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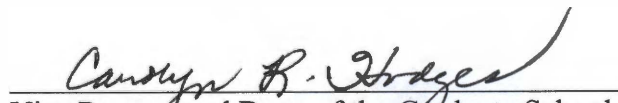
I am submitting herewith a thesis written by David N. West entitled "Late Holocene Charcoal Stratigraphy and Modern Charcoal Deposition in the Pine Rocklands of Great Abaco Island, the Bahamas." I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

  
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LATE HOLOCENE CHARCOAL STRATIGRAPHY AND  
MODERN CHARCOAL DEPOSITION IN THE PINE ROCKLANDS OF  
GREAT ABACO ISLAND, THE BAHAMAS

A Thesis  
Presented for the  
Master of Science Degree  
The University of Tennessee, Knoxville

David Norman West  
August 2007

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## **DEDICATION**

This thesis is dedicated to my parents,

Johnnie E. West and Grace M. West

## ACKNOWLEDGEMENTS

I owe special thanks to the students in the Laboratory of Paleoenvironmental Research for field and laboratory assistance, especially Allison Stork, Martin Arford, Joe Burgess, Chad Lane, and Zack Taylor. I would also like to thank the members of my committee, Dr. Ken Orvis, Dr. Sally Horn, and Dr. Henri Grissino-Mayer, for their assistance and support over the course of this project. They, along with Dr. Anita Drever, Dr. Ronald Foresta, Dr. Lydia Pulsipher, Dr. John Rehder, and Dr. Bruce Ralston, have trained and encouraged me in all aspects of geography and in all else required for success in the pursuit of a Masters degree.

The sediment core I analyzed was recovered during a field expedition led by Drs. Horn and Orvis and funded by the Global Environmental Change Research Group (GECRG) at the University of Tennessee. The GECRG also funded initial radiocarbon determinations on the core. Other radiocarbon dates critical to this thesis were kindly provided to me by Dr. Timothy Jull and the NSF-Arizona AMS Laboratory. My field sampling of charcoal during a pine rockland fire on Abaco Island took advantage of a controlled burn funded and coordinated by The Nature Conservancy and the USDA Forest Service in collaboration with Bahamian resource agencies. For allowing me to conduct my research as part of this burn and for their support in the field, both of my study and so much other work on pine rockland ecology, I thank Chris Bergh and Alison Higgins of The Nature Conservancy, and Dr. Mac Callaham and Dr. Joe O'Brien of the USDA Forest Service. My laboratory analyses of modern and fossil charcoal samples were conducted in the Laboratory of Paleoenvironmental Research in the Department of

Geography at the University of Tennessee. The aerial photographs included in this thesis were taken by Dr. Ken Orvis with funding from the National Geographic Society.

## ABSTRACT

The paleoecological history of the Bahamas archipelago is one of change throughout the Holocene, and is recorded in the sediments deposited in solution holes. However, with its karstic pine rocklands landscape, Great Abaco Island has virtually no overland flow of water, neither rivers nor sheet-flow. This means that transport of charcoal produced through biomass burning and deposited in local ponds and solution holes is primarily microscopic in size and is probably transported by wind. Fires in the pine rocklands are mainly low-intensity ground fires that result in very little aerial transport of charcoal. Unless a fire occurs immediately adjacent to a pond, very little microscopic or macroscopic charcoal is deposited in it.

Split Pond, located in the northeast portion of Great Abaco Island, yielded a 2.7 m long core retrieved beneath 30 cm of water. A piece of charcoal recovered from near the base of the core has been dated to  $5830 \pm 50$   $^{14}\text{C}$  yr BP. At approximately 250 cm in the core, there is a discontinuity in the sediments, with a layer of dense, clayey material below 230 cm abruptly changing to organic-laced marl above. This is possibly due to a period when the lake became completely dry, exposing the sediments to erosive processes. The  $5830 \pm 50$   $^{14}\text{C}$  yr BP date was recovered from the dense clay layer, but because of the condition of the sediments, a full examination of material from this layer was not practical. Immediately above the discontinuity, at approximately 220 cm, material yielding a date of  $1503 \pm 37$   $^{14}\text{C}$  yr BP was recovered, which serves as the basal date for the studied portion of the core. Two dates above the discontinuity ( $2910 \pm 40$

and  $1152 \pm 36$   $^{14}\text{C}$  yr BP) are considered to be older, redeposited material and have been discussed as such.

Pollen preservation is poor throughout the core, with pine pollen, presumably of *Pinus caribaea* var. *bahamensis*, robust enough to be present in sufficient amounts to allow for counting, but even that is poorly preserved at certain levels possibly due to water alkalinity or periods of drying. Charcoal analysis of the core indicates a period of increased burning in the area of Split Pond ca. 1300  $^{14}\text{C}$  yr BP, which correlates with the suggested arrival time of the Lucayans in the Bahamas. In the upper portion of the core, the data indicate a prolonged period of increased burning since ca. 1000  $^{14}\text{C}$  yr BP. Pine pollen also increased during this period. In most levels of the core neither microscopic nor macroscopic charcoal fragments are found in abundance, a finding that fits with other paleoenvironmental studies conducted in the pine rocklands.

As a second portion of the study, samples of air-fall charcoal were collected in open Petri-dish traps during a controlled burn in the recently chartered Great Abaco National Park. The fire was a low-intensity ground fire type that most commonly occurs in the pine rocklands. For those traps placed down-wind of the burn, microscopic charcoal was deposited in significant amounts, but macroscopic charcoal was not found in quantity. The traps placed approximately 1 km upwind of the burn as controls yielded no charcoal of any size. This supports the hypothesis that the low intensity ground fires in the pine rocklands produce low amounts of microscopic charcoal that is wind-transported into local ponds, but are not intense enough to transport appreciable amounts of macroscopic charcoal. This helps explain the relatively low amounts of charcoal

found in my Split Pond study and in other paleoecological studies conducted in the Bahamian archipelago.

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# CHAPTER 1

## Introduction

The long-term history of fire in different world ecosystems and how this history has been influenced by climate and human activity are key themes in biogeography. Fire, as one of the earliest tools adapted by humans, has been instrumental in the social development of the species. As human society developed, so did the creative use of fire in the environment. It is understood that in almost all societies, particularly early societies, fire has been ubiquitous and essential. Although fire has been adapted for use, it has not been mastered. When slash-and-burn agriculture is used or when wildfire occurs, there is a durable mark left upon the local environment. If fire occurs often enough, it can usher in changes in the makeup of vegetation, favoring fire-tolerant species, for example *Pinus*, over fire-intolerant hardwoods. An understanding of the past climate and fire history of an ecosystem can prove to be a useful, if not essential, tool for developers and land managers in establishing current land use and conservation practices. My thesis research, directed by Dr. Ken Orvis with Drs. Sally Horn and Henri Grissino-Mayer serving as my committee members, involves examining microscopic charcoal in a Late Holocene sediment record recovered from Split Pond, Great Abaco Island, the Bahamas. To better understand microscopic charcoal transport and deposition in Abaco's pine rocklands, I also collected and processed air-fall charcoal samples deposited during a controlled burn in Abaco National Park.

My thesis work is part of a larger project directed by Drs. Orvis, Horn, and Grissino-Mayer on the climate and fire history of Great Abaco Island. Although the pine

rocklands of the Florida Keys are floristically similar to those in the Bahamas, we chose Great Abaco Island as a study area for two reasons. First, it is uniquely located in the northern tropical Atlantic, very near the boundary between the temperate and sub-tropical climatic regions, but has had very few paleoecological studies conducted in the area. Second, the Nature Conservancy is actively engaged with the Bahamian natural resource agencies in establishing a fire management policy for the recently chartered Great Abaco National Park (Myers et al. 2004). The larger project is designed to provide information on the long-term fire and vegetation history of the pine rocklands on Great Abaco. The information collected during this project is intended to be used by land management entities such as The Nature Conservancy and will contribute to public education efforts in local communities.

Several paleoecological studies have been completed or are currently underway in pine rocklands on Abaco, funded by the University of Tennessee, The Nature Conservancy, and the National Geographic Society, with logistical support from Bahamian resource agencies and Friends of Abaco, a local NGO interested in conservation. Stork (2006) reconstructed vegetation dynamics from sediment cores recovered from West Pond on Great Abaco, and I report in this thesis on charcoal in a core recovered from Split Pond on Great Abaco. Studies of cores from two other Abaco sites are in progress. Dr. Grissino-Mayer and Alison Miller (2007) are establishing reference tree-ring chronologies from Split Pond and West Pond and are in the process of reconstructing recent fire history using samples collected from fire-scarred trees there. They and other students have collected similar samples from other Abaco sites. In Florida, Joshua Albritton is now in the initial stages of a study of sediments from pine

rockland sites on Big Pine Key and neighboring keys, a project funded by the U.S. Fish and Wildlife Service with additional support from The Nature Conservancy. The other portion of my study examines charcoal transport and deposition processes in the pine rocklands. The information from this part research may prove to be of great assistance in interpreting results from the aforementioned pine rockland sediment studies of charcoal, which have yielded relatively little charcoal of any size and almost no macroscopic charcoal.

Although few paleoecological studies have been conducted on the islands of the Bahamas, paleoecological studies have been published for the mainland North American tropics, the greater Caribbean area, and the adjacent tropical Atlantic. In the Dominican Republic, Drs. Orvis, Horn, and Kennedy and their students are reconstructing climate and fire histories from lake and swamp sediments and soils (Horn et al. 2000, Kennedy et al. 2006, Lane 2007, and Horn et al. unpublished data). Lake sediment studies have also been conducted in Jamaica (Street-Perrott et al. 1993), Haiti (Higuera-Gundy et al. 1999), Puerto Rico (Burney et al. 1994), and Grenada (Barbour and McAndrews 1995) that provide insights into the climatological dynamics of the Caribbean during the Quaternary.

The Bahamas provide a particularly ideal location for paleoenvironmental research, as humans did not settle them until ca. 1200 years ago or even later (Berman and Gnivecki 1995, O'Day 2002). The potential exists for a record of climate or environmental change unrelated to human activity to be present in any core sections deposited prior to 1200 years ago. Studies conducted in Puerto Rico and other areas around the world have shown a correlation between human activity and an increase in charcoal deposition (Siegel et al. 2005, Asselin and Payette 2005, Burney et al. 1994). It

is likely that human colonization of Great Abaco similarly resulted in increased burning, the evidence of which should have accumulated in the local environment over long periods. A charcoal spike in the Split Pond record that can be tied to human arrival would complement the limited archaeological research that has been conducted on the island, and could also provide a means for assessing the timing of human arrival with greater certainty.

Split Pond is located on the southwest outskirts of the city of Marsh Harbour. It is an alkaline pond surrounded by pine rockland vegetation, which is the most widespread vegetation assemblage on the island. The pine rocklands include plant species that are fire-adapted and depend on disturbance for propagation, with *Pinus caribaea* Morelet as the dominant upper-canopy species. With funding from the University of Tennessee Global Environmental Change Research Group, Professors Orvis and Horn and students Allison Stork and Lisa LaForest recovered a 2.7 m core from Split Pond in October 2003. The sediment stratigraphy switches between bands of peat, marl, and clastic/rotted limestone. A piece of charcoal from near the base of the 2.7 m long core yielded a date of  $5830 \pm 50$   $^{14}\text{C}$  yr BP.

The high alkalinity of Split Pond may have caused degradation of pollen grains. At any rate, with low pollen concentrations and diversity in test samples, this proxy appears unusable for paleoenvironmental reconstruction. I did, however, find it useful to record pine pollen, as *Pinus caribaea* is the dominant species in the area. Pine pollen is large and robust, wind-dispersed, and produced in prodigious amounts around my study site, resulting in a substantial number of grains in my samples. Absence or degradation of pine pollen in a given level could be due to water chemistry (alkalinity) or, because of

the shallow nature of Split Pond, periodic drying and aeolian disturbance of surfacial material might also be factors. The lowest 52 cm of the core consist of dense clayey material that may have been deposited when Split Pond was open to the ocean. It proved impractical to do charcoal counts on this part of the core because of a viscous, dense, black substance found in the section, which is most likely micronodules of Fe-Mn oxides and hydroxides (Rothwell 1989).

In the second portion of my thesis research, I processed and examined air-fall charcoal samples collected during a prescribed burn conducted in Abaco National Park by The Nature Conservancy in November 2004. In previous work on Bahamian sites, very little microscopic charcoal and almost no macroscopic charcoal has been found (Kjellmark 1995, Stork 2006). I hypothesize that the lack of macroscopic charcoal fragments can be ascribed to the lack of overland flow of water on Great Abaco Island (cf. Sealy 1994). Without overland flow, there is no secondary transport of material after a fire event. A great deal of microscopic charcoal is transported by wind during the actual fire event, especially during modern fires that are generally considered to be of low intensity in the pine rocklands of Great Abaco (Myers et al. 2004). But, under these circumstances little or no macroscopic charcoal is lofted to end up in local ponds. My air-fall charcoal experiments sought to demonstrate how much microscopic charcoal is transported by wind during such low-intensity fires, which may in turn illuminate why so little microscopic charcoal has been deposited in local ponds.

The specific questions I address in the study as a whole are:

1. Can a more complete fire history be revealed by a sampling method that examines .25 cm<sup>3</sup> samples taken along a 4 cm section of the core, as opposed to the traditional method of taking a 1 cm<sup>3</sup> sample at every 4 cm interval?

2. Is there a paucity of macroscopic charcoal in my samples compared to microscopic charcoal, suggesting that little to no overland transport is taking place in this environment?
3. How is microscopic charcoal transported in the pine rocklands environment?
4. Is there evidence of past human influence on fire in the environment? If so, can this evidence be used to estimate when human beings arrived on Great Abaco?
5. How can current fire management practices benefit from what we learn through an examination of fire history?

My thesis is divided into seven chapters. In Chapter 2, I summarize existing paleoecological records that are relevant to my study site and review selected methodological papers related to my study. Chapter 3 examines the geology, climate, vegetation, and human history of the Bahamas in general and Great Abaco Island in particular. Chapter 4 presents the field and laboratory methods used to conduct microscopic charcoal analyses of the Split Pond sediments and the macroscopic charcoal from air-fall samples. Chapter 5 presents the results of the charcoal analysis. Chapter 6 is a discussion of my results and how they fit with other research conducted in the region, in the broader context of climate change and anthropogenic impacts on the environment. In Chapter 7, I conclude this thesis by summarizing my results and offering some suggestions for future research on Great Abaco Island.

