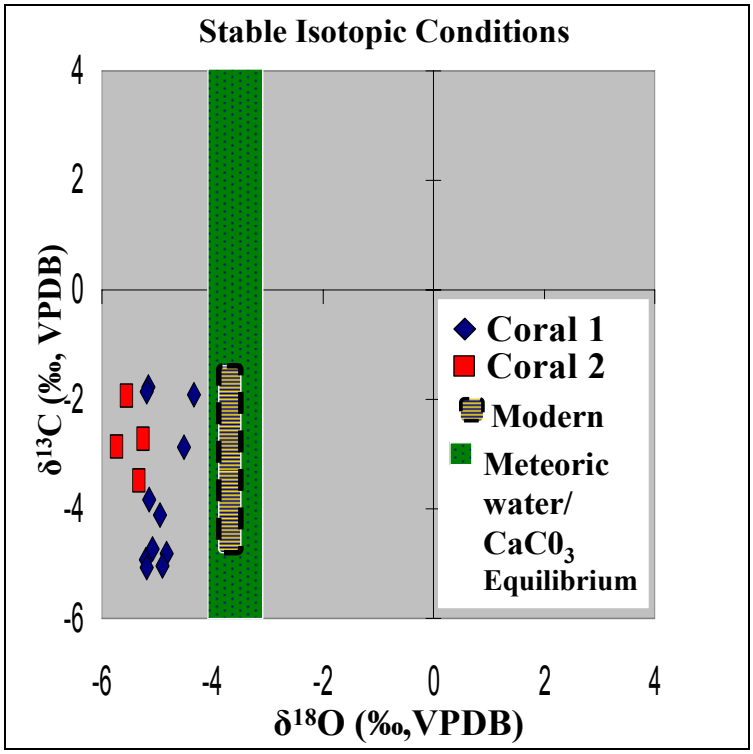

Figure 23: A comparison between isotopic values of Key Largo Limestone coral, modern coral and the isotopic composition of rainwater. Notice that the isotopic oxygen values of the rain water overlap with modern coral oxygen values, indicating that alteration to the Key Largo Limestone may have resulted from meteoric interaction.

environment, and have the same compositions as the ancient corals, this is consistent with wholesale oxygen isotope re-equilibration of the Key Largo Limestone with meteoric fluids.

The high variability of values in meteoric cements is only partially dependent on the $\delta^{18}O$ values of the original limestone rock. The origin of carbon in the meteoric cements may be from dissolution of metastable carbonate minerals, carbon dioxide from the organic matter decay of soil/calcrete, and atmospheric carbon dioxide. Carbon isotope variations are attributed to organic production of carbon dioxide, mineralogical preferences in different carbonate sequences, and the interaction between water and rock to yield mineral stabilization (Rahimpour-Bonab and Bone, 2000). The overall isotopic composition of cement produced by meteoric water is controlled by the compositions of surrounding marine calcite and the meteoric fluids (Rahimpour-Bonab and Bone, 2000).

Internal Marine Sediment

Burial of the coral heads occurs as internal sediments, micrite, shells, and broken coral – mostly created through bioerosion - gradually accumulate. To further evaluate the taphonomic process, these components were similarly analyzed for their isotopic compositions (Fig. 20). As a whole, the internal marine cement has a much wider distribution of both carbon and oxygen isotopes. This clastic carbonate has a heterogeneous source and mineralogy, and may have come from almost anywhere on the reef, as well as from the rain of calcareous plankton. However, the isotopic composition of the internal sediment does partially overlap with that of the coral. This overlapping implies that the addition of broken up coral material is most likely included in the overall heterogeneous marine sediment (if it was not included, there is less likelihood the compositions would overlap). Ultimately, it becomes very likely that bioerosion of the coral contributed significantly to the ultimate burial of itself.

FUTURE RESEARCH

While many different types of analysis were used in this senior thesis study to better understand the fundamental question of coral reef preservation, more research is clearly warranted. For example, one major aspect that could significantly add to the content of this topic would be to determine the relative amounts of *in-situ* branch coral in Florida patch reefs. This information would be very helpful in order to quantitatively decipher their relative spatial importance in the taphonomic process and how important their lack of preservation aids to the overall loss of coral coverage. Another aspect of this topic that could be studied would be quantitatively evaluating the degree and rate of bioerosion on coral in the natural oceanic laboratory as a function of time and environment.

Additional sampling of the various sites and samples would also aid in increasing the accuracy of the research. Transects could be done in Windley Key, with more advanced analysis to determining if a fossil is in growth position, while correlating that information with direct sampling from the site. Also, more samples could be analyzed with X-ray diffraction and isotopic techniques to gain a more precise picture of 3-D

alteration of ancient reefs. A comparison could also be conducted of trace elements found in the fossils verses what is found in modern coral and modern meteoric waters to attempt to find a natural tracer of fluid alteration.

