2008

A 5000-year history of Caribbean environmental change and hurricane activity reconstructed from coastal lake sediments of the West Indies

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A 5000-YEAR HISTORY OF CARIBBEAN ENVIRONMENTAL CHANGE
AND HURRICANE ACTIVITY RECONSTRUCTED FROM COASTAL LAKE SEDIMENTS
OF THE WEST INDIES

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

In

The Department of Geography and Anthropology

By

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May 2008
To the expedition
ACKNOWLEDGMENTS

First and foremost I would like to thank my major professor, Dr. Kam-biu Liu, for his support and guidance throughout my academic career. Through his direction and generosity I have embarked on research expeditions spanning five continents and nearly all of the environments the planet has to offer, from the coastal jungles of Central America and the beaches of the Caribbean, to the arid savannas of East Africa and the frigid colds and high elevations of Andean Ice Caps and the Tibetan Plateau. Were it not for him I would not be where I am today and for that I sincerely thank him.

I would also like to thank Drs. Robert Rohli, Steve Namikas, Michael Leitner, and Laurie Anderson for all of their assistance on this project and for serving on my committee. Thanks are due to Dr. Ron Delaune for his assistance with the $^{137}$Cs analysis and Dr. Fred Thompson for his help with the fossil mollusk identification.

For their tireless help in the field gathering data for this project I would like to extend my gratitude to the members of my field expeditions; Jon Breaux, Tom Blanchette, and Dr. Kam-biu Liu. In addition I would also like to thank the Governments of Anguilla, Barbuda, and the Bahamas for their permission and the scientific research permits that made this project possible.

I would like to thank CARTOGRAPHIC PERSPECTIVES and the North American Cartographic Information Society (NACIS) for their permission to use my 2007 article as Chapter 3 in this dissertation.

I wish to acknowledge my gratitude for the financial support for this project from: National Science Foundation’s Doctoral Dissertation Research Improvement (DDRI) Grant (BCS-0623287), The LSU Department of Geography and Anthropology’s R.J. Russell Field Research Grant and again, Dr. Kam-biu Liu for a seemingly endless supply of good will and funding for radiocarbon dating.

Finally, I could never have done this without the continual support and devotion from my family and above all my wonderful fiancée Lacy Little, whose patience has been an inspiration, and whose unfailing love has made this difficult journey all the more bearable.
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ABSTRACT

A ~5000 yr history of modern and prehistoric hurricane landfall and environmental change has been reconstructed from coastal lake sediments of the northern West Indies. Hurricane overwash layers and environmental shifts were identified by changes in biological and sedimentary stratigraphies, core lithology, and loss-on-ignition techniques. $^{14}\text{C}$ and $^{137}\text{Cs}$ were used to establish a chronology of events. Many hurricane-induced overwash layers were identified within the lake sediments. Evidence indicates distinct periods of temporal shifts in hurricane activity for the Northern Caribbean islands of Anguilla, Barbuda, and Acklins Island, Bahamas, providing the first paleotempestological records for the region. The northern Caribbean record appears to exhibit an anti-phase relationship with the results from the U.S. Gulf coast, in apparent agreement with the Bermuda High hypothesis. Comparison with studies basin-wide indicates three temporal shifts in basin-wide activity occurring at ~1000, 2500, and 3500 yr BP.
CHAPTER 1 INTRODUCTION

Tropical cyclones kill more people and cause more insured losses than any other natural disaster (Murane, 2004). Consequently, it is not difficult to comprehend the importance and significance associated with understanding hurricanes and any changes in their activity and landfall frequencies. The devastation brought about by the landfall of intense hurricanes was brought center stage during the hurricane season of 2005, which saw an unprecedented number of named storms (twenty seven), including fifteen hurricanes of which seven were of category 3 or higher on the Saffir-Simpson scale (www.noaa.gov) with four making landfall in the United States. The socioeconomic toll of the 2005 hurricane season on the U.S. alone was unprecedented, with damage in the hundreds of billions, and over 1,300 lives lost. The numbers alone can only provide an indication of the damage done to infrastructure and industry, but the emotional and societal costs both at the community and the individual level are all but impossible to quantify. With an ever increasing migration of populations and infrastructure toward coastal areas susceptible to hurricane landfalls, the potential for tragic loss of life and severe property damage increases (Pielke and Pielke, 1997). This elevated risk potential only further highlights the need for the formulation of a solid understanding of the changing patterns in hurricane activity and landfall frequencies.