## CHAPTER 2

### Literature Review

#### *Paleoecological Studies in the Tropical Atlantic and Caribbean Region*

The paleoecological history of Great Abaco Island is, like most of the rest of the circum-Caribbean region, characterized by distinct wet and dry periods. Although there is a paucity of literature on the paleoenvironmental history of Great Abaco, several studies have been conducted in the circum-Caribbean region that highlight overarching trends in climate that may have influenced human societies and local-scale environmental conditions. Three extensive studies conducted in Jamaica, Yucatan (Mexico), and Haiti indicate wetter climatic conditions in the early to middle Holocene (ca. 7000 cal. yr BP–3000 cal. yr BP) and drier conditions in the late Holocene (ca. 3000 cal. yr BP–present).

In their examination of Wallywash Great Pond, Jamaica, Street-Perrott et al. (1993) determined that in addition to two humid/warm phases during the Late Pleistocene, their study site also experienced three alternating wet/dry Holocene cycles that could not be accurately dated due to temporally varying inputs of “dead” carbon from local springs. Wallywash Great Pond is similar to Split Pond in that it is located in a limestone-dominated area, with thinly developed *terra rossa* paleosols in the higher portions of the catchment. It is also very alkaline, with a pH of 8.2–8.6. The Wallywash sediment core consists of alternating layers of marl, organic calcareous mud, organic mud or peat, and brown calcareous mud. They suggested that the marls represent wet/warm periods during sea-level highstands. The brown calcareous muds, they suggested, were deposited during periods when the lake was, at the least, ephemeral and at the worst,

completely dry. During what would be considered the late Holocene, they suggested that several ephemeral-to-dry periods occurred in the Wallywash Pond area. However, they did not offer specific dates for those dry periods, possibly because of dead-carbon contamination of datable material (Street-Perrott et al. 1993).

Hodell et al. (2000), examined temporal variations in oxygen isotopes and sediment composition in a core recovered from Lake Chichancanab, Yucatan, Mexico. They found evidence of a severe drought during the late Holocene that coincided with the collapse of the Maya civilization. Lake Chichancanab is located in an area of karstic geologic substrate similar to Great Abaco. Between ca. 7,100 and 5,000 cal. yr BP, high calcite and low sulphur concentrations coupled with low  $\delta^{18}\text{O}$  values indicate what they considered the wettest Holocene conditions throughout the circum-Caribbean region, conditions they attributed to an increase in the intensity of the annual cycle caused by the earth's precessional cycle. About 3,000 cal. yr BP, carbonate content in Lake Chichancanab decreased and  $\delta^{18}\text{O}$  values of ostracods increased, which, they suggested, indicates the beginning of a drying period (Hodell et al. 2000). Their findings parallel those of Higuera-Gundy et al. (1999) in Lake Miragoane, Haiti. Unlike Wallywash Great Pond, however, Hodell et al. were able to suggest dates of exceptionally dry periods that occurred at their study site: ca. 1520, 1171, 1019, and 943 cal. yr BP. The drying trend appeared to increase until reaching a maximum at  $1,140 \pm 35$   $^{14}\text{C}$  yr BP, coinciding almost exactly with the collapse of Mayan civilization at ca. 1,100 cal. yr BP (Hodell et al. 2000).

Higuera-Gundy et al. (1999) examined sediments recovered from Lake Miragoane, Haiti, and found three distinct periods of change in evaporation and

precipitation. Near the base of their core, dated at ca. 10,000  $^{14}\text{C}$  yr BP, pollen and  $\delta^{18}\text{O}$  results indicated cool and dry conditions. Throughout the middle Holocene sections (ca. 7000–3200  $^{14}\text{C}$  yr BP), high lake levels and abundant moist forest taxa indicate a period of warm and wet conditions, which agrees with studies conducted in Haiti and Yucatan, Mexico. A period of drying began ca. 3200  $^{14}\text{C}$  yr BP and may have been intense enough to drive some mesophilic species to local extinction. During the last 1000 years, the record is heavily influenced by pre- and post-Columbian human impacts on the environment. Higuera-Gundy (1999) also speculated that pollen from successional tree species and abundant charcoal fragments in part of the Miragoane core may provide evidence of human disturbance on the island. Although the inferred impacts predate Columbus, they do not extend to the period of early human occupation of the island, so they cannot be used to define the date of human arrival.

#### *Paleoecological Studies from Mainland Florida*

The eastern shore of the state of Florida is located approximately 100 km from Great Abaco Island. A portion of Florida's southern tip, as well as some of the lower islands of the Florida Keys, has in common with Abaco a geologic substrate of oolitic limestone. Those areas also have pockets of pine rockland vegetation very similar to Abaco's. Because many more studies have been conducted in Florida than on Abaco, it is useful to compare possible associations between the two. Watts and Hansen (1994) found a marked difference in vegetation between the northern and southern portions of the Florida peninsula during both the Pleistocene and Holocene epochs. During glacial periods, frost-tolerant species such as spruce and beech were present well into the central

portion of the Florida peninsula. The southern portion was, and continues to be, covered by tropical vegetation floristically similar to the Bahamas. This is most likely because the warm current flowing from the Gulf of Mexico and between the southern tip of the peninsula and Cuba maintained warmer, frost-free conditions there. However, as glaciers retreated, tropical vegetation does not appear to have advanced beyond the south-central portion of the state, possibly because polar outbreaks still brought sub-freezing temperatures into the central portion of Florida. Although Watts and Hansen (1994) did not collect sediment cores from what they referred to as tropical Florida, their study sites at Lake Annie and Lake Tulane are nonetheless located south of the frost line of the Florida peninsula. These sites offer pollen evidence that complements findings at other sites in the circum-Caribbean region, even though they suggested that the area around Lake Tulane was drier during the early Holocene and wetter in the late Holocene, which seems to conflict with findings from other studies. They suggested, however, that wet and dry conditions in this area of the mainland may be more a function of sea level change and its effect on the proximity of the water table to the surface than of regional climatic conditions (Watts and Hansen 1994). Their pollen evidence suggests that ca. 13,730 cal. yr BP, pine was the dominant forest species, but oak-dominated forests were on the rise. *Quercus* then dominated until ca. 4650 cal. yr B.P, at which time *Pinus* resumed dominance and has retained it until the present. In the late Holocene, insolation and seasonality returned to present-day levels. Sea level rose, which led to a higher water table throughout Florida. Even though climate conditions in the late Holocene may be drier in the region, a higher water table can provide moisture to shallow-rooted pines. And, due to their fire adaptive nature, pines would remain the dominant species on the

southern Florida peninsula even during the periods of more frequent burning that dry conditions would create (Watts and Hansen 1994).

Grimm et al. (2001) had findings similar to those of Watts and Hansen. With rising sea levels and increased precipitation, *Pinus* became much more abundant on the Florida peninsula after 5500 cal. yr BP, an indicator of a rising water table. The increase in *Pinus* comes later than at sites located farther north. Watts and Hansen (1994) documented this increase in northern lakes beginning as early as 7000 cal. yr BP and as late as 5000 cal. yr BP in southern sites. This suggests that the southern portion of the Florida peninsula was drier than sites farther north during the early to middle Holocene.

#### *Previous Paleoecological Research in the Bahamas*

One of the few paleoecological studies conducted in the Bahamas Archipelago, Eric Kjellmark's 1995 dissertation has become a benchmark for subsequent studies in the area. By examining the effects of both natural and anthropogenic fire in the pine woodlands of Andros Island, he offered insights into the development of the pine woodlands found throughout the archipelago. By examining modern vegetation, tree-ring samples, and sediment cores, he hoped that his study could serve as a model for the effects of anthropogenic fire both on the islands and the mainland neotropics. Andros Island is located close to Great Abaco and is floristically similar.

Kjellmark determined that vegetation on Andros Island burns with an average frequency of six to seven years based on dendrochronological analysis of fifteen 50 x 10 m plots of fire-scarred pines, as well as the percent cover of different species present. By examining fossil pollen and charcoal taken from three sediment cores recovered from

three blue holes located 1 km, 5 km, and 17 km inland from the east coast of Andros Island, Kjellmark provided an extensive reconstruction of vegetation dynamics throughout the Holocene. However, his detailed palynological analyses of the cores were complicated by the slumping of older sediments from shelves in the upper portions of the blue holes onto younger sediment accumulating at the bottom. This led to many dating reversals in his profiles, which made interpretation of the records difficult (Kjellmark 1995).

At his first site, Rainbow Blue Hole, the core yielded an abundance of pollen from wetland species from the lower portion, indicating a wetter period ca. 1,500 cal. yr BP. This would seem to conflict with the findings of Hodell et al. (2000) of consistently dry conditions during that time. Between 1,500 cal. yr BP and 800 cal. yr BP, Kjellmark suggested that the pollen record showed a drying period on Andros culminating in an increase in pine pollen and charcoal concentrations ca. 800 cal. yr BP. This finding suggests an increase in fire frequency on the island, possibly as a result of human impact during already dry conditions. From 400–500 yr BP, the time at which native humans were thought to have been removed by Europeans from the islands, a sharp decrease was found in both pine pollen and charcoal. Pine pollen increased again at 200 yr BP, at the time when the Bahamas were recolonized by Europeans (Kjellmark 1995).

Kjellmark's second site, Church's Blue Hole, is the core that showed intervals of slumping. This made interpretation of the core difficult, but Kjellmark found evidence that through time, three plant communities replaced each other in the vicinity of the site. The oldest sediments in the core indicated the presence of shrub species that typically grow in dry sites, such as *Trema lamarkianum*. Again, around 1,500 cal. yr BP, evidence

suggests a transition to a mesic hardwood/pine woodland community. Then, at ca. 900–1000 cal. yr BP, *Pinus caribaea* and other more fire-adapted species found in the current pine woodland community dramatically increased. He found very little charcoal throughout the core, but considered a peak in charcoal that occurred during the conversion to pine woodlands ca. 900 yr BP to be an indicator of human colonization (Kjellmark 1995).

Stalactite Blue Hole, the site farthest from the coast, showed very little change in the last ca. 2400 cal. yr BP. Throughout the core, pollen assemblages reflect pine woodland vegetation. The charcoal evidence, plotted in relation to pollen concentrations, did not demonstrate any significant impact of fire on the ecosystem locally (Kjellmark 1995).

The results of Kjellmark's study (1995) on Andros Island showed that each site responded differently to changes in climate and human presence during the late Holocene. Pollen evidence from Church's Blue Hole and Rainbow Blue hole suggests a drier climate 2,400–1,500 cal. yr BP, switching to a wetter climate between 1,500 and 900 cal. yr BP.

Kjellmark also found that charcoal concentrations are low throughout all the cores, although Rainbow Blue Hole showed a distinct relative peak in charcoal that coincides with what is believed to be human arrival on the island. The generally low amounts of charcoal overall may indicate that humans did not have a major impact on vegetation assemblages, or that some other environmental factor may influence charcoal deposition in these lake sediments. Kjellmark (1995) concluded that a combination of

human activity and a gradually drying climate during the Holocene contributed to the expansion of the pine woodlands on Andros Island.

Stork (2006) examined sediments from West Pond, which is located on Great Abaco Island. Her work is particularly useful to my study because it is the closest geographically to my study site. Stork concluded that pollen assemblages found in West Pond indicate significant environmental change during the last 1500 years. The pollen of hardwood taxa dominated the lower portion of the core, suggesting a climate wetter than today's prior to ca. 770 cal. yr BP. At ca. 550 cal. yr BP, the sediments change from peat to marl and the pollen assemblage switches from hardwoods to *Pinus* for the upper portion of the core. A peak in *Rhizophora* pollen between ca. 1190 and 1100 cal. yr BP may indicate an earlier dry phase.

Like Kjellmark, Stork (2006) found very little microscopic charcoal throughout the West Pond core, indicating low fire frequency, low fire intensity, or very little secondary transport of charcoal after fire events, although she did find a relative peak in charcoal production near 1190 cal. yr BP that may be an indicator of initial human arrival on Great Abaco Island. Taken as a whole, her findings suggest a shift from a hardwood dominated community influenced by high severity fires to a pine dominated community influenced by frequent, low-severity fires.

### *Charcoal Transport During Fire Events*

Several obstacles stand in the way of calibrating paleorecords of biomass burning against measurements of charcoal fragment production and transport during fire events.

Clark et al. (1998) conducted an in-depth study of the size distributions of charcoal

fragments transported by wind, those actually deposited on the water surface of a pond, and those eventually deposited in lake sediments. Their study was conducted during an experimental burn in the boreal forest of west-central Siberia.

To trap the air-fall charcoal particles, Clark et al. (1998) used 21 traps located at approximately 10 m intervals along three transects extending away from the fire, with the most distant at ca. 70 m from the burn area. The traps were 400 cm<sup>2</sup> pans filled with deionized water to simulate the surface of a pond. Their results showed that the distance from a fire to which larger sizes of charcoal particles are transported depends on several factors, including the type and amount of biomass consumed, the intensity of the fire, wind speed, and terrain. A high-intensity crown fire that occurred during their experimental burn transported particles as far as 70 m from the burn area. These were later sieved through 180, 250, and 500 µm mesh screens. Size distribution was as expected from settling velocities, with the largest particles falling within the burn and the smallest in the most distant traps (Clark et al. 1998). They also found no correlation between the amount of charcoal deposited in lake sediments and the amount of airborne charcoal generated by a particular burn. Charcoal in lake sediments appeared to aggregate over time and may represent an accumulation of several fires during that time. They concluded that although charcoal particle sizes encountered in lake sediments maintain diameter distributions similar to those in the air, secondary transport of charcoal particles by surface flow leads to an increase in actual charcoal amounts deposited in lakes as opposed to the amounts suggested solely by their air-fall traps (Clark et al. 1998).

### *Charcoal as a Proxy for Past Fires*

Fire history information recorded in lake sediments can be gleaned by counting charcoal particles on pollen slides, although whether such small particles are specific to the local watershed is still debated. Several alternatives to the pollen slide charcoal method have been suggested in order to better reconstruct local-scale fire events. These include the use of larger charcoal fragments found in thin sections (Clark 1982) or extracted by sediment sieving (Whitlock and Larsen 2001), organic matter digestion, and filtration. Indirect records of past fire events are also used, including changes in pollen and diatoms. Pollen-slide methods used to reconstruct long-term fire history usually consider the number of charcoal particles per sampling level, the total cross-sectional area occupied by charcoal particles per sampling level, or the charcoal-to-pollen ratio. Asselin and Payette (2005) proposed a new method, which they referred to as the Charcoal Size Distribution, or CSD, method. This method takes into account the size distribution of the charcoal fragments in each sample. They compared their results with several other widely accepted methods, including dendrochronology, radiocarbon-dated soil charcoal, charcoal concentration, and charcoal-to-pollen ratio.