CONCLUSIONS

The transformation of coral skeleton into lithified limestone is a complicated process where bioerosional, chemical, and physical interactions must be taken into account during all stages of taphonomy. The Key Largo Limestone, well represented at Windley Key, embodies an excellent example of a "well-preserved" fossilized coral reef. Because the modern Florida Keys patch reefs can represent the once-living reefs that formed the Key Largo Limestone, an evaluation can be conducted to determine the degree of taphonomic alteration the Key Largo Limestone system has endured. A comparison of preserved *in-situ* coral coverage at Windley Key with the coral coverage of living and standing dead coral in the modern Florida Keys patch reefs indicate that ~38% of *in-situ* coral coverage is lost in the preservation process. The largest major factor for the loss of coral is a high degree of bioerosion. The effects of bioerosion are significant; the process creates sediment that ultimately buries the corals, and develops a highly porous framework for fluid flow through the fossilized reef. Another possible reason for the loss is the lack of branching coral preserved in the quarry.

The interaction of meteoric water with fossilized coral and sediment constitutes a major contributor to coral reef taphonomy. The bioerosion-induced increase in permeability aids the transformation of aragonite to calcite by the process of dissolution and reprecipitation. Through X-ray diffraction and stable isotopic analysis, meteoric alteration appears to be the dominant cause of chemical and mineralogical changes to the Limestone. The degree of chemical alteration appears to depend on the amount of time a particular section of the formation is above sea level, susceptible to rainwater percolation, and how long the section is exposed to other eroding elements such as wind and moisture. The results of this study falsify the original null hypothesis. Not only is there a definite statistically significant spatial change in coral coverage, but there are clear signs that bioerosion and secondary alteration have a significant role in facilitating the spatial difference.

The realization that over one third of *in-situ* coral coverage is lost through the taphonomic processes must be taken into account when any scientific study involves the use of fossilized reefs, no mater how "well preserved" the fossils appear. Bioerosional changes to coral skeletons can be hard to identify but are prevalent in all fossil reef systems. These chemical and biological processes also have varying degrees of influence on fossilized reefs, which need to be accounted for when applying chemical analyses to the study of ancient ocean chemistry and climate. A detailed history of taphonomic reduction should accompany the studies of ancient reefs in order to better calibrate scientific results.

ACKNOWLEDGEMENTS

This paper marks the culmination of my geology studies at the University of Maryland. Because it consisted of work done in Florida and Maryland, a coordinated effort was needed. I would like to specially thank my advisor, Dr. Alan J. Kaufman, for assistance, suggestions, supporting knowledge and financial assistance and education, and Dr. Robert Ginsburg, who gave me the opportunity to work with him in Miami, providing me with experience in the field of marine geology. Dr. Rodrigo Garza has also been extremely helpful in Florida as a correspondent, providing biological and technical support in Miami, assistance with the AGRRA database, and field method advice.