The overall relationship between hurricanes and climate is poorly understood. It is well known that there are fluctuations in hurricane activity within the Atlantic and Caribbean basins, fluctuations that range on the orders of seasonal to decadal (Elsner et al., 2000; Gray, 1990; Landsea, 1992, 2005; Reading, 1990). What is not known however, is whether or not these fluctuations are entities unto themselves or shifting patterns superimposed upon a lower frequency system? Scientists studying hurricanes have been limited to the purview of the modern instrumental record, a record spanning only the last 150 years at best (Landsea et al., 2004). This time frame is far too short to address any long-term changes in hurricane activity. There is a desperate need for adequate long-term records, which at present are scarce. If we are to truly understand changes in hurricane frequency on a larger temporal scale we need records spanning thousands of years. Such long-term records would allow for the identification of low-frequency shifts in hurricane activities, and in conjunction with other proxy studies, perhaps shed some light on the climatic mechanisms controlling the low-frequency shifts.
Paleotempestology

Great promise for the retrieval of these critically needed long-term records lies within the field of paleotempestology. Paleotempestology is defined by Liu (2004) as “an emerging field of science that studies tropical cyclone activity mainly through the use of geological proxy techniques.” The field has tremendous potential to reconstruct long-term changes in tropical cyclone frequency. Liu and Fearn (1993) have shown that distinct overwash sand layers may be deposited in the sediments of coastal lakes and marshes due to the storm surges and tidal overwash processes that are typically associated with a catastrophic hurricane landfall. Ideal sites are situated behind a sandy barrier close to the sea so that they are susceptible to hurricane overwash and adjacent to a source of sand, they are situated on tectonically and morphologically stable coastlines with a relatively stable sea level history. They should be small, tranquil, coastal lakes that are not fed by major rivers so that their sedimentary record will not be complicated by fluvial or hydrological events unrelated to hurricane strikes.

These overwash storm deposits can be radiocarbon (\(^{14}C\)) dated using the surrounding organic sediments to give a chronology of hurricane strikes. The identification and dating of these hurricane overwash sand layers allows for the estimation of return periods and annual landfall probabilities. By looking to the proxy record we can overcome the limitations of the instrumental record and potentially identify hurricane frequency changes previously unseen, allowing for the reconstruction of hurricane landfalls spanning several millennia. These long-term hurricane history reconstructions can then be used to identify periods of shifting activity that, in conjunction with other proxy records (e.g., fossil pollen climate reconstructions) can help to develop an understanding of Caribbean Basin hurricane activities as a whole.

Hard work in this relatively new field has paid off with good spatial coverage of research sites along the U.S Gulf coast from Pascagoula, Mississippi, to Western Lake, Florida, and the Atlantic coast from Cape Cod, Massachusetts, to South Carolina and a few burgeoning sites for the Caribbean region (Donnelly, 2005; Donnelly et al., 2001a, 2001b, 2004; Hippensteel et al., 2005; Liu and Fearn, 1993, 2000a, 2000b, 2002; Scott et al., 2003; Scott et al., 2003; Scileppi and Donnelly, 2007). The majority of the seminal paleotempestological papers (Donnelly et al., 2001a, 2001b; Liu and Fearn 1993, 2000a, 2000b) look to overwash storm deposits found in coastal lake sediments as the main source of paleoenvironmental data about prehistoric hurricanes. However, over the years paleotempestology has seen the development of many new
proxies exceeding those used in the incipient studies. Paleotempestologists are now also looking to coral reefs (Scoffin, 1993), stalagmites (Malmquist, 1997; Frappier et al., 2007), foraminifera (Scott et al., 2003; Collins et al., 1999), tree-rings (Miller et al., 2003; Doyle and Gorham, 1996; Johnson and Young, 1992), phytoliths (Lu and Liu, 2005), and radio-isotope geochronology analysis of deep ocean-bed cores (Keen et al., 2004) to reconstruct long term prehistoric hurricane activities. Recent years have also seen a major upswing in the use of historical data: ship logs (i.e. Milas, 1968.), Spanish and English colonial archives (Reading, 1990; Caviedes, 1991), historical records in the form of local Chinese gazettes (Liu et al., 2001) and old U.S newspapers (Chenoweth, 2006; Mock, 2002; Mock et al., 2004) for reconstructing past hurricane activity, as well as for use in quality control in conjunction with NOAA’s ‘best track data’ (Neumann et al., 1999).