### *Evidence of the Timing of Human Migration into the Bahamian Archipelago*

Because islands are so sensitive to introduced environmental actors, humans can leave marked evidence of their initial appearance on the landscape, for example through their use of fire for the clearing of land. Although archaeological evidence is lacking that indicates the arrival of any pre-ceramic-using human cultures in the Bahamas, Burney et al. (1994) concluded in a Puerto Rico study that a spike in microscopic charcoal can serve

as a proxy indicator of when humans first settled an island. They compared charcoal data retrieved from a sediment core to similar data from an earlier study on the island of Madagascar. They attributed a marked spike in microscopic charcoal found in the sediment stratigraphy at ca. 5300 cal. yr BP to human colonization. This evidence predates available archaeological evidence of human presence by almost two millennia.

Berman and Gnivecki (1995) characterized the prehistoric settling of the Bahamas as a 2000-year-long process of exploration and settlement by early ceramic-bearing cultures. Many theories have been put forth concerning patterns of migration, but these lack a strong chronological foundation. Early sites are particularly vulnerable in the Bahamas, and preservation unlikely, because of a number of factors, including dense vegetation, traditional agricultural practices, coastal erosion, and re-occupation of early sites by later peoples. The very earliest sites are the most vulnerable because of their age.

Berman and Gnivecki (1995) listed the three primary variables that cause human migration as push, pull, and ease of transport. Paleoecological data indicate a dry period between 2500 cal. yr BP and 1000 cal. yr BP, which may have generated the push factor of negative home conditions, such as drought. Poor environmental conditions at home during that period and the resultant need to access unexploited resources might possibly have redefined the resources of the north-central and south-central islands of the Bahamas as “pull factors” for early Lucayans. The primary pull factors would have been unexploited marine and terrestrial resources plus suitable environmental conditions to support root-crop horticulture, which involved burning to prepare agricultural plots. A spike in microscopic charcoal may for that reason serve as a good indicator of the approximate time of human arrival and the beginning of exploitation. With the relative

proximity of the Bahamian islands and with their skills in exploiting marine resources, the Lucayans already had the technology and navigation skills to allow successful transport of emigrant populations to new territory, fulfilling the third factor of ease of transport (Berman and Gnevecki 1995).

Their study also discussed the ongoing debate among archaeologists as to when and along what paths the Lucayans arrived in the Bahamas. They mentioned at least five differing models—by DeBooy (1912), Sears and Sullivan (1978), Rouse (1982, 1986, 1989, 1992), and Keegan (1985 and 1992). Berman and Gnevecki (1995), however, concluded that the migration and colonization of the Bahamas was undertaken by the Lucayans of northern Cuba. Factors that influenced migration were most likely dry conditions creating an environmental push factor, the pull of mesic islands and unexploited marine resources, and the ease of transport afforded by the proximity of the islands, currents, winds, and the transportation technology and navigation strategies employed by the Lucayans.

## CHAPTER 3

### Environmental and Cultural Setting

#### *Study Area*

The Bahamas Archipelago is composed physically of approximately 29 islands, 661 cays and an estimated 2400 exposed rocks, and encompasses the two modern island nations of the Commonwealth of the Bahamas and the Turks and Caicos Islands (Britton and Millspaugh 1962, Correll, 1979, Berman and Gnivecki 1994) (Figure 3.1). Only 29 currently support permanent human habitation. The larger islands, including Andros, Great Abaco, and Grand Bahama, are the most suitable for human habitation because of their greater resources. The archipelago runs approximately 1,000 km north to south, resulting in a strong environmental gradient, with different temperatures, rainfall amounts, and vegetation (Correll and Correll 1982, Kjellmark 1995). Great Abaco Island has an area of 1,690 km<sup>2</sup> and approximately 13,000 residents (Wikipedia 2007).

#### *Site Description*

My study site, Split Pond (26° 33' N, 77° 04' W, ca. 7 m elevation), is a shallow, alkaline, freshwater pond located on Great Abaco Island (Figures 3.2 and 3.3). It is located southwest of Marsh Harbour and occupies an area of approximately 2 ha (Figures 3.3 and 3.4). Split Pond is a solution hole and is quite shallow, with a maximum recorded water depth of approximately 30 cm. "Solution hole" is a local name for a sinkhole or fissure in the limestone formed as the surface is dissolved by rainwater. Initially, the hole can drain easily but usually becomes blocked by carbonate sand and

# CENTRAL AMERICA AND THE CARIBBEAN



**Figure 3.1** Map of Caribbean Sea and tropical Atlantic showing the location of the Bahamian Islands. Provided by the University of Texas at Austin Library.

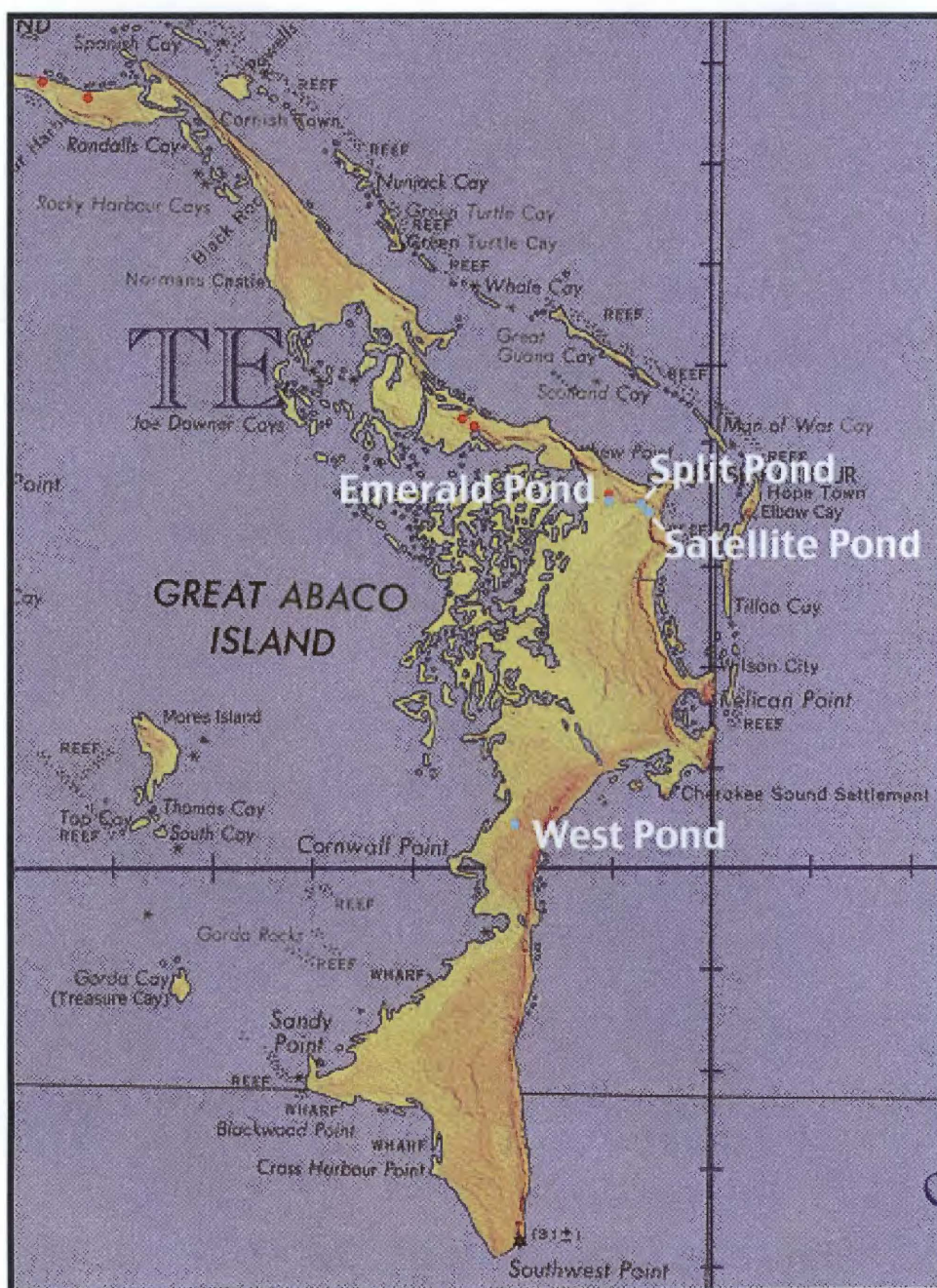


**Figure 3.2** Location of Split Pond and other coring sites on Great Abaco Island. Map created by K. Orvis from Army Map Service aeronautical chart and shuttle radar topography.



**Figure 3.3** Oblique aerial photograph of Split Pond. The town of Marsh Harbour is in the background. View is from approximately the SSW. Photograph by K. Orvis.



**Figure 3.4** Pine rockland vegetation near Split Pond, Great Abaco Island. Photograph by K. Orvis.

collapse material. As time progresses, the sand and debris cements together, or organics accumulate, sealing the bottom. The depression will eventually collect and retain water, forming a pond or wetland area. As water collects, further dissolution of material occurs, ultimately resulting in a maze of water- and soil-filled fissures in the rock (Sealey 1994). Split Pond is most likely a combination of features, originating as a sinkhole and eventually filling with water.

### *Geologic and Physiographic Setting*

Most of the islands in the Bahamian Archipelago are consistent in geology and share many landscape characteristics with portions of southern Florida. Great Abaco Island, specifically, has a surface material composed of lithified sand dunes that accumulated on an oolitic limestone substrate. Oolites are formed when several layers of calcium carbonate adhere to a particle nucleus under saturated conditions. Layers of calcium carbonate form around the nucleus in much the same way as pearls are formed, but the resulting particle is approximately the size of a sand grain. The oolitic limestone built up through continuous deposition of oolites over the last 140 million years (Dodge 1995).

The Bahama Platform became exposed during low sea-level stands that coincided with periods of continental glaciation during the Pleistocene. Eolian dunes formed during the drier parts of these periods and became lithified into eolianites through cementation either after inundation by the surrounding ocean or by percolating meteoric precipitation when the climate turned wetter, a process of cyclic inundation and exposure that gradually formed the upper geologic layers of the island (Fairbanks 1989). When sea

level was lower, the sand dunes were first active and subsequently stabilized to form soils, some of which oxidized into extremely hard reddish crusts, referred to as *terra rossa* paleosols (Hearty and Kaufman 2000). As a result of the glacial-cycle control of limestone deposition in the Bahamas, the lithostratigraphic units that correspond to major glacial stages are usually bounded by *terra rossa* paleosols (Carew and Mylroie, 1995). In this way, *terra rossa* paleosols serve as records of intervals of lower-than-present sea level during midglacial and full-glacial periods.

Oolitic limestone layers erode or dissolve easily when they are exposed to pluvial climate conditions. As a result, during wetter glacial periods, weathering processes altered the landscape into karst formations of caves, sink holes, and solution holes that now honeycomb the islands. Because of the resulting high porosity of the limestone, water from rainfall and runoff is rapidly delivered underground via the conduit networks, resulting in a paucity of rivers or streams on any of the islands, though numerous lakes, marshes, ocean holes, and solution pits dot the landscape (Correll 1979, Byrne 1980, Keegan 1997, Mylroie 2006). With rapid erosion and removal of sediments down into the karst, the structure of soils is limited to only one or two horizons, and as they are very thin and discontinuous, Abaco's soils are classified as immature, or as protosols (Sealey 1994). Much of the surface is bare rock, however, and is limestone in composition and extremely pitted and rough (Watts 1987, Sealey 1994).

With the depositional history of the islands of the Bahamas being controlled by sea-level changes associated with periods of continental glaciation, and with significant deposition of sediments and cementing of calcareous materials occurring during periods of inundation, the sedimentary record shows indications of varying depositional factors

across the full spectrum of sea levels.

### *Climate*

The Bahamian archipelago lies at the boundary between the temperate and tropical zones of the western Atlantic Ocean. Its climate is subtropical, with a warm temperate winter and a tropical summer. It is a north-south oriented chain of islands that display a marked environmental gradient across the islands, with average yearly temperatures approximately 3–4 °C cooler in the northern islands than in the southern islands (Sears and Sullivan 1978). The Bahamas are located between two warm ocean currents, the Gulf Stream and the Antilles Current, both of which modify the air masses crossing them. This creates a strong maritime effect, keeping winter temperatures warmer than one would expect to find at mainland sites at the same latitude (Storr 1964).

The Bahamian climate is greatly influenced by the persistent northeast trade winds, which almost continually draw maritime air across the islands. During the northern hemisphere summer, low pressure systems embedded in the trade winds, called easterly waves, can produce large rainfall events on the islands (>10 cm of precipitation). The Bahamas also lie astride the paths of many Atlantic hurricanes and tropical storms, which are capable of inflicting incredible amounts of disturbance on the local environment. As a result of the easterly waves, intermixed with hurricanes and tropical storms, summer is the primary season of rainfall in the Bahamas. During the northern hemisphere winter, continental airmasses that originate in North America can move offshore and across the islands, producing cooler temperatures, but no periods with below-freezing temperatures occurred during the period of record (Sealey 1994).

Rainfall totals change from north to south in the archipelago. Average annual rainfall on Great Abaco has been reported at 836 mm (Sealey 1994) and 1600 mm (Sears and Sullivan 1978). Both sources reported that the southern islands on average receive 300–700 mm less rainfall than the northern islands. As a result of midlatitude cold fronts that affect the northern islands, Great Abaco does receive more consistent rainfall throughout the year. Great Abaco benefits from some rainfall produced through convectional heating, but with such low topographic relief, no orographic rainfall occurs (Sealey 1994) except for minor effects of the contrast in meteorological roughness.

### *Vegetation*

The vegetation of the Bahamas varies greatly from north to south, possibly as a result of the marked gradient in rainfall manifest from north to south along the archipelago. Although few vegetation studies have been conducted on Great Abaco Island, the vegetation of most of the other large islands has been mapped extensively. On the northern islands, vegetation tends to be lush because of the higher annual rainfall (Kjellmark 1995). However, Correll (1979) suggests that limiting conditions such as the absence of mountains or running streams, and the lack of large freshwater lakes (presumably compounded by the lack of regolith and the porosity of the underlying limestone), produce, in general, relatively dry conditions among plant communities throughout the islands.