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APPENDIX

A. Coral Gables Field Map

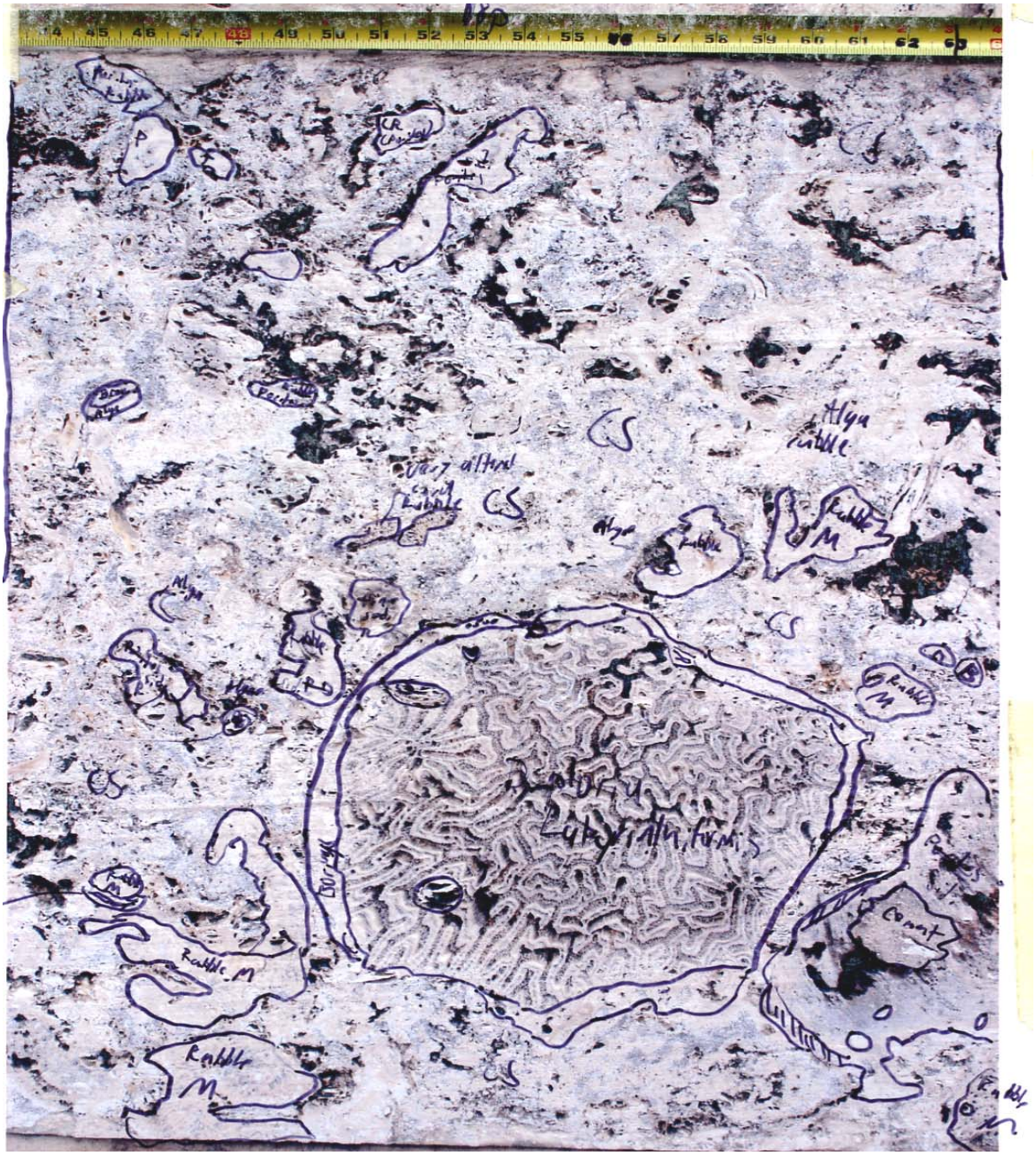


Figure A1: Field map of a limestone block from the Coral Gables old fire station. The large circled fossilized coral is *Diploria labryinthiformis.* The sides of the coral show noticeable alteration. Tiny white circles in some sections of the transition zone represent sponge boring holes, filled in with internal sediment. The coral to the lower right (which engulfs a chunk of cement) is *Porites* sp., with the lined edges indicating more alteration. Other map features are coarse sediment matrix (CS), Cement (added by a construction company to fill in holes), *Montastraea* rubble (M), *Porites* rubble, *Porties sp.* branch coral (P), unknown branch coral (B). Small circles outline bivalve borings.

B. Windley Key Research/Collecting Permit

Florida Department of Environmental Protection
Division of Recreation and Parks

Permit Number

5-06-70

RESEARCH/COLLECTING PERMIT

This Permit Must Be Carried At All Times While Researching/Collecting

Names of Collectors	Address/Telephone	Issue - Expiration Dates
Robert Ginsburg, Ph.D.[1], David Weinstein[2]	Rosentiel School of Marine & Atmospheric Science 4600 Rickenbacker Causeway Miami, FL 33149 (305) 421-4875	8-01-06 to 12-31-06

Representing: University of Miami[1], University of Maryland[2]

Permitted Activity: Taphonomic Comparison Between the Lake Pleistocene Key Largo Limestone and its Living Coral Reef Counterparts

Permitted Collection: No collecting is permitted. Fossil coral to be measured and photographed for comparison and analysis to determine the amount of coral in the limestone and the relative amount of coral rubble vs. coral in growth position.

In the Following Areas: Windley Key Fossil Reef Geological State Park Melba Nezbed, Park Manager – (305) 664-2540

NOTE: Contact Park Manager two weeks prior to your arrival at the park.

Special Conditions or Restrictions:

1. Contact the Park Manager in advance of visits (minimum 2 weeks notice) for coordination and arrangements.
2. Check in at park entrance station upon arrival at and departure from the park. Collected material is subject to inspection.
3. Collect only materials as stated above, in the quantities and manner indicated in the attached application form or proposal.
4. Any other applicable state and federal permits are the responsibility of the permittee.
5. Collected objects may not be sold, bartered, or traded.
6. **Species lists, including voucher numbers of museum donations, and any research reports concerning project data shall be submitted to the district biologist and the park by 12/31/06. Incidental observations and species lists are also appreciated.**
7. Collecting shall be conducted in such a manner as not to attract attention or cause damage to the environment.
8. The permit is non-transferable. At least one named collector (above) must be present. Copy of permit must be carried while in the park.
9. The permittee and research associates will not be subject to park day-fees.
10. The permit is revokable.
11. **Collect no state or federally listed, or rare endemic species or forms. (Special permit required from FFWCC & USFWS)**
12. Collected specimens shall be donated to university or museum collections if they are intact following study.