While making significant strides over the last few years, paleotempestology still has many areas that necessitate future research, especially in the arena of modern analog studies as well as greater spatial coverage of research sites. The specifics of the sedimentary signature that a hurricane leaves in a coastal lake or marsh is controlled by a host of factors, such as beach geomorphology, barrier width, barrier height, distance from shore, sediment supply, surrounding topography, and offshore bathymetry, as well as the intensity and duration of the hurricane. To be useful, prehistoric events must be calibrated by means of a modern analog approach to provide a solid foundation for the interpretation of the paleorecord. A good modern analog will allow for a calibration of the intensity of prehistoric storms. The application of a modern along study to multiple sites in close proximity also allows for a better historical reconstruction, enabling the researcher to even out the effects of individual lakes sensitivity to storm strikes. Modern analog studies are especially useful across sites of close proximity in allowing the researcher to better quantitatively determine the spatial impact of the storm signature along a coast. In fact, there have been calls for more modern analog studies to be done (Donnelly, 2005; Liu, 2004; 2007).

As mentioned previously, the U.S. Gulf and Atlantic coasts have fairly decent spatial coverage in terms of research sites but in order to begin to draw real conclusions about the macro-scale variations on hurricane frequency, more research must be done in underrepresented areas (Caribbean and Central America) that have the potential to reveal key patterns in the spatial and temporal variations of hurricane frequency for the entire Gulf and Caribbean basins. With a
larger spatial coverage, hypotheses such as the Bermuda High hypothesis (Liu and Fearn, 2000a) and perhaps patterns yet unknown may allay themselves.

This Project

The Caribbean, a region that is crucial to building a solid foundation for understanding basin-wide shifts in hurricane activities and landfall frequencies throughout the Holocene, is a vastly under-represented region in paleotempestological studies. Also lacking is the quantitative analysis of modern analog hurricane deposits across multiple differing geographical settings. This study will use an innovative approach to paleotempestology by following a storm of known intensity to three different Caribbean islands to determine its geological impact at each location using multi-proxy reconstruction techniques. This project will contribute to the science of paleotempestology by developing an applicable modern analog methodology through the comparative investigation of historically documented hurricane impacts in the northern Caribbean. It will add much needed valuable knowledge to the paucity of the northern Caribbean paleo-record by allowing for an accurate calibration of prehistoric storm intensities.

Hurricane Donna, the only major hurricane of 1960, began as a tropical depression off the west coast of Africa on August 29, reaching hurricane strength on Sept 1. Moving into the warmer waters of the Caribbean it rapidly intensified to Category 4 as it tracked toward the Leeward Islands. On September 4, 1960, while still a Category 4 storm, the eye wall of Donna slammed the islands Barbuda, St. Bathelmy, St. Maarten, and Anguilla. For the next ten days Donna tore through the Caribbean, passing directly over the Bahamas and south Florida. Hurricane Donna caused damage to the tune of 3.3 billion (2005 dollars) with 364 direct fatalities. The significance of this storm with such a vast area of impact is not reflected in the literature. Current published literature on the impacts of Hurricane Donna (Craighead and Gilbert, 1962; Dunion et al., 2003; Shin et al., 2003; Ball et al., 1967; Perkins and Enos, 1968) are confined mostly to its ecological impacts in the U.S., with an emphasis on southern Florida, but largely ignoring the northern Caribbean.

By using Hurricane Donna (a Category 4 hurricane that ravaged the Northern Caribbean in August and September of 1960) it will be possible to quantify the impact of the overwash signature deposited by a storm of known intensity that made direct hits on the three different Caribbean islands, Barbuda, Anguilla, and Acklins Island, Bahamas (Fig. 1-1). The eastern Caribbean is an ideal region for studying past tropical cyclone activity because of the extensive
depositional environments well situated to record past tropical strikes and the extremely small tidal ranges that can reduce uncertainty with respect to prehistoric storm surge heights (Donnelly, 2005). There is also good historical evidence of sea level changes for the Caribbean (Blanchon et al., 2002; Digerfeldt and Hendry, 1987; Taylor et al., 1985; Slowey et al., 2002; Toscano and Macintyre, 2003) that can be used when calibrating historical storm surges and their resulting overwash layers.

Coastal lake sediment cores taken from the three northern Caribbean islands were analyzed using multiple geological and biological proxies in concert with radio-isotope dating techniques ($^{14}$C and $^{137}$Cs) to identify the stratigraphic signature of Hurricane Donna. Once identified, the overwash layer from Hurricane Donna was used to calibrate the proxy records of prehistoric storm strikes in an effort to reconstruct a mid-to late-Holocene history of hurricane activities for the northern Caribbean. The calibration of paleo-overwash deposits against modern overwash layers from a well-documented modern analog permits good estimation of the size and intensity of prehistoric events.