A variety of plant communities exists in the Bahamas, but only 10% of plant species are endemic to the islands, with most of the rest originating from the south and west, particularly from Cuba (Correll 1979). The communities found in the Bahamas are

typically listed as the coastal rock community, beach/strand community, coastal hardwood thickets, pinewood rocklands, savannas, and freshwater swamps (Correll 1979, Kjellmark 1995). A coastal rock community exists on Great Abaco Island near Hole-in-the-Wall and consists of a variety of shrubs and stunted trees, with *Borrchia arborescens* (L.) DC, *Strumpfia maritima* Jacq., *Rhachicallis americana* (Jacq.) Ktze., and *Casasia clusiifolia* (Jacq.) Urban dominating (Correll 1979). Hole-in-the-Wall is located immediately southeast and adjacent to Abaco National Park, which is primarily covered by what is considered pinewood rocklands.

The beach/strand community extends from the high tide mark to the coastal hardwood thickets and is characterized by herbaceous and semi-woody trailing vines, especially *Ipomoea pes-caprae* (L.) R. Br., *I. stolonifera* J.F. Gmel., *Canavalia rosea* (Sw.) D.C., and *Ambrosia hispida* Pursh (Correll 1979). Adjacent to the beach/strand community is the coastal hardwood thicket. It is mainly composed of tropical hardwood trees, especially *Metopium toxiferum* (L.) Krug & Urban, *Coccoloba diversifolia* Jacq., *Pithecellobium keyensis* Britt. ex Britt. & Rose, *Jacquinia keyensis* Mez. in Urb., *Byrsonima lucida* (Mill.) DC, and *Erithalis fruticosa* L. (Kjellmark 1995).

Pine rockland vegetation is restricted to the Bahamas Archipelago and areas of the Florida Keys and the southeastern Florida peninsula. My core site, Split Pond, is presently surrounded by pine rockland vegetation (Figure 3.4), although the site has been heavily modified by the local human population. Severe landscape modifications include use as an illegal dump site and construction of a road along the southern edge of the pond. The upper canopy is strictly *Pinus caribea* var. *bahamensis* (Griseb.) Barrett & Goldfari (Caribbean pine), and the understory is composed of a variety of tropical

hardwoods including *Metopium toxiferum* (poison wood), *Tabebuia bahamensis* (Northrop) Britt. (chicken toe), *Tetrazigia bicolor* (Mill.) Cogn. (tetrazigia), and *Bumelia salicifolia* (L.) Sw. (cassada wood), along with *Serenoa repens* (Bartr.) Small (saw palmetto) (Correll 1979, Kjellmark 1995).

Savannas are broad, flat, prairie-like areas dominated by *Cladium jamaicensis* Crantz (saw grass), with scattered patches of *Cocothrinax argentata* (Jacq.) Bailey (silver palm) (Kjellmark 1995). Often found as a transitional area between pine rocklands and the savanna are the freshwater swamps. Correll (1979) defines these as areas where the water table rises to the surface, creating viable conditions for the growth of the buttonwood mangrove (*Conocarpus erectus* L.), myrsine (*Myrsine floridana* A. DC.), bush iva (*Iva cheranthifolia* H.B.K.), and other shrubs. Extensive wetlands, both coastal and inland, are found on Great Abaco Island with swampy islands of red mangrove dotted throughout. These are usually shallow, rarely more than 3–4 meters deep (Sealey 1994).

### *Pre-Columbian Human History*

Archaeologists believe that the early inhabitants of the Bahama Islands, previously known as the Taino Arawaks, more recently as the Lucayans, originally migrated from the Orinoco River region of South America. An ongoing debate is occurring among archaeologists concerning the exact causes of the migration of the Lucayans to the relatively inhospitable islands of the Bahamas, but most suggest that it was a combination of social and environmental factors. Berman and Gnivecki (1995) described the factors driving migration to the Bahamas as: push, pull, and ease of

transport, a concept initially described by Anthony (1990). Negative home factors, such as increasing population, may have pushed the early Lucayans into expanding from Venezuela into the nearby Antilles islands around 2500 cal. yr BP. At a later date, the Lucayans may possibly have been pushed north from the lesser Antilles by a second wave of aggressive, cannibalistic migrants known as the Caribs. No matter the reason, they continued their northward expansion through the lesser Antilles, reaching Puerto Rico by 2400 cal. yr BP.

Environmental factors may also have played a role in encouraging the Lucayans to migrate. Hodell et al. (1991) suggested that ca. 1500 cal. yr BP, a 1500-year dry period was coming to an end. If that was the case, the newly wetter Bahamas might have offered unexploited resources to pull the Lucayans north at some point in this dry period and, ultimately, to most of the inhabitable islands. The exact route of migration into the Bahamas that the Lucayans took is still a matter of speculation. Some argue that the Bahamian Lucayans originally migrated from Cuba or Hispaniola on their journey north (Berman and Gnivecki 1995, Keegan 1997). Regardless of which path they took, around 1400 cal. yr BP the Lucayans arrived and occupied the larger islands of the Bahamian Archipelago until after the arrival of Columbus in 1492, a tenure of 700–1000 years. They left few archaeological artifacts from their culture, mostly pot shards, and some written accounts exist of them, written by Christopher Columbus and other Spanish explorers (Berman and Gnivecki 1994, Dodge 1995). This is late in the overall time span of human migration through the Caribbean basin, making the Bahamas an excellent area for examining sediment records of environmental change that until quite recently were unaffected by local human activities.

According to Byrne (1980) and Keegan (1997), the Lucayans most likely cleared the land using fire, evidence of which should be recorded as charcoal deposits in lake sediments. For their slash and burn agriculture, the Lucayans introduced a variety of crops to the Bahamian ecosystem, including manioc, sweet potato, peppers, guava, cotton, tobacco, and cocoplum. Manioc was the staple food of the Lucayan diet and would have been easily grown in the undisturbed soil. In addition, the low rainfall amounts would have produced manioc roots with a high starch content that would have provided additional nutritional value. Although the Lucayan settlers of Hispaniola are known to have cultivated maize (Lane et al. 2005), no evidence of maize cultivation appears in the Bahamian record (Keegan 1992).

### *Post-Columbian Human History*

When a new wave of immigrants arrived in the Bahamas in October 1492, they ushered in events that would ultimately end with the extinction of the Arawak Lucayans (Watts 1987). Christopher Columbus and his group of Spanish explorers are believed to have landed first on the island of San Salvador (Craton 1968). As this voyage was originally chartered as a mission of exploration in search of a new trade route to China, the Spanish did not establish successful colonies in North America until around 1500 (Watts 1987). This did not prevent them from exploiting the natives as slave labor, which, along with introduced diseases and attrition, resulted in the rapid depopulation of natives in the Bahamas (Keegan 1997). As the Spanish colonies in the Caribbean began to decline, the British, Dutch, and French began to establish small colonies throughout the area, located mainly near good harbor sites (Watts 1987). The English settled the

Bahamas permanently in the early 18<sup>th</sup> century, with colonists successfully fishing, whaling, and cultivating crops (Craton and Saunders 1992). This represents the beginning of the exploitation of Bahamian *Pinus caribaea*, initially as masts for sailing ships and eventually as material for paper production (Craton and Saunders 1992).

Around 1900, timber companies began to clear-cut Great Abaco Island in earnest. The Bahamas Timber Company employed 12% of the population of Abaco by 1912, but as stands were harvested, the company was forced to harvest at greater distances from its mill. This eventually became cost prohibitive, and the mill was closed by 1916 (Dodge 1995).

Exploitation of *Pinus caribaea* culminated in the mid-20<sup>th</sup> century with the arrival of the Owens-Illinois Corporation. Their pulpwood timber operation is considered by some to have been the most influential factor in Abaco's development. They removed timber from all areas of the island and shipped it to Jacksonville, Florida through a shipping terminal they constructed on Snake Cay. Snake Cay is located approximately six miles south of Marsh Harbour. Beginning in 1959, Owens-Illinois dredged channels, built an airport, and built the first major highway on Great Abaco, which bisects Split Pond, hence, the name. The harvest was planned to last ten years, which is how long it was expected to take to remove all the usable timber. Owens-Illinois left approximately five seed trees per acre so the forest could replenish itself (Dodge 1995).

At the culmination of their pulpwood operation in 1969, experts predicted that the pine stocks on Great Abaco would not recover until after the year 2000. Owens-Illinois promptly traded their timber licenses for 50,000 acres of land near Snake Cay in an effort to grow sugar cane for export. Poor growing conditions led to poor yields and resulted in

a sell-off within two years. Between then and now, the vegetation of the pine rocklands has recovered from harvesting. Currently, the *Pinus caribaea* are of uniform age and form a relatively open overstory. Locals regularly set fires for a variety of reasons, including to aid in the hunting of feral pigs. In some areas, fires are occurring too frequently to allow seedlings to survive (Myers et al. 2004).

Efforts are currently underway by The Nature Conservancy to assist Bahamian resource managers in establishing sound fire management practices. Myers et al. (2004) described the fire history of the pine rocklands of Andros and Great Abaco Island and the steps needed to develop a fire management plan. Their plan calls for frequent, low-intensity surface fires at intervals of between 1 and 7–10 years. Frequent, low-intensity burns will help maintain biodiversity in the rocklands as this community has developed adaptations to fire. *Pinus caribaea* has a thick bark, clusters of needles that protect buds, and high, open crowns to protect against crown fires and to allow heat to dissipate. Many of the herbs and small shrubs have developed fire recovery mechanisms, with the exception being poisonwood which suffers high morbidity and mortality rates during fires. Animals such as the Bahamian parrot have also adapted to fire by nesting in solution pits, which protect their chicks from the heat.

As part of their 10-year plan, The Nature Conservancy recommends continuing current fire management practices to allow time to develop a continuing fire management plan for the rocklands. As a side note, they cited public education about fires as a key component of future management plans. This dedication to local education is what afforded me the opportunity to collect my air-fall charcoal samples. I collected them during a prescribed burn in Abaco National Park that was used as a “classroom” exercise

for fire fighters from all the islands of the Bahamas Archipelago. Abaco National Park is located on the southern portion of the island. The Nature Conservancy burn was conducted in an area formerly used for the harvesting of indigenous pines by the Owens-Illinois Corporation.

## CHAPTER 4

### Methods

#### Field Methods

##### *Sediment Samples*

In October 2003, a 2.7 m sediment core was recovered by Drs. Orvis and Horn and students Allison Stork and Lisa LaForest from near the center of Split Pond (26° 33' N, 77° 04' W), using three successive 1-m drives with a Colinvaux-Vohnout piston corer (Colinvaux et al. 1999). The shallow water depth (<30 cm) at the core site precluded the use of a standard floating platform, so the field team used an underwater platform. Two planks of plywood weighed down with cinder blocks were carefully placed parallel to each other on the sediment surface with 15 cm left undisturbed between them to provide access to a coring space with its sediment-water interface intact. The interface was collected using the Colinvaux-Vohnout corer rather than a plastic tube core. This was possible because the surface was covered with an algal mat that held the uppermost sediments together.

##### *Air-Fall Samples*

To help interpret the charcoal recovered from the core and to address other questions regarding charcoal taphonomy in pine rocklands and similar microtopography, I sampled air-fall charcoal deposition during a controlled burn conducted by The Nature Conservancy on Abaco Island in November 2004. In karstic environments of high micro-relief such as the Abaco pine rocklands, air-fall charcoal deposition may be more

important than water transport because the oolitic limestone bedrock has myriad solution holes and fissures that effectively eliminate overland flow and prevent fluvial transport. My charcoal traps consisted of plastic Petri dishes (both lids and bottoms) and square, plastic Rubbermaid® food containers (both lids and bottoms) coated on the inside with a thin layer of petrolatum (Figure 4.1). Several hours before the controlled burn, I placed approximately half my traps in an upwind area to serve as controls. The other half I placed in the expected downwind area of the fire perimeter. Wind direction assumptions were based on the local dominance of the Northeast Trade Winds during that time of year (Sealy, 1994). Traps were placed approximately 10 m apart along two parallel lines separated by 50 m. The placement of traps was approximate because of the rugged nature of the Pine Rockland terrain, but I recorded trap locations using a Trimble GeoExplorer III GPS unit (Figure 4.2).

## **Laboratory Methods**

### *Radiocarbon Dating*

To determine the chronology of the sediment profile, I obtained standard AMS dates on plant macrofossils found at different levels through the core. These samples consisted of a seed, a piece of bark, a plant stem, an herb stem, a bit of unidentified vascular plant material, and a fragment of charred material recovered from the bottom portion of the core. All dates were calibrated using CALIB rev. 5.0 (Stuiver and Reimer 1993) and the dataset of Reimer et al. (2004). S. Horn calculated the weighted means of the calibration probability distributions (Telford et al. 2004), and I used these single-year age estimates to calculate sedimentation rates.



**Figure 4.1** Photograph of air-fall charcoal traps in use. Each trap consisted of the tops and bottoms of two plastic petri dishes coated on the bottom (inside) with petrolatum. Photograph by D. West.