Approved:	Title:
G. L. Jones George L. Jones	Chief, Bureau of Parks District 5 Administration

cc: District Biologist
Park Manager(s)

FPS-R010 02/95

C. Biscayne National Park Collection Permit

SCIENTIFIC RESEARCH AND COLLECTING PERMIT

Grants permission in accordance with the attached general and special conditions

United States Department of the Interior
National Park Service

Biscayne NP

Study#: BISC-06013
Permit#: BISC-2006-SCI-0031
Start Date: Jun 22, 2006
Expiration Date: Dec 31, 2006
Coop Agreement#: n/a
Optional Park Code: n/a

Name of principal investigator:

Name: David Weinstein **Phone:** (301) 775-8250 **Email:** Dave090@hotmail.com

Name of institution represented:

Rosenstiel School for Marine and Atmospheric Science

Co-Investigators:

Name: Dr. Alan J Kaufman	**Phone:** (301) 405-0395	**Email:** kaufman@geol.umd.edu
Name: Dr. Robert N. Ginsburg	**Phone:** (305) 421-4875	**Email:** rginsburg@rsmas.miami.edu
Name: Dr. Thomas Holtz	**Phone:** (301) 405-4084	**Email:** tholtz@geol.umd.edu

Project title:

Taphonomic Comparison Between the Late Pleistocene Key Largo Limestone and its Living Coral Reef Counterparts

Purpose of study:

Understanding transformation of unconsolidated sedimentary deposits to their liquefied components (rocks) is an essential problem in geology. For coral reef deposits, this transformation is especially complex. Coral skeletons are constantly modified --even while the organisms are still alive-- until they eventually become part of the geologic rock record as limestone. Coral modifications recorded in the geologic record consist of biological processes such as cavities produced by boring animals, incrustation by attached epibionts and internal sedimentation (cavities filled in by skeletal sediment from the reef surface). Other modification consists of physical abrasion and breakage of coral skeletons by storm-generated wave action. Some of these processes have been described but there has been no attempt to apply the results to a preserved coral reef limestone.

Subject/Discipline:

Geomorphology / Surface Processes

Locations authorized:

Offshore waters of Biscayne National Park, specifically near Marker 9, Caeser Creek, and the reefs bordering Hawk Channel.

Transportation method to research site(s):

Personal boat

Collection of the following specimens or materials, quantities, and any limitations on collecting:

No collections of living material is authorized. The incidental collection of small sediment samples and coral fragments needed to characterize sediment type is authorized

Name of repository for specimens or sample materials if applicable:

Repository type: Will be destroyed through analysis or discarded after analysis
Objects collected:
small sedimentary material needed to characterize sediment type. samples will be discarded after analysis

Specific conditions or restrictions (also see attached conditions):

1. The permittee will advise the park (305-230-1144, extension 3006) when they will be working in the park at least three

day prior to conducting field work.

2. All NPS support (logistical or physical) will coordinated through the Park Science Coordinator only
3. This permit is only valid within the boundaries of Biscayne National Park
4. The permittee will inform the Science coordinator of any unusual conditions of observations as soon as reasonable.
5. The total amount of collected material shall not exceed 4 kg (~9pounds)

Recommended by park staff(name and title):

Reviewed by Collections Manager:

Yes ___ No X

Approved by park official:

Date Approved: 6/21/06

Title:

Science Coordinator for Superintendent

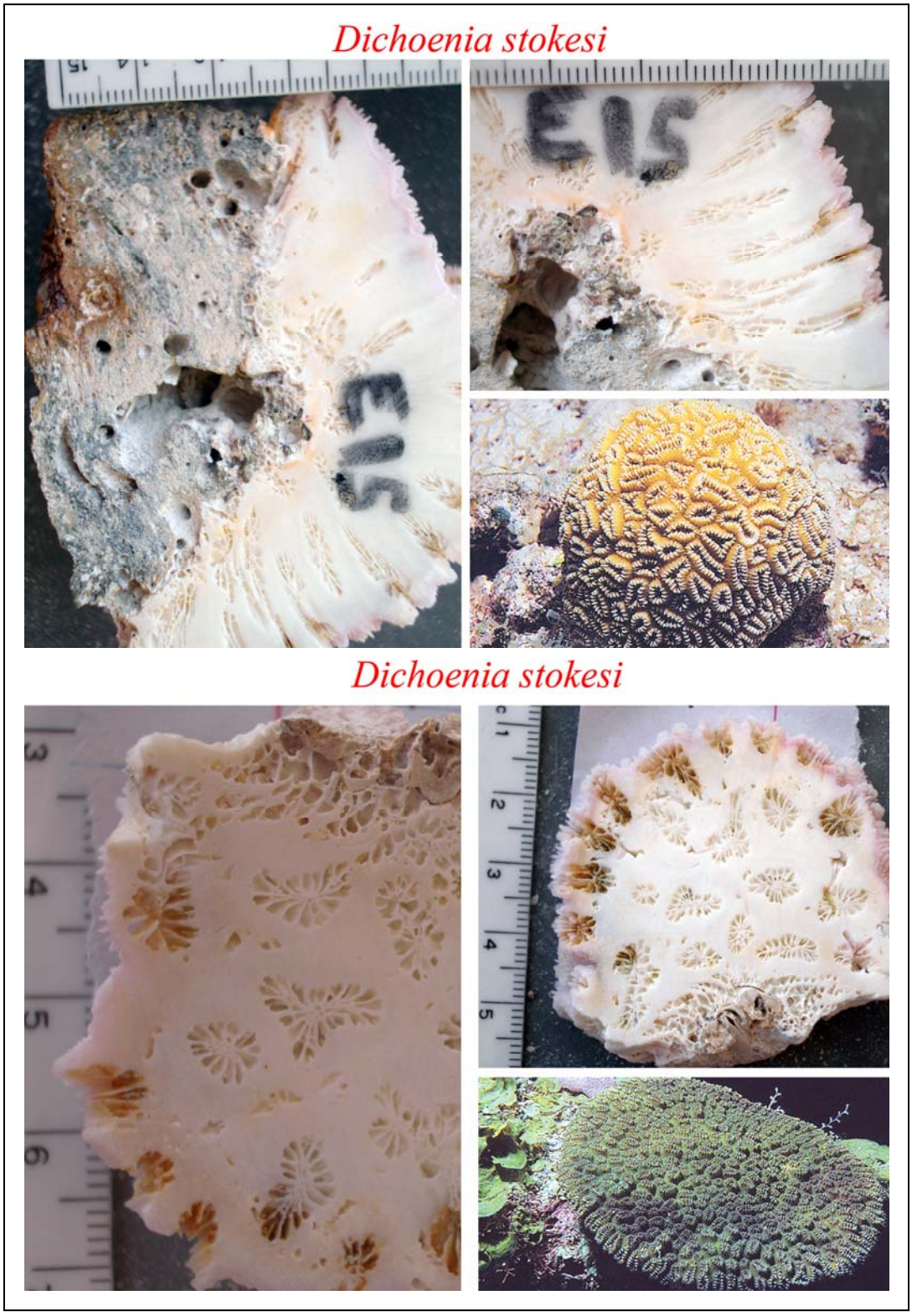
I Agree To All Conditions And Restrictions Of this Permit As Specified
(Not valid unless signed and dated by the principal investigator)

David Weinstein
(Principal investigator's signature)

7/3/2006
(Date)

THIS PERMIT AND ATTACHED CONDITIONS AND RESTRICTIONS MUST BE CARRIED AT ALL TIMES WHILE CONDUCTING RESEARCH ACTIVITIES IN THE DESIGNATED PARK(S)

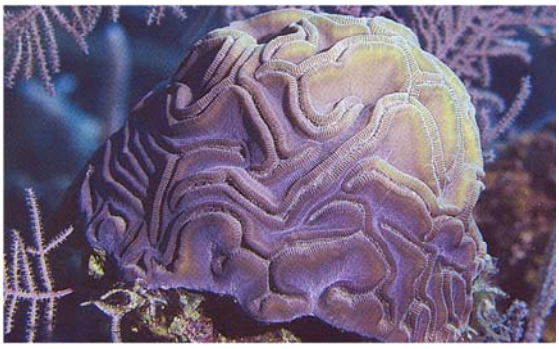
D. Coral Identification Field Guide



Samples provided by the National Coral Reef Institute, Ft. Lauderdale, Florida. Photographs of samples taken by David Weinstein. Living coral picture from Veron, 2000.

Diploria labyrubthiformis

Diploria labyrubthiformis



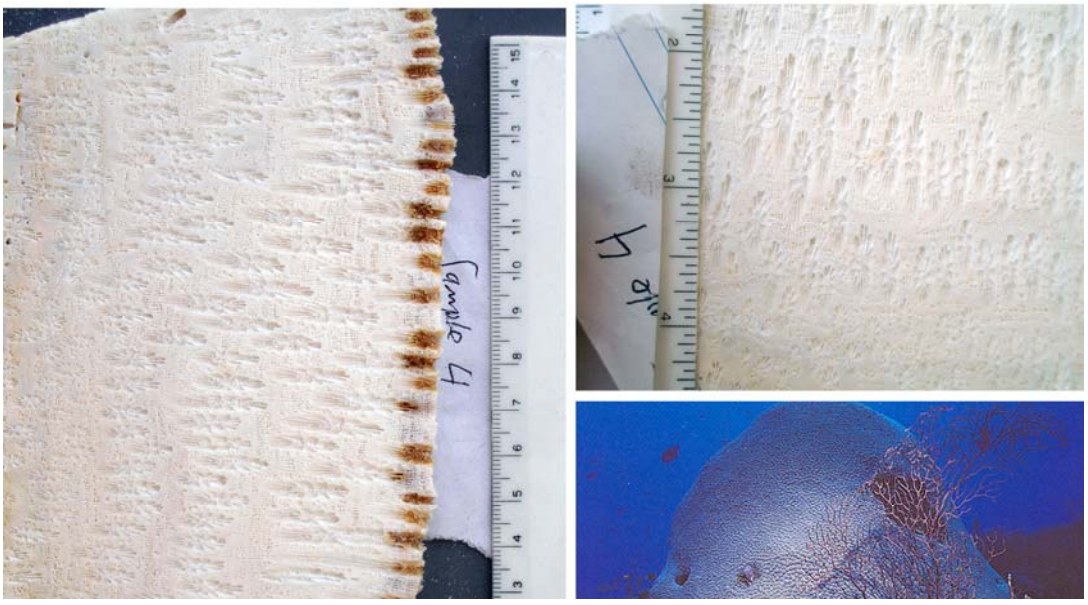
Samples provided by the National Coral Reef Institute, Ft. Lauderdale, Florida. Photographs of samples taken by David Weinstein. Living coral picture from Veron, 2000.