Figure 1-1. Path of Hurricane Donna (1960) and project research locations.
Hurricane Donna is the ideal storm for this type of study. Having occurred in 1960, there is the excellent chronological control available for dating the stratigraphic signature using the radioisotope Cesium-137 ($^{137}$Cs). $^{137}$Cs, a short-lived radioisotope, was produced as a result of atmospheric nuclear weapons testing and has no natural source. The ban of atmospheric nuclear testing in 1963 provides a way to date sediments by locating the stratigraphic peak in $^{137}$Cs activity, which should indicate the calendar year of 1963 (Ritchie and McHenry, 1990; Keen et al., 2004; Graustein and Turekian, 1986; Auerbach et al., 1964). Hurricane Donna’s direct strike on all three aforementioned islands in 1960 should have left a stratigraphic signature in the lake sediments that occurs only slightly below the 1963 $^{137}$Cs peak, thereby allowing for precise dating control in the identification of the Donna overwash layer. Once identified as Donna, it will be possible to identify numerous other recent hurricanes of varying strengths passing near the three islands. For example, Barbuda had significant hurricane impacts from Dog in 1950 (Cat 2), Luis in 1995 (Cat 4), and Debbie in 2000 (Cat 1), allowing for the potential use of these other hurricanes of differing strengths as additional modern analogs for calibration with Donna.

**Hypotheses**

Two main hypotheses are tested using the proxy records of recent and prehistoric hurricanes recovered from the three northern Caribbean islands.

**Hypothesis 1**: A basic assumption in paleotempestology is that catastrophic hurricanes leave a distinct stratigraphic record in coastal lake sediments in the form of overwash sand layers, and sand layer thickness is generally proportional to hurricane intensity (Liu, 2004). This hypothesis will be tested by examining Donna’s sedimentary signature in the Caribbean lakes and comparing it with those of other hurricanes of different intensities and impacts. Two prominent sand layers are expected to be found within the sediments from Barbuda and Anguilla, representing the two catastrophic hurricanes strikes from Donna and Luis, and one prominent sand layer for Acklins Island representing Donna only. The other weaker hurricanes in the modern record are not anticipated to have left any sedimentological evidence.

**Hypothesis 2**: Like Donna many past catastrophic hurricanes that passed through the northern Caribbean also recurved to affect the U.S. Atlantic coast. This implies that, in terms of the temporal patterns of hurricane activities, proxy records from my northern Caribbean sites will be positively correlated with those from the Atlantic coast and negatively correlated with those from the Gulf coast. Therefore, it is anticipated that in the longer sediment cores, there will be
more overwash sand layers occurring in the upper parts of the cores (<1000 yr BP) than in the lower parts (2000-3000 yr BP), since more (fewer) hurricanes were found to occur in the Atlantic (Gulf of Mexico) coast in the past 1000 yrs than in the previous 2000 yrs (Liu and Fearn, 2000a).

**Expected Significance**

This study will be the first to identify and record the impacts of Hurricane Donna in the northern Caribbean. By using Hurricane Donna in a pioneer modern analog study, we will be able to accurately interpret prehistoric overwash layers found within the coastal lake sediments of the Caribbean. In addition, this study will advance the young science of paleotempestology by providing the first proxy records of catastrophic hurricane strikes for this under-represented region. These calibrated events may then in turn be used to reveal shifting periods of increased and decreased hurricane activities across the Caribbean basin, thereby providing vital data for identifying large scale low-frequency shifts in hurricane activity.

In addition to these scientific merits, the results from this study have important societal significance. The reconstruction of long-term paleohurricane records will allow for the calculation of the return periods and average annual landfall probabilities of catastrophic hurricanes, which are indispensable to local governments and societies for use in risk assessment and mitigation planning. For this project local officials and the representative governments of each island have provided permission and permits for conducting field research (Appendix 1). In exchange the results of this study have been presented to local researchers and government officials, so that local stakeholders can be involved in this research. These outreach activities will contribute to promote science education and capacity building in these Caribbean island nations.
CHAPTER 2 LITERATURE REVIEW

A major question regarding paleotempestology is: how can one be certain that the “overwash” layers found within the cores are indeed deposited by hurricanes, and not some other catastrophic event, e.g., tsunamis? This question is especially pertinent in a region such as the Caribbean that is susceptible to both forces. The first part of Chapter 2 focuses on a review of the relevant literature to help answer this question of hurricane vs. tsunami deposits. The latter part of the literature review section examines Caribbean Holocene climate and sea level changes, gastropods, and the unique sedimentation regimes of Caribbean hypersaline salt ponds.