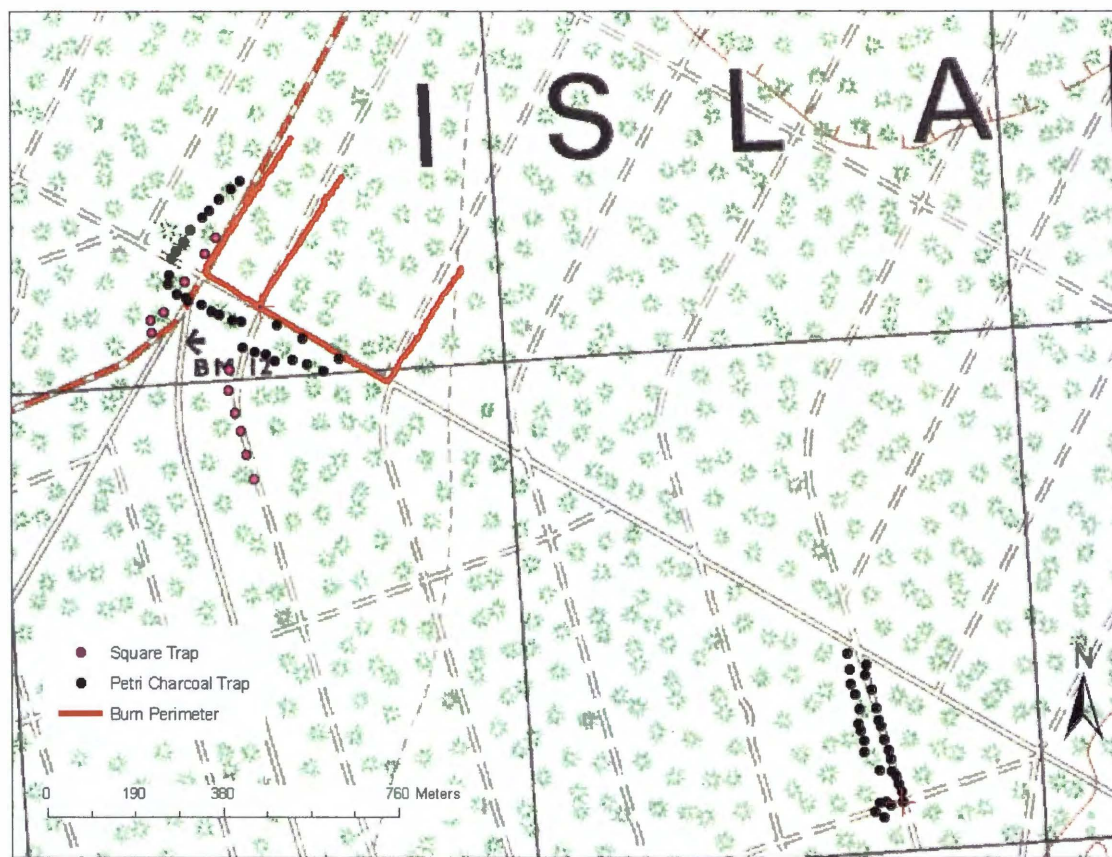


**Figure 4.2** Area map of The Nature Conservancy burn site. Map is taken from Sheet 26 of the Abaco 1:25,000 series. GPS locations of charcoal traps and margins of controlled burn are superimposed. Original sheet copyright: Department of Lands and Surveys, Nassau, Bahamas, 1975.

## *Charcoal Analysis*

My sampling procedure combined four subsamples of  $0.25\text{ cm}^3$  taken at 1 cm intervals over a 4 cm extent. These were collected centered at the 0.5 cm marks on a ruler along a line running down the center of the core half. The four  $0.25\text{ cm}^3$  samples were placed together in a clean polypropylene centrifuge tube and were then treated as a standard  $1\text{ cm}^3$  sample (normally these are taken every 4–8 cm) used for processing. This sampling method was designed to balance the desirability of contiguous sampling against the time demands of chemical processing using standard pollen preparation techniques. Six such  $1\text{ cm}^3$  samples at a time were prepared and chemically processed using standard pollen processing techniques (Appendix A).

During pollen processing, samples were washed through  $125\text{ }\mu\text{m}$  sieves to remove non-microscopic particles (Appendix A). As I processed each sample, I used a boom-mounted stereoscope to examine each sieve for macroscopic charcoal fragments. This allowed me to quickly determine if macroscopic charcoal was present in the sample and to assign the number of fragments to groups of either none present (zero), 1–4, 5–9, 10–14, or  $\geq 15$ . These data are useful because presence of macroscopic charcoal is evidence that a fire may have occurred close to Split Pond during the period when the sample was deposited.

I prepared microscope slides using pollen slide preparation procedures and then, using the point counting techniques outlined by Clark (1982), I quantified the microscopic charcoal present on the slides. I used the numbered axis of the eyepiece reticule to apply 11 points to each field of view for approximately 25 fields of view per transect along a total of 45 transects per slide, for 12,375 total points per slide. For each

field of view, I recorded each instance in which a point intersected a charcoal fragment, as well as the number of *Lycopodium* marker spores and pine pollen grains present. Calculation of the area of the slide in which charcoal is present is based on Clark (1982), as modified by S. Horn (Appendix B).

### *Loss-on-Ignition*

At the same time that the pollen/charcoal samples were collected from the core, loss-on-ignition samples were collected in an adjacent line at whole-cm marks along the ruler. The four 0.25 cm<sup>3</sup> LOI samples were placed together in a standard laboratory crucible, weighed, and then dried in an oven at 100 °C for 24 hours. They were then cooled, re-weighed, and ignited in a furnace at 550 °C for one hour to remove organics. After re-cooling and re-weighing, they were ignited at 1000 °C for one hour, re-cooled and re-weighed. This process allows estimation of pore water, organic content, and carbonates (Dean 1974).

I entered all pine pollen, fern spore, and LOI data into the C<sup>2</sup> program. C<sup>2</sup> is “software for the analysis and visualization of ecological and paleoenvironmental data. It fits paleoecological transfer functions, or inference models, to modern training sets of species and environmental data and allows quick and efficient management and representation of data” (Juggins 2003). Diagrams were generated using this program, and the Postscript output was edited using Adobe Illustrator.

### *Air-Fall Samples*

I examined all traps recovered after the burn for macroscopic charcoal using a boom-mounted stereoscope. Because ash fragments, but no macroscopic charcoal, were present on all the traps placed adjacent to the fire, I also selected a spatially distributed subset of 6 traps for microscopic charcoal examination, with methods as follows.

In collaboration with my committee, I developed a special method of processing the samples that dealt with the requirements of petrolatum. Using a metal scraper that had been ground to a width of 2.5 cm, I removed petrolatum and adhering particles from a sample area of 6.25 cm<sup>2</sup> from the center of each lid or base of each petri dish trap. Petrolatum must be dissolved in a suitable solvent. I chose a “low odor” variety of mineral spirits available at most hardware stores. After the petrolatum was dissolved and decanted after centrifuging, I used two washes of 95% denatured ethyl alcohol to remove the remaining mineral spirits. A *Lycopodium* tablet containing a known number of control spores was added to each sample and dissolved using a wash of 10% hydrochloric acid (Stockmarr 1971). This step was followed immediately by two hot distilled water washes to neutralize any acid remaining in the sample and to ensure removal of any petrolatum residue. To complete the process, I added Safranin stain, dried the sample using tertiary butyl alcohol, and finally added silicone oil to preserve the samples and allow mounting. After the TBA dissipated from the samples, I made microscope slides for examination.

To quantify charcoal in the air-fall samples, I examined eight complete transects on each slide, counting all charcoal particles and *Lycopodium* spores encountered, allowing me to calculate the total concentration of charcoal. By ratioing the spore count

to the full number of spores added, I was able to estimate the total number of charcoal particles collected, and by dividing that number by the  $6.25 \text{ cm}^2$  sample area, estimate charcoal deposition per unit area.

## CHAPTER 5

### Results

#### *Core Stratigraphy*

The sediment core recovered from Split Pond was 284 cm in length (Figure 5.1 and Table 5.1). Basal sediments rested on limestone and were composed of silty clay with shell fragments, small pebbles, and coarse sand. The pebbles dropped out by 247 cm, but otherwise this facies continued up to 230 cm. At approximately 230 cm, an unconformity occurs in the core, possibly as a result of the lake becoming completely dry. Some material may have been lost. The sediments then changed to fibrous organics by 227 cm which continued to 224 cm, followed by organic-rich marl extending to 201 cm, and fine, loose marl from there to 150 cm. At 150 cm, a sharp transition occurred to watery, fibrous organics with some interbedded layers of slightly calcareous organics, which continued to 10 cm. An algal mat that covers the bottom of Split Pond defined the top 10 cm of the core, which was composed of peaty organics.

#### *Radiocarbon Dating*

The radiocarbon results (Table 5.2) include one reversal. A piece of plant material, possibly sawgrass, returned an AMS date of  $2910 \pm 40$   $^{14}\text{C}$  yr BP. That is out of sequence with the other dates and appears too old, suggesting it had been redeposited, so I excluded that date from the age-depth diagram (Figure 5.2). The  $1152 \pm 36$   $^{14}\text{C}$  yr BP date on a seed from 43.6 cm is not technically out of sequence, but does imply a sedimentation rate immediately below it that seems unrealistically high. I believe that

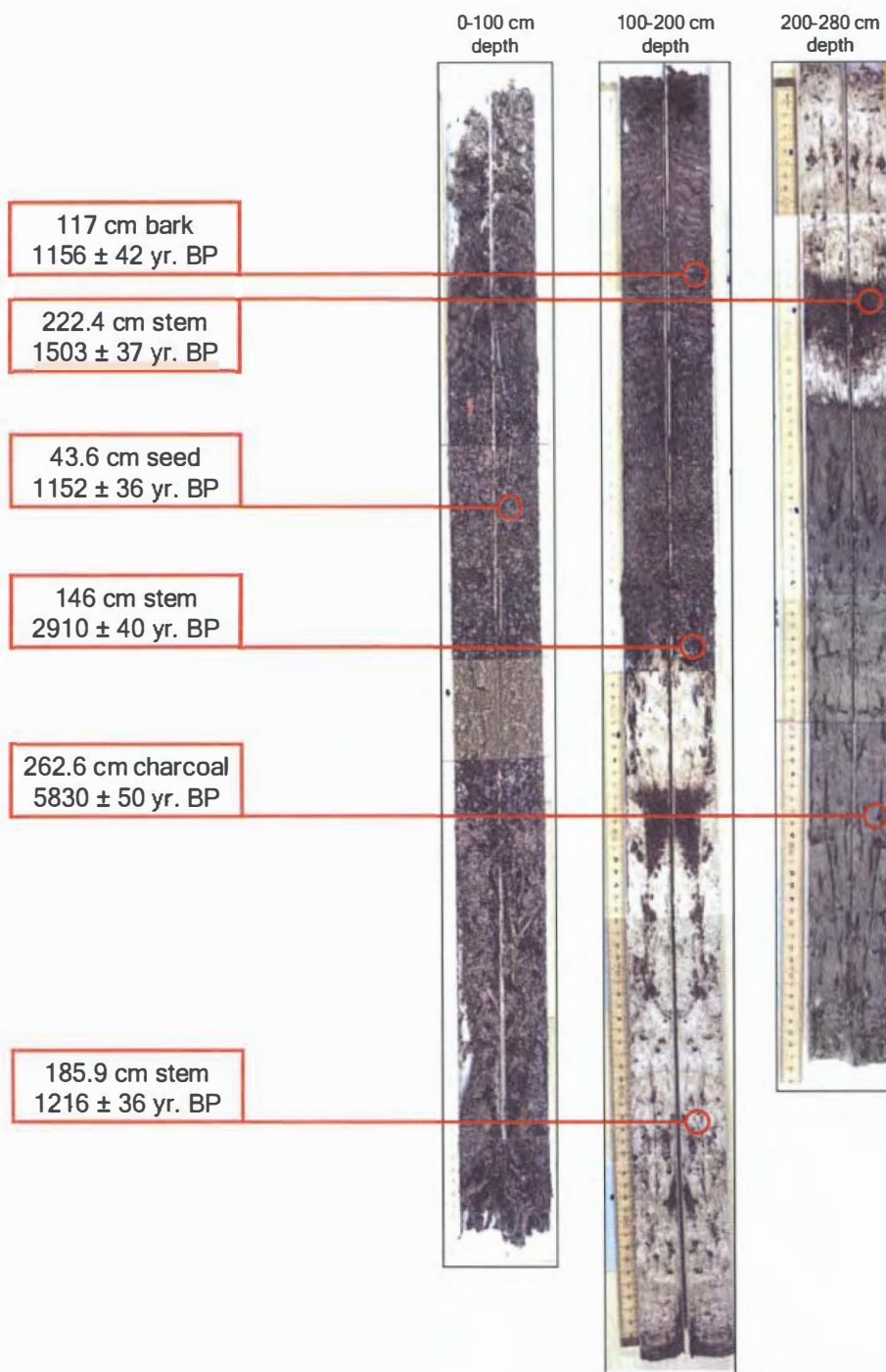


**Figure 5.1** Core stratigraphy of Split Pond. Arrows indicate location and type of material used for radiocarbon dating. The material in the first section of the core is loose sediment with a high amount of fibrous organics which led to some compaction. Dates are in radiocarbon years. Photos by S. Horn.

**Table 5.1** Core Stratigraphy of Split Pond Core. Based on core description by K. Orvis

| Depth (cm) | Sediment Description                              | Munsell Color                           |
|------------|---------------------------------------------------|-----------------------------------------|
| 0–10       | peaty organics                                    | 2.5Y3/3 with mixture of 5Y8/2 and 5Y6/4 |
| 10–66      | watery organics and fibrous organics              | 5YR2.5/1                                |
| 66–99      | very coarse fibrous organic masses                | 5R2.5/1                                 |
| 99–102     | very coarse fibrous organic masses                | 5R2.5/2                                 |
| 102–106    | fibrous organics                                  | 10YR2/2                                 |
| 106–111    | finely divided mucillagenous material             | 2.5YR3/2                                |
| 111–122    | slightly calcareous organics                      | mottled 10YR3/1 to 10YR3/2              |
| 122–133    | fibrous organics                                  | mottled 10R2.5/2 to 10YR3/1             |
| 133–140    | slightly calcareous organics                      | mottled 10YR2/1 to 10YR3/2              |
| 140–150    | fibrous organics                                  | 10YR2.5/2 to 10YR3/1                    |
| 150–198    | marl                                              | 10YR6/2 to 10YR8/3                      |
| 198–201    | slightly denser marl                              | 10YR6/2                                 |
| 201–203    | organic-rich marl                                 | 10YR5/3                                 |
| 203–205    | organic-rich marl                                 | 10YR5/2                                 |
| 205–225    | slightly banded marl with occasional organics     | 10YR6/3 to 10YR8/2                      |
| 225–227    | fibrous organics                                  | 10YR2/1                                 |
| 227–230    | marl                                              | 10YR6/1 to 10YR8/1                      |
| 230–231    | coarse silt with small bits of shell              | 10Y2.5/1                                |
| 231–247    | sandy clay grading to silty clay                  | 10Y4/1 to 10GY4/1                       |
| 247–270    | silty clay with occasional sand and small pebbles | 5GY4/1                                  |
| 270–284    | silty clay with sand and small pebbles            | 10Y5/1                                  |