Diploria strigosa

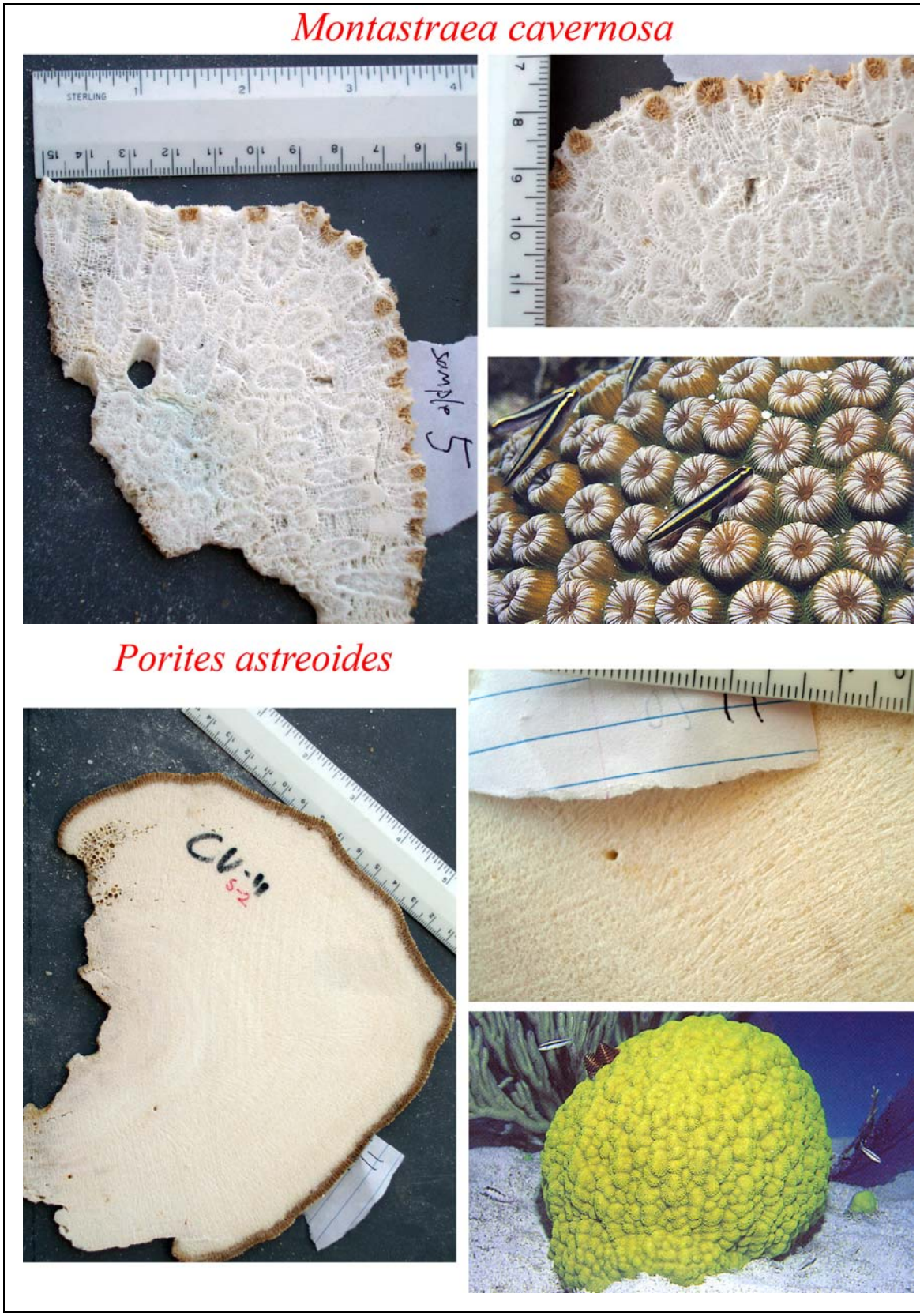
Montastraea sp.