**Table 5.2** Radiocarbon dates from samples from Split Pond.

| Lab Number | Material         | Depth:<br>Segment/cm in<br>Segment | Depth in<br>Profile<br>(cm) | $\delta^{13}\text{C}$<br>(‰) | Uncalibrated<br>$^{14}\text{C}$ Age<br>( $^{14}\text{C}$ yr BP) | Calibrated<br>Age Range<br>(cal. yr BP)<br>$\pm 2\sigma$ | Area Under<br>Probability<br>Curve | Weighted Mean<br>Calibration Age<br>(cal. yr BP) |
|------------|------------------|------------------------------------|-----------------------------|------------------------------|-----------------------------------------------------------------|----------------------------------------------------------|------------------------------------|--------------------------------------------------|
| AA 65807   | seed             | 0-/36                              | 43.6                        | -25.4                        | $1152 \pm 36$                                                   | 975–1171                                                 | 1                                  | 1061                                             |
| AA 65809   | bark             | 100-/16.5                          | 117                         | -27.4                        | $1156 \pm 42$                                                   | 967–1175                                                 | 1                                  | 1070                                             |
| B-204697   | plant material   | 100-/45                            | 147.7                       | -25.7                        | $2910 \pm 40$                                                   | 2946–3209                                                | 1                                  | 3053                                             |
| AA 65808   | plant stem       | 100-/83                            | 185.9                       | -25.2                        | $1216 \pm 36$                                                   | 1059–1190                                                | 0.78289                            | 1141                                             |
|            |                  |                                    |                             |                              |                                                                 | 1197–1262                                                | 0.21711                            |                                                  |
| AA 65806   | herb stem        | 200-/18                            | 222.4                       | -27.5                        | $1503 \pm 37$                                                   | 1309–1422                                                | 0.828938                           | 1383                                             |
|            |                  |                                    |                             |                              |                                                                 | 1432–1442                                                | 0.01547                            |                                                  |
|            |                  |                                    |                             |                              |                                                                 | 1459–1515                                                | 0.155592                           |                                                  |
| B-187020   | charred material | 200-/57                            | 262.6                       | -25.4                        | $5830 \pm 50$                                                   | 6497–6744                                                | 1                                  | 6638                                             |

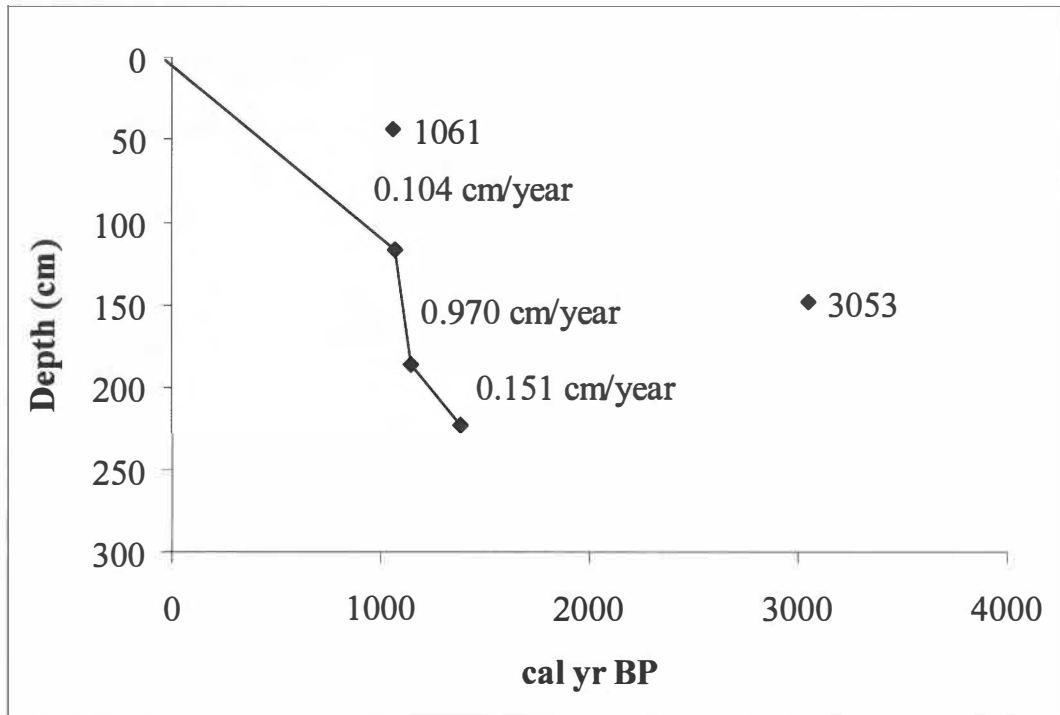


**Figure 5.2** Age-depth diagram of the core above the discontinuity. The slope of the line represents inferred sedimentation rate.

this seed may also be older redeposited material and have discounted it from my discussion of sedimentation rates as well. Sedimentation rates calculated from the weighted mean of the probability distribution indicate an increasing rate of sedimentation  $1503 \pm 37$   $^{14}\text{C}$  yr BP and  $1156 \pm 42$   $^{14}\text{C}$  yr BP. From  $1156 \pm 42$   $^{14}\text{C}$  yr BP to the present, sedimentation rates have slowed considerably.

### *Loss-on-Ignition*

Loss-on-ignition values correspond closely to the visible stratigraphy of the core. Non-carbonate inorganic levels are high (~90%) in the silty clay layer of the lower core section, with organic and carbonate levels below 10%. The marl layer that extends from 230 cm to 150 cm is highly inorganic, with non-carbonate inorganic content of approximately 55% on top of a carbonate content of 40% (Figure 5.3). The layer of fibrous organics extending from 227–224.5 cm is highlighted by a spike in organic levels to near 50% and a sharp drop in carbonate and non-carbonate inorganic. The watery organic layer starting at 150 cm is highly organic, with organic levels reaching ~90%. A section with increased carbonate levels (8–10 %) is found at 130–110 cm, but organic levels remain near 90%. The upper 20 cm of the core show a drop in organic content toward the surface as carbonate and inorganic values rise.

### *Pollen Concentration and Preservation*

Pollen preservation was not adequate at all places in the profile to allow rigorous, detailed pollen analysis. However, pine pollen can be readily identified even in a

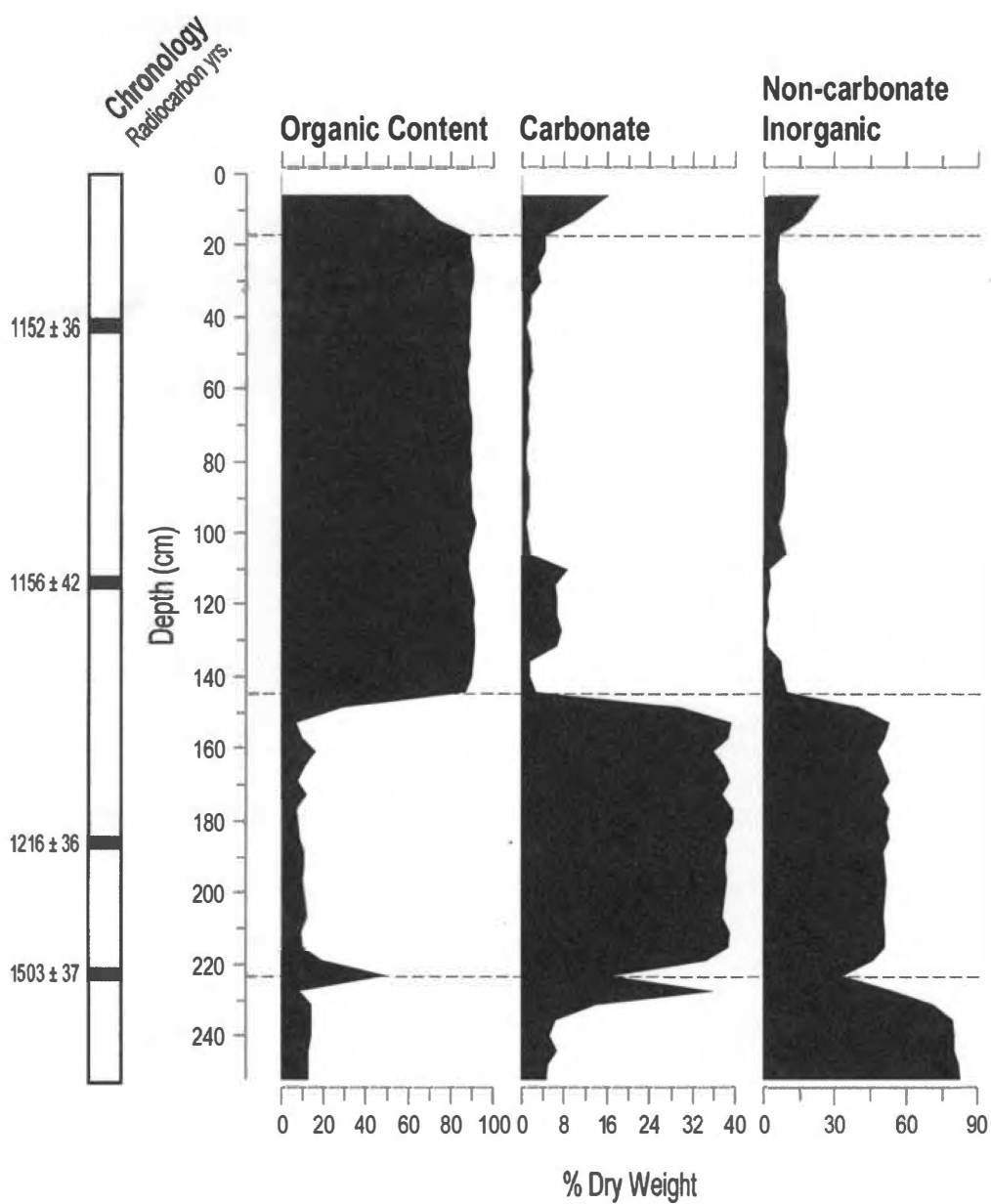


**Figure 5.3** Loss-on-ignition results for Split Pond. Dashed lines highlight areas of significant change.

deteriorated state, so I included that pollen type in my study. In the lower portion of the core, most of the samples included one class of material that was not completely dissolved and removed during processing. It is a black residue that obscured both the pollen grains and charcoal. *Pinus* pollen concentrations in samples from Split Pond that were successfully analyzed varied from 2,200 to over 133,000 pollen grains/cm<sup>3</sup> wet sediment (Figure 5.4). The sediments in the uppermost portion of the core were best preserved, except for the portion between 63.6 and 46.8 cm. The interval between 220 and 210 cm had the highest *Pinus* pollen concentration.

### *Charcoal Stratigraphy*

Little microscopic charcoal was present in the sediment core, and almost no macroscopic charcoal was found. The areal density of microscopic charcoal on the pollen slides was low in all samples. Of the ca. 8,000–11,000 points that I examined on each slide, between 3 and 44 coincided with charcoal. Point counting of charcoal assumes a certain amount of error. The more points applied and the more charcoal fragments found, the lower the error estimate. For 12 of the 18 levels examined, the relative error of the estimate of the areal density of charcoal was 15–57.7%, but the majority fall in the 20–40% error range (Clark 1982). For level 196.9, I found only one charcoal fragment for the entire sample, resulting in a 100% error estimate. Figure 5.4 shows a spike in pine pollen amounts just before a marked spike in charcoal amounts between 215 and 195. After they peak, both drop back to relatively low levels at 190 cm. The second highest peak in *Pinus* pollen occurs at 123 cm, which follows a corresponding peak in charcoal concentrations at 128 cm.

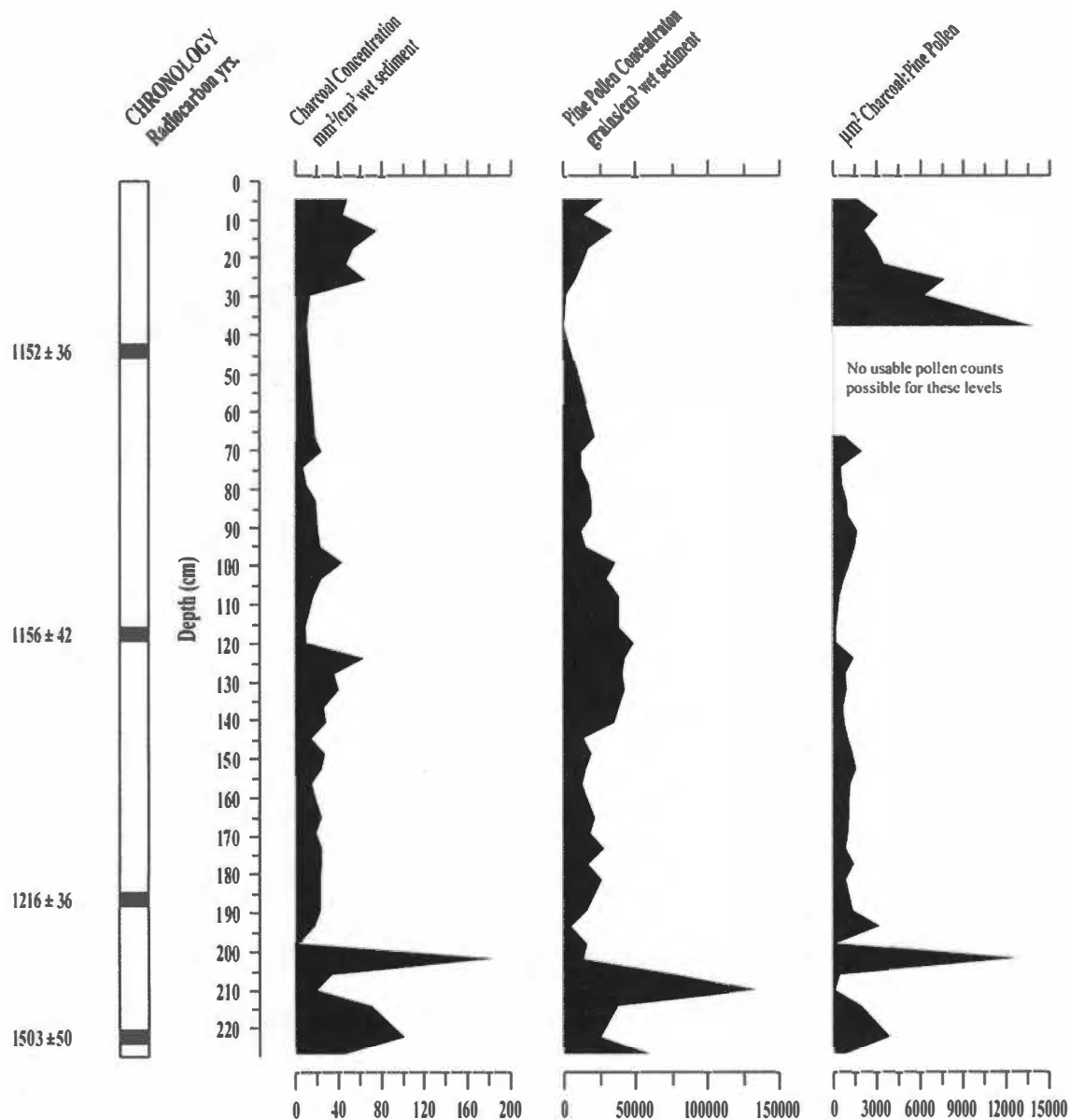


**Figure 5.4** Microscopic charcoal and pine pollen concentrations in the Split Pond core. The area (mm<sup>2</sup>) is conventional cross-sectional area as estimated from point counting.

### *Macroscopic Charcoal in Sediments*

The macroscopic charcoal fragment counts show a spike at 240 cm. This is the only instance of more than 15 macroscopic fragments remaining on a sieve. One other instance was observed of an appreciable amount of macroscopic charcoal (10 to 15 particles in a sample) in the lower portion of the core, occurring at 225 cm. Through the middle portion of the core, from approximately 150 cm to 45 cm, macroscopic charcoal is present in each sample, ranging between very little (<5 particles) and some (5–9) in abundance. The other two spikes of 10 to 15 occur in the upper portion of the core at 35 cm and 15 cm. No macroscopic charcoal fragments were found between 223 and 215 cm and none at 183 cm, 178 cm, 161 cm, and 42 cm (Figure 5.5).

### *Air-Fall Charcoal*

All samples collected from the smoke column of a low-intensity controlled burn conducted in the pine rocklands were examined for macroscopic charcoal, and results were consistent across all the samples. Macroscopic particles of ash (not charcoal, though they may have contained small charcoal particles within them) were observed on the Petri traps before processing, but these fragmented or dissolved during laboratory processing. No particles that were considered macroscopic ( $>125\ \mu\text{m}$ ) in size were found after processing. Microscopic charcoal was present in all 6 of the downwind samples that were examined for it. In each of those, I found between 29 and 177 microscopic charcoal particles and between 110 and 202 *Lycopodium* spores. From these data and the area sampled, I calculated the estimates of total microscopic fragments of charcoal per  $\text{cm}^2$  shown in Figure 5.6.

## Macroscopic Charcoal

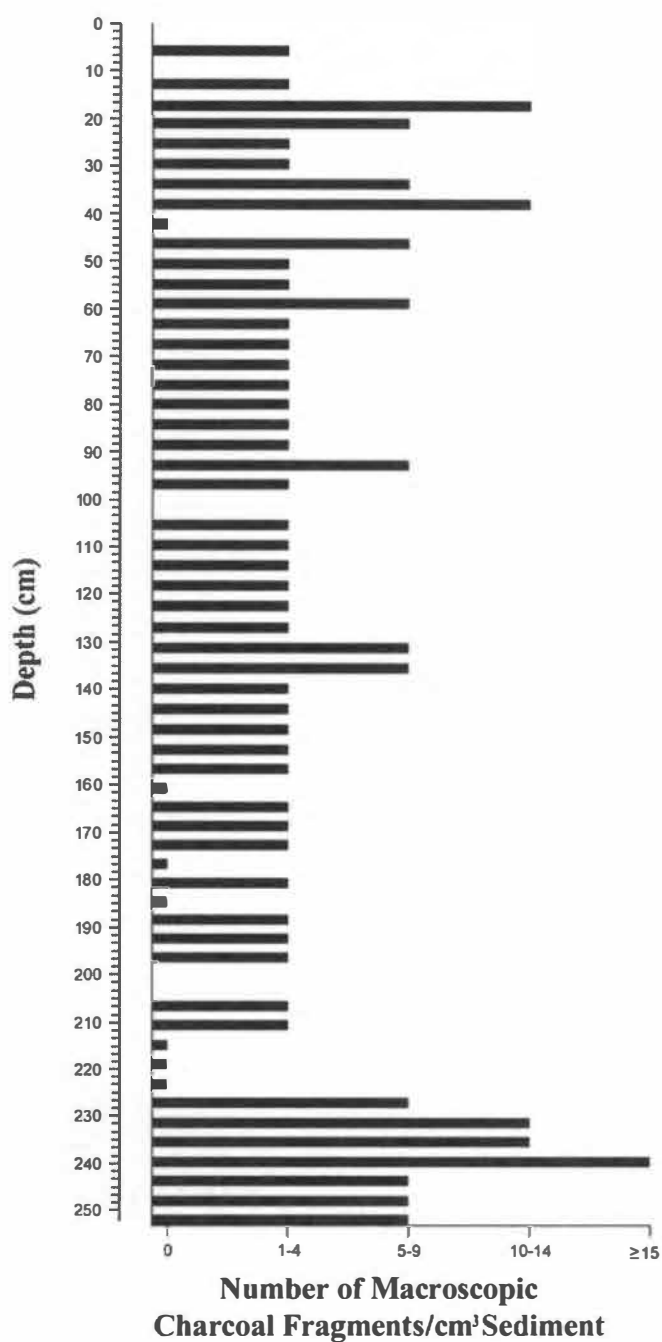


**Figure 5.5** Macroscopic charcoal fragments remaining on 125  $\mu\text{m}$  sieve from Split Pond core samples. This analysis extends deeper in core than results shown on Figure 5.4.

### Air-fall Charcoal



**Figure 5.6** Distance of traps from edge of burn and number of microscopic charcoal particles per cm<sup>2</sup> of trap, for a spatially distributed subset of 6 traps. No macroscopic charcoal was found on any of my 6 upwind and 6 downwind traps, and no microscopic charcoal was found on any of the 6 upwind control traps I examined.

On the traps placed upwind of the burn as controls, no charcoal of any type or size was present in any of the six samples I examined, demonstrating that during the time of the burn, no outside charcoal was drifting into the area. All the charcoal in the downwind traps derived from the smoke column of the burn.

## CHAPTER 6

### Discussion

My analysis of microscopic charcoal in the sediments of Split Pond developed the second paleoecological record for Great Abaco Island. Based on the age of a charcoal fragment recovered from the lower portion of the profile, the record covers approximately 6000 years, representing a considerable span of time before human occupation of the island. However, a unconformity exists at approximately 230 cm which may represent a period when the pond dried out, allowing loss of exposed sediments. Because the 6000 yr BP date is most likely from below a discontinuity, I have not considered it in my discussion. In addition, I was unable to fully examine the samples recovered from the silty clay portion below 230 cm because they are infused with what I suspect to be an iron and magnesium complex that obscures the microfossils (Horn, personal communication). The profile shows distinct stratigraphic changes, including marked shifts: from non-carbonate inorganic to carbonate inorganic at ca. 1500  $^{14}\text{C}$  yr BP and from carbonate inorganic to organic at ca. 1190  $^{14}\text{C}$  yr BP. The reconstructed environmental history of Split Pond displays trends similar to some of those discussed in other studies from the circum-Caribbean region.

#### *Reconstruction of Paleoecological History Using Charcoal and Pinus Pollen*

My microscopic charcoal analysis revealed that only small amounts of microscopic charcoal have ever been deposited in Split Pond. However, there are marked fluctuations in concentrations that allow for interpretation of fire history. A spike in

microscopic charcoal deposition at ca. 230 cm (ca. 1500  $^{14}\text{C}$  yr B.P) coincides with a spike in macroscopic charcoal, possibly due to a relatively high-intensity fire adjacent to Split Pond. At ca. 205 cm (ca. 1350  $^{14}\text{C}$  yr BP), an even larger spike in microscopic charcoal occurs in the core, but only accompanied by a moderate increase in macroscopic charcoal. This may be due to a higher intensity fire close to, but not immediately adjacent to, Split Pond. Another possibility is that there was a lower intensity fire immediately adjacent to the pond ca. 1,500  $^{14}\text{C}$  yr BP.

Using the approach of Burney et al. (1994) and Burney and Burney (2003), who interpreted initial spikes in charcoal concentration as indicators of human arrival on islands, the data from Split Pond would suggest that humans arrived in the area ca. 1500  $^{14}\text{C}$  yr BP. The initial spike in charcoal appears in my record at ca. 1500  $^{14}\text{C}$  yr BP, but the largest spike in charcoal that occurs relatively early in my record is at ca. 1300  $^{14}\text{C}$  yr BP. In the period between these two spikes, a visible increase in macroscopic charcoal suggests burning very close to Split Pond, which could be attributed to human-generated fires, but could also represent natural wildfires, in either case possibly of higher than usual intensity. The Split Pond charcoal record does not extend beyond ca. 1500  $^{14}\text{C}$  yr BP, so whether these spikes contrast with what went before is unknown. However, the established chronology of human migration to the Bahamas as suggested by paleoecological and archaeological studies indicates that this period is probably too early for human arrival on Great Abaco.

These large spikes in microscopic and macroscopic charcoal do fit with the close of a period of intense drought in the circum-Caribbean region suggested by Higuera-Gundy et al. (1999) and Hodell et al. (2000). Higuera-Gundy et al. (1999) postulated

that the drought did not end until ca. 1100  $^{14}\text{C}$  yr BP and was severe enough to encourage migrations of prehistoric peoples throughout the region. The data from Split Pond also indicate a sharp increase in sedimentation after 1500 yr BP, possibly due to the destruction of vegetation in the area, likely as a result of wildfires, drought conditions, or a combination of the two. The LOI record indicates almost exclusive deposition of carbonate and non-carbonate inorganics in Split Pond from ca. 1500  $^{14}\text{C}$  yr BP until ca. 1200  $^{14}\text{C}$  yr BP, at which point there is a precipitous change to deposition of organics. In a karstic environment such as Great Abaco Island, the inorganic sediment deposition could indicate a drought that greatly reduced the amount of water in the basin, which would lead to an increase in carbonate material precipitating out of the water column. This continued until ca. 1100  $^{14}\text{C}$  yr BP.

Several smaller peaks in charcoal concentration indicate increased burning ca. 1200  $^{14}\text{C}$  yr BP, which correlates well with the suggestion that humans may have arrived in the area around West Pond ca. 1200  $^{14}\text{C}$  yr BP (Stork 2006). Kjellmark (1995) attributed an increase in *Pinus* pollen and charcoal concentrations in the sediments of Church's Blue Hole ca. 850 cal. yr BP to human colonization. These similar results suggest that, within the temporal resolutions of the three studies, humans may have first arrived on both Abaco and Andros Islands within this 300-year period.

Based on archaeological evidence, Keegan (1997) suggested that humans first arrived on Great Inagua Island, the southernmost island in the Bahamas, between 600 AD and 800 AD (ca. 1400–1200 yr BP). Berman and Gnivecki (1995) suggested humans occupied San Salvador between 800 AD and 900 AD (ca. 1200–1100 yr BP), and Byrne (1980) suggested that humans arrived on Cat Island ca. 950 AD (ca. 1050 yr BP). Taken

together, the charcoal and archaeological evidence indicate that humans most likely migrated into and settled the Bahamas from south to north, colonizing all habitable islands within a relatively short period.

After 1200  $^{14}\text{C}$  yr BP, charcoal concentrations and the number of *Pinus* pollen grains decrease. Both fluctuate, which might only be visible due to the small sampling intervals I used. By taking samples continuously instead of every 4 cm, I hoped to achieve better resolution of fire events. At West Pond, Stork (2006) had very little microscopic charcoal in her samples, which might have reflected missed fires using a 4 cm interval, rather than absence of burning. I also found relatively low amounts of charcoal at Split Pond, but the results do suggest that more individual fire events were detected by using continuous sampling.

At ca. 17 cm, a peak in both microscopic and macroscopic charcoal occurs, immediately preceded by an increase in *Pinus* pollen. Kjellmark (1995) attributed similar fluctuations he found near the top of his cores to removal of the natives by the Spanish around 450 cal. yr BP and the resettlement of Andros Island by the British about two centuries later. I was unable to recover samples for radiocarbon dating from that portion of my core, but my pattern resembles Kjellmark's.

### *Transport Mechanisms of Microscopic Charcoal*

Both paleoecological studies conducted thus far on Great Abaco Island, at West and Split Ponds, yielded relatively low levels of microscopic charcoal from their lake sediments (Stork 2006 and this study). When compared to other studies conducted in area of similar vegetation, this seems an unexpected result, but assuming a history of low-

intensity fires in the pine rocklands, it may not be surprising. Charcoal concentrations at Laguna Tortuguero, Puerto Rico, expressed on a wet volume basis (Burney et al. 1994), ranged from ca. 250–4250 mm<sup>2</sup>/cm<sup>3</sup>, which is one to two orders of magnitude higher than values at Split Pond (ca. 7 to 184 mm<sup>2</sup>/cm<sup>3</sup>) and West Pond (ca. 4 to 170 mm<sup>2</sup>/cm<sup>3</sup>) (Stork 2006).

Field work in 2003 revealed many fire-scarred trees present in the forest adjacent to Split Pond, but no visible evidence was seen of fires intense enough to cause tree mortality (personal communication, Stork 2006). Crown fires have been shown to produce large amounts of air-borne microscopic charcoal carried in the smoke column, along with macroscopic charcoal fragments typically carried into lakes by overland flow of water (Whitlock and Larsen 2001). On Great Abaco Island in recent decades, fires have typically occurred frequently enough to remove understory vegetation and leaf litter, maintaining low-fuel conditions that are not conducive to allowing wildfires to ladder into the canopy.

Based on my observations, the charcoal generated by fires on Great Abaco is not transported via overland water flow, and this inhibits secondary charcoal deposition after fire events, e.g. as discussed in Whitlock and Larsen (2001). The bedrock of Great Abaco is oolitic limestone and weathers into extreme solution forms, both at the surface and through karstic processes at depth. The island contains no rivers or creeks, nor even supports sheet flow sufficient to transport charcoal fragments appreciable distances. Rains appear to immediately transport such material down into the fissures and solution holes found ubiquitously on the surface (Sealey 1994).

Several studies have shown that the intensity of a fire determines how microscopic charcoal is transported (Whitlock and Larsen 2001, Clark et al. 1998, Umbanhower and McGrath 1997). The charcoal particles I collected in air-fall traps during the controlled burn in Great Abaco National Park lend support to my hypothesis that microscopic charcoal is being deposited in Abaco's ponds primarily via air-fall during fire events. The Nature Conservancy's controlled burn was a low-intensity, prescribed burn and the samples collected in my traps reflect that fact. Even traps placed less than 10 m from the edge of the burn did not collect any fragments larger than 125  $\mu\text{m}$  in size after processing. All the air-fall charcoal traps located beneath the smoke column did collect microscopic charcoal fragments smaller than 125  $\mu\text{m}$  after processing. As expected, the control traps, placed approximately 1.5 km upwind of the burn site, did not contain any charcoal fragments, demonstrating that no charcoal was being transported from outside the area.