Samples provided by the National Coral Reef Institute, Ft. Lauderdale, Florida. Photographs of samples taken by David Weinstein. Living coral picture from Veron, 2000.

Montastraea cavernosa



Samples provided by the National Coral Reef Institute, Ft. Lauderdale, Florida. Photographs of samples taken by David Weinstein. Living coral picture from Veron, 2000.



Samples provided by the National Coral Reef Institute, Ft. Lauderdale, Florida. Photographs of samples taken by David Weinstein. Living coral picture from Veron, 2000.

E. Example of Field Measurements and Calculations: Transect #1

Field recorded Data

Start (m)	End (m)	Length (m)	Type	Comments
0.130	0.281	0.151	*Diploria* sp.	
0.281	0.440	0.159	Coarse Sed.	
0.440	0.445	0.005	Coralline Algae	
0.445	0.540	0.095	Coarse Sed.	
0.540	0.570	0.030	Branch	*Porites* sp.
0.570	0.620	0.050	Fine Sed.	
0.620	1.010	0.390	Unidentified	
1.010	1.223	0.213	small polyp corals	
1.223	1.315	0.092	Rubble	
1.315	1.330	0.015	small polyp corals	
1.330	1.450	0.120	Coarse Sed.	
1.450	1.550	0.100	Unidentified	
1.550	1.675	0.125	Coarse Sed.	
1.675	1.775	0.100	*Montastraea* sp.	
1.775	1.805	0.030	rubble	
1.805	1.895	0.090	small polyp corals	
1.895	2.115	0.220	Coarse Sed.	sediment filled
2.115	2.170	0.055	Fine Sed.	
2.170	2.223	0.053	Coarse Sed.	
2.223	2.252	0.029	Coralline Algae	
2.252	2.440	0.188	Coarse Sed.	
2.440	2.485	0.045	Unidentified	
2.485	2.580	0.095	Coarse Sed.	
2.580	2.630	0.050	Fine Sed.	filled shell
2.630	2.650	0.020	Coarse Sed.	
2.650	2.975	0.325	rubble	
2.975	3.240	0.265	*Montastraea* sp.	
3.240	3.350	0.110	Coarse Sed.	
3.350	3.510	0.160	Unidentified	
3.510	3.592	0.082	Coarse Sed.	
3.592	3.609	0.017	Fine Sed.	
3.609	3.790	0.181	Coarse Sed.	
3.790	3.815	0.025	Fine Sed.	
3.815	3.950	0.135	Coarse Sed.	
3.950	3.990	0.040	rubble	
3.990	4.220	0.230	Coarse Sed.	
4.220	4.240	0.020	rubble	small polyp corals
4.240	4.340	0.100	Unidentified	
4.340	4.390	0.050	rubble	small polyp corals
4.390	4.470	0.080	Coarse Sed.	
4.470	4.516	0.046	rubble	*Montastraea* sp.
4.516	4.930	0.414	Weathered	

4.930	5.005	0.075	Rubble	*Montastraea* sp.
5.005	5.230	0.225	Unidentified	
5.230	5.380	0.150	Coarse Sed.	w/ definite polyps
5.380	5.430	0.050	rubble	
5.430	5.520	0.090	rubble	small polyp corals
5.520	5.640	0.120	Unidentified	
5.640	5.680	0.040	Coarse Sed.	
5.680	6.130	0.450	Unidentified	
6.130	6.340	0.210	Coarse Sed.	
6.340	6.390	0.050	rubble	*Montastraea* sp.
6.390	6.520	0.130	Rubble	*Montastraea* sp.
6.520	6.565	0.045	Coarse Sed.	
6.565	6.640	0.075	rubble	small polyp corals
6.640	6.750	0.110	Coarse Sed.	
6.750	6.960	0.210	Unidentified	
6.960	7.250	0.290	Coarse Sed.	
7.250	7.270	0.020	Rubble	*Montastraea* sp.
7.270	7.540	0.270	Coarse Sed.	
7.540	7.690	0.150	Rubble	*Montastraea* sp.
7.690	7.720	0.030	Coarse Sed.	
7.720	8.080	0.360	Weathered	
8.080	8.205	0.125	Coarse Sed.	
8.205	8.230	0.025	Rubble	*Montastraea* sp.
8.230	8.450	0.220	Coarse Sed.	
8.450	8.478	0.028	Rubble	*Montastraea* sp.
8.478	8.580	0.102	Coarse Sed.	
8.580	8.700	0.120	Unidentified	
8.700	8.758	0.058	Coarse Sed.	
8.758	9.105	0.347	*Montastraea* sp.	
9.105	9.180	0.075	Coarse Sed.	
9.180	9.195	0.015	Fine Sed.	
9.195	9.250	0.055	*Montastraea* sp.	
9.250	9.390	0.140	Fine Sed.	
9.390	9.520	0.130	*Porites* sp.	
9.520	9.665	0.145	Unidentified	
9.665	9.706	0.041	small polyp corals	(altered)
9.706	9.951	0.245	small polyp corals	
9.951	10.000	0.049	Unidentified	
	Sum =	9.870		