This offers an explanation of the large spikes in charcoal deposition in the lower portion of the Split Pond core. Before the arrival of humans on the island, any peaks in charcoal deposition during drier conditions would most likely indicate wildfires in the immediate area. A spike in charcoal at ca. 230 cm (ca. 1500  $^{14}\text{C}$  yr B.P) is followed by a spike in *Pinus* pollen at ca. 212 cm, which is immediately followed by the largest spike in charcoal at ca. 205 cm (ca. 1350  $^{14}\text{C}$  yr BP). In conjunction with the fact that large spikes in macroscopic charcoal also occur at ca. 250 and ca. 215 cm, the results suggest a period of intense fires followed by the recovery of pines, immediately followed by another period of intense fires. This fits with other paleoecological reconstructions that show a drying trend since ca. 3200 cal. yr BP that appears in Lake Miragoane, Haiti (Higuera-

Gundy et al. 1999) and the Chichancanab, Yucatan, Mexico (Hodell et al. 1991) records. Hodell et al. (2000) also discuss exceptionally dry periods that occurred at ca. 1510, 1171, 1019, and 943 cal. yr BP in the area of lake Chichancanab, which are coincident with peaks in charcoal deposition recorded in Split Pond. This could indicate that decadal changes in atmospheric and oceanic cycles may affect the circum-Caribbean region in some unified manner and may have resulted in drier conditions on Great Abaco Island. However, much of the time frame represented by the Split Pond core also corresponds to the period of time after what is generally accepted as the arrival of humans in the area (ca. 1200 cal. yr BP). So, any increases in burning could be attributed to anthropogenic activities, climatic influences, or a combination of the two.

## CHAPTER 7

### Conclusions

The pine rocklands that surround Split Pond have been affected by both climatic and anthropogenic influences. With the poor state of pollen preservation in Split Pond sediments, it is not possible to determine the nuances of vegetation shifts within the community, but by using pine pollen and charcoal concentrations, it is possible to see the effects of climatic and anthropogenic impacts on a small portion of the community. Increases in the amount of *Pinus* pollen and charcoal concentrations, especially before human arrival, highlight what are likely to have been periods of relative aridity. The data indicate that the area surrounding Split Pond has been in a dry phase, with some variation, since ca. 1000 cal. yr BP and has most likely been exposed to frequent human generated fires. Higuera-Gundy et al. (1999) mention a temporary period of wetter conditions ca. 1700–1000 cal. yr BP that appears in the Lake Miragoane, Haiti study. At ca. 1000  $^{14}\text{C}$  yr BP, the LOI results from Split Pond show a marked decrease in organic content and an increase in carbonate and non-carbonate inorganic sediments, suggesting that the site has been drier during the last 1000 years. Split Pond is extremely shallow, possibly allowing drier conditions to increase precipitation of carbonates from the water column. This may also explain the unconformity that occurs at 230 cm. The pond may simply have dried out, allowing sediments to be removed through aeolian transport.

Fluctuations in pollen assemblages, microscopic charcoal concentrations, and sediment type throughout the profile correlate broadly with inferred regional climate shifts during the Late Holocene. Humans, beginning with their arrival on the island as

early as ca. 1200 cal. yr BP, likely influenced the fire history near Split Pond. The probable time frame for the appearance of humans on Great Abaco is consistent with the idea that the native Lucayans settled Great Abaco Island after migrating from the islands to the south (Berman and Gnivecki 1995, Keegan 1997).

Future research on sediments from other lakes on Great Abaco Island could help confirm some of my interpretations of the core from Split Pond and could also improve understanding of charcoal deposition in lake sediments. Sediment cores have been recovered from two promising sites, Emerald Pond and Satellite Pond, which might, in conjunction with the data recovered from West Pond and Split Pond, offer clearer insights into regional climate shifts that are free of noise occasioned by the local changes recorded in any individual pond. Analysis of additional sediment cores may also strengthen evidence for the estimation of human arrival on the island as ca. 1200 cal. yr BP. The Lucayans were not known to cultivate maize on a large scale, but if pollen evidence of maize cultivation were to be found, that would provide indisputable evidence of human arrival (Horn 2006).

Further study of transport mechanisms of macroscopic charcoal during and after fires would also help establish exactly how charcoal fragments are transported in the pine rocklands. By lining small fissures in the karst with fine-mesh screens in a multi-year study, this could perhaps be accomplished.

For Split Pond, a study of diatoms would help determine past changes in salinity that could establish whether the sediments from the lower portion of the core represent, as I suspect, marine incursion. Spectral analysis of the black, viscous substance in the lower core might determine if it is, indeed, an Fe-Mn residue.

Archaeological studies have suggested that the unique geology and climate of the Bahamas provided a setting with ample and desirable resources for prehistoric settlers. In modern times, it appears that the proximity of the islands to the east coast of Florida, along with their balmy climate, is attracting a new wave of immigrants who create pressure to develop the islands. Exploitation of the landscape is now and, the data suggest, has always been the primary motivation for the presence of humans in the Bahamas. Whether it was the Lucayans, possibly seeking relief from a severe drought that affected the Caribbean ca. 1500–1200 cal. yr BP, or the Owens-Illinois Corporation, who harvested almost every tree on Great Abaco Island during the mid-20<sup>th</sup> century, humans have always dramatically affected the environment. Understanding how the ecosystem of Great Abaco responded to human and climatic influences in the past can provide greater insight into how agencies such as The Nature Conservancy and the Friends of Abaco can better manage the island's resources into the future.

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## **APPENDICES**

## APPENDIX A: POLLEN PROCESSING PROCEDURE

I used the following schedule to concentrate pollen in sediment samples from the Split Pond sediment core. This processing schedule was developed by Drs. Sally Horn and John C. Rodgers III, following standard palynological techniques (Berglund, 1986); in our lab it is known as the “JR-2 HCl rinse” procedure. It takes about six hours to complete with a batch of six samples, and must be performed in a laboratory fume hood. We use an IEC benchtop centrifuge with a 6 x 15 ml swinging bucket rotor set to rotate at about 2500 RPM. All centrifuge times are 2 minutes with time measured from initial start up. Gloves and goggles should be worn for all chemical steps and use of HF also requires use of a respirator and face shield.

1. Place wet sediment in pre-weighed, 15 ml polypropylene centrifuge tubes and reweigh.
2. Add 1 tablet *Lycopodium* spores to each tube (Batch # 710961 = 13,911 spores/tablet).
3. Add a few ml 10% HCl, and let reaction proceed; slowly fill tubes until there is about 10 ml in each tube. Stir well, remove stirring sticks, and place in hot water bath for 3 minutes. Remove from bath, centrifuge, and decant.
4. Add 10 ml hot distilled water, stir, centrifuge and decant. Repeat for a total of two washes.
5. Add about 10 ml 5% KOH, stir, remove stirring sticks, and place in boiling bath for 10 minutes; stir again after 5 minutes. Remove from bath and stir again. Centrifuge and decant.
6. Add 10 ml hot distilled water, stir, centrifuge, and decant. Repeat for a total of 4 washes.

7. Fill tubes about  $\frac{1}{2}$  way with distilled water, stir, and pour through 125  $\mu\text{m}$  mesh screen, collecting liquid in a labeled beaker underneath. Use a squirt bottle of distilled water to wash the screen, and to wash out any material remaining in the centrifuge tube.
8. Centrifuge down material in beaker by repeatedly pouring beaker contents into correct tube, centrifuging, and decanting.
9. Add 8 ml of 49–52% HF and stir. Place tubes in boiling bath for 20 minutes, stirring after 10 minutes. Remove from bath and centrifuge and decant.
10. Add a few ml 10% HCl, let reaction proceed, and then slowly increase volume in tube to 10 ml. Stir well, remove stirring sticks, and place in hot water bath for 3 minutes. Remove from bath, centrifuge, and decant.
11. Add 10 ml hot Alconox<sup>®</sup> solution (made by dissolving 4.9  $\text{cm}^3$  commercial Alconox<sup>®</sup> powder in 1000 ml distilled water). Stir well and let sit for 5 minutes. Centrifuge and decant.
12. Add more than 10 ml hot distilled water to each tube, so that top of water comes close to top of tube. Stir, centrifuge, and decant. Check top of tubes for oily residue after decanting. If present, remove carefully with wadded paper towel. Also at this time, examine the tubes to see if they still contain silica. If silica is present, repeat steps 9–11. Assuming that no samples need retreatment with HF, continue washing with hot distilled water as above for a total of 3 hot water washes.
13. Add 10 ml of glacial acetic acid, stir, centrifuge, and decant.
14. Make acetolysis mixture by mixing together 9 parts acetic anhydride and 1 part concentrated sulfuric acid. Add about 8 ml to each tube and stir. Remove stirring sticks and place in boiling bath for 5 minutes. Stir again after 2.5 minutes. Remove from bath and centrifuge and decant.
15. Add 10 ml glacial acetic acid, stir, centrifuge, and decant.
16. Add 10 ml hot distilled water, stir, centrifuge, and decant.
17. Add 10 ml 5% KOH, stir, remove stirring sticks, and heat in vigorously boiling bath for 5 minutes. Stir again after 2.5 minutes, then remove sticks. After 5 minutes, centrifuge and decant.

18. Add 10 ml hot distilled water, stir, centrifuge, and decant. Repeat for a total of 3 washes.
19. After decanting last water wash, use vortex mixer for 20 seconds to mix sediment in tube.
20. Add 1 drop 1% safranin stain to each tube. Use vortex mixer for 10 seconds. Add distilled water to make 10 ml. Stir, centrifuge, and decant.
21. Add a few ml tertiary-butyl alcohol (TBA), use vortex mixer for 20 seconds. Fill to 10 ml with TBA, stir, centrifuge, and decant.
22. Add 10 ml TBA, stir, centrifuge, and decant.
23. Vibrate samples using the vortex mixer to mix the small amount of TBA left in the tubes with the microfossils. Carefully transfer the liquid to pre-cleaned and labeled glass vials. Centrifuge down residue in vials and decant. Repeat as necessary until all material is transferred from tubes to vials.
24. Add several drops of silicone oil (2000 cs viscosity) to each vial, more if a lot of residue remains. Stir with a clean toothpick.
25. Place uncorked samples in a dust-free cabinet to let the residual TBA evaporate.
26. Stir again after 1 hour, adding more silicone oil if necessary.
27. Check the samples after 24 hours; if there is no alcohol smell, cap the vials. If the alcohol smell persists, allow more time for evaporation.

## APPENDIX B: CHARCOAL POINT COUNTING CALCULATIONS

Calculations below are based on Clark (1982), with modifications in some cases by S. Horn. This appendix is based on an unpublished laboratory handout by S. Horn prepared February 8, 2005 and modified May 3, 2006, further modified by D. West in 2007.

### Abbreviation Key:

$S_p$  = standard deviation of P

$P_o$  = points applied in each field of view

P = estimated probability of a random point falling on charcoal

F = the number of fields of view you looked at

N = total number of points applied (equal to  $P_o \times F$ )

$F_a$  = area in  $\text{mm}^2$  of each field of view

$F_{at}$  = Total area in  $\text{mm}^2$  on slide in which you looked at charcoal (equal to  $F_a \times F$ )

C = the number of applied points that “touched” charcoal

V = volume in  $\text{cm}^3$  of original wet sediment sample processed for pollen

W = mass in g of original wet sediment processed for pollen (from LOI sheet)

$P_w$  = percent water in the wet LOI sample from same level as pollen sample

M = number of *Lycopodium* marker spores added to original sample processed for pollen

$M_c$  = the number of *Lycopodium* marker spores you counted in the fields of view in which you did the point counting.

$M_{po}$  = the number of *Lycopodium* marker spores you counted in the pollen count from the same level.

$P_{opc}$  = the total number of pollen grains (excluding spores and indeterminates) counted in the pollen count from the same level.

**Areal density of charcoal on the slide (P) (e.g., the estimated probability that a random point will fall on charcoal):**

$$P = C/N$$

**The accuracy, or relative error, of the estimate of P ( $S_p/P$ ):**

$$(S_p/P) = \sqrt{(1 - P)/C}$$

**Areal density of charcoal (total) in mm<sup>2</sup> in all the fields of view you counted ( $A_f$ ):**

$$A_f = P \times F_{at}$$

**Estimated area of charcoal in mm<sup>2</sup> in the entire pollen sample ( $A_{ps}$ ):**

$$A_{ps} = \frac{M \times A_f}{M_c}$$

**Charcoal area in mm<sup>2</sup> expressed on the basis of volume of wet sediment ( $A_{cc}$ ):**

$$A_{cc} = A_{ps}/V$$

**Charcoal area in mm<sup>2</sup> expressed on the basis of wet sediment mass ( $A_{wm}$ ):**

$$A_{wm} = A_{ps}/W$$

**Charcoal area in mm<sup>2</sup> expressed on the basis of dry sediment mass ( $A_{dm}$ ):**

$$A_{dm} = A_{ps}/W(1-P_w)$$

**Charcoal area in mm<sup>2</sup> expressed on the basis of annual influx ( $A_{cy}$ ):**

$$A_{cy} = A_{cc} \times \text{sedimentation rate expressed in cm/yr}$$

**Charcoal: Pollen ratio (C:P) expressed as mm<sup>2</sup> charcoal per pollen grain:**

$$C:P = \frac{M_{po} \times A_f}{M_c \times P_{opc}}$$

**Charcoal: Pollen ratio (C:P) expressed as  $\mu\text{m}^2$  charcoal per pollen grain:**

$$\text{C:P} = \frac{M_{\text{po}} \times A_f \times 10^6}{M_c \times P_{\text{opc}}}$$

## VITA

David N. West was born in Ten Mile, Tennessee in 1969. After graduating from Midway High School, he attended the University of Tennessee, Knoxville until 1992. After pursuing a career in Information Technology, David returned to the University of Tennessee to complete his undergraduate degree in Geography, with a minor in History, graduating Magna cum Laude in 2003. He stayed at UT in order to seek his Masters in Geography with an emphasis on paleoenvironmental studies.

As an undergraduate, David received the Outstanding Senior award in 2003 and as a Masters student was awarded the Outstanding Teaching Assistant award in 2005. David is also a member of Gamma Theta Upsilon, the national geography fraternity.

David received his Master of Science from the University of Tennessee in August 2007 and hopes to pursue a career in environmental science and conservation.

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