Calculations for Transect #1

Categories	Length (m)	Total length error (± $2\sigma_M$)	Percent	Percent*	Percent error (± $2\sigma_M$)	Percent* error (± 2σM)
Diploria	0.151	9.0550E-03	1.530	2.163	9.1753E-02	1.2971E-01
Small polyp corals	0.734	2.2180E-02	7.437	10.513	2.2483E-01	3.1782E-01
Montastraea	0.767	2.0248E-02	7.771	10.985	2.0527E-01	2.9017E-01
Branch	0.03	9.0550E-03	0.304	0.430	9.1743E-02	1.2969E-01
Coarse grained sediment	3.652	4.6172E-02	37.001	52.306	4.6903E-01	6.6303E-01
Unidentified	2.114	3.1367E-02	21.418	0.000	3.1841E-01	-
Fine grained sediment	0.352	2.3957E-02	3.566	5.042	2.4275E-01	3.4316E-01
Coral Rubble	1.296	3.7335E-02	13.131	18.562	3.7846E-01	5.3500E-01
Weathered	0.774	1.2806E-02	7.842	0.000	1.2994E-01	-
Total	9.87	7.9457E-02	100.000	100.000	8.1025E-01	8.1025E-01

Table A1: Calculations from transect #1 measurements. Percent* indicated a scaled ratio, factoring out the weathered and unidentified category.

F. Windley Key Classification

Groups	Memebers	Description	Characteristics
***In-Situ* Coral**	*Diploria* sp.	"Brain Corals"	All corals were longer than 10 cm across at its longest horizontal girth (not necessarily where the transect intersected it), because modern reef measurements only recorded lengths for corals larger than 10 cm.
	small polyp corals	Primarily *Porites* sp., and *Siderastrea siderea*	
	Montastraea sp.	most commonly *Montastraea annularis*	
Coral Rubble	Coral Rubble	distinguishable fossilized polyps at least .5 cm across at their largest lengths, not in growth position. The genus or species of coral may not be identifiable. This category also includes any large corals that are not in their original growth position.	
	Branch Coral	circular or elliptical cross sectional views of corals with branching growth form not in growth position, typically consisting of *Acropora cervicornis* and *Porites* sp.	
Coarse Sed.	poorly sorted calcareous sediment, consisting of shell fragments and grains ranging from very fine to very coarse, with an average medium (250-500 μm) grain size		
Fine Sed.	well sorted, fine to very fine (88-250 μm) grain sediment.		
Other	Unidentified	voids that will be scaled out of the linear transect because there was no way of being sure what features existed at those location.	voids that will be scaled out of the linear transect because there was no way of being sure what features existed at those location.
	Coralline Algae	laminated	
	Breccia	surface "pits" filled in with angular, calcareous solution breccia	
	Weathered Sections	sections of the wall where particular features could not be recognized due to excessive weathering or erosion	

``

G. Error Analysis Chart and Equations

Transect #	Marker 1 (m)	Marker 2 (m)	Marker 3 (m)
1	1.192	4.194	5.692
2	1.224	4.227	5.726
3	1.206	4.221	5.710
4	1.222	4.224	5.724
5	1.235	4.236	5.734
6	1.206	4.208	5.708
7	1.202	4.206	5.706
8	1.202	4.206	5.707
9	1.197	4.200	5.699
10	1.204	4.203	5.702
σ	1.352E-02	1.358E-02	1.316E-02
2σ	2.703E-02	2.717E-02	2.633E-02
σ_X	4.505E-03	4.528E-03	4.388E-03
$2\sigma_X$	9.010E-03	9.055E-03	8.776E-03

Table A2: Error analysis at Carter Rocks, Maryland.

The largest possible error calculated for each individual measurements is $\pm 9.055 * 10^{-3}$ m ($\pm 2\sigma_M$).

To calculate the propagated total length error ($\pm 2\sigma_M$) error for each group in the transect, the addition propagation of indeterminate error equation was used:

$$\sigma_y = \sqrt{(\sigma_a^2 + \sigma_b^2)}$$

where the total error for the combination of random measurements added together equals the square root of the sum of each individual error squared. Because the individual error was the same for every measurement, the equation became:

$$\sigma_y = \sqrt{(n*(9.055 * 10^{-3})^2)}$$

where n is the number of members in each group.

To format this error into the percent error ($\pm 2\sigma M$):

$$\sigma_x = (b/a)\sqrt{((\sigma_a/a)^2) + (\sigma_b/b)^2)}$$

where z is the total length of the group, a is the entire length of the transect, σ_a is $9.055 * 10^{-3}$, and σ_b is the σ_y value that was calculated in the previous equation. This gives the percent error for each group.

H. Honor Code

"I pledge on my honor that I have not given or received any unauthorized assistance or plagiarized on this assignment."

David Weinstein