Hurricane Overwash

Over recent years paleotempestology has seen a rise in the use of new proxies and methodologies (Chapter 1). However, to date the best method for reconstruction of hurricane landfalls still lies in the interpretation of storm surge-generated overwash sand fans deposited along the bottoms of coastal lakes and lagoons (Donnelly, 2005; Donnelly et al., 2004; Donnelly et al., 2001a, 2001b; Liu, 2004; Liu and Fearn, 1993, 2000a, 2000b). Given the importance of overwash deposits to the science, this section seeks to provide a broad overview of overwash literature and the processes responsible for generating overwash fans, with a particular focus on the structure and analysis of hurricane-driven deposits.

To begin, a working definition of overwash deposits is needed and there is much ambiguity in the terminologies used to describe overwash throughout the literature of various disciplines. They range from general “supratidal sedimentation” (Perkins and Enos, 1968), “spillovers and spillover sand-lobes” (Ball et al., 1967), to the specific “the transfer of beach sand across to the lagoonal side of the barrier through sluiceways during a hurricane or other violent storm” (Sheppard and Wanless, 1971). Leatherman (1981) illustrates the distinction between overwash (the process) and washover, the morphological feature created by the overwash process. The washover itself can be divided into separate physiographic features: the throat, which characterizes the channel or breach that runs through the dune or barrier field, and the fan, the portion of the washover that has been deposited behind the barrier onto land (Fig. 2-1). The fan shape of the washover occurs from the lateral dispersal of the sediments due to a lack of horizontal constraints. For the purposes of consistency I will adhere to Leatherman’s definition distinguishing between the process (overwash) and the resulting depositional landform (washover) for this section.
Identified as early as 1890 (McGee, 1890), overwash in conjunction with aeolian processes has been studied extensively as the agents of landward barrier migration. However, the actual overwash process itself was not defined and described until Johnson’s (1919) paper on shoreline processes and development where he describes the accumulation of back barrier sediments deposited by large storm waves along the Massachusetts coast. After witnessing the 4-foot deep washover deposits following the great New England hurricane of 1938 Wilby et al., (1938) noted that the major effect of overwash on barrier islands was to widen the island. Following the 1938 hurricane washover features began to be noticed with some regularity. Howard (1939) was the first to document the irregularity of lagoonal shorelines (crenulated margins) due to the presence of washovers and that older irregularities may be interpreted as older overwash deposits (washovers).

This period also saw the first studies using aerial photography (Morgan, 1959; Jacobson, 1968) to identify and analyze pre and post-storm changes caused by overwash and the resulting washovers. Stoddard (1962) and Vermeer (1963) were the first to chronicle the effects of vegetation on reducing overwash and its role in limiting the lateral deposition of washover sediments. In a study on the effects of Hurricane Donna by comparing photographs, cores, and maps collected for their study both before and after the storm’s landfall Ball et al. (1967), discovered that there is discernable bias toward the preferential preservation of washovers from only the largest “high-energy” storm events. In studying the variations in washover deposits between Hurricanes Donna (many) and Betsy (few) along south Florida’s coral reefs and cays, Perkins and Enos (1968) stated that it is not possible to equate every hurricane with supratidal
deposition. While both storms were of equal strength (~ 120-140 mph) the damage and depositions were not. Corals beds were affected by both, though to a lesser extent during Hurricane Betsy some five years later due to the slow regeneration of the corals from the damage received from Hurricane Donna. Washover deposit patterns were also different; while Hurricane Donna left large amounts of washover, Hurricane Betsy did not. The authors surmise that this was due to the orientation of the storm track and eye-wall in relation to the coast.

A seminal paper by Kraft (1971) described the nature of the washover deposits themselves: “washovers consisting of clean, well-sorted sand, characterized by typical horizontal stratification at the apex and delta foreset bedding at the fan margin”. In addition Kraft (1971) identified the source of the washover sands as originating on the eroding beach face, which acts as to store materials in low supply areas. Overwash processes have also been identified in the U.S. Great Lakes region (Schwartz, 1975; Hester and Fraser, 1973) produced by large storm waves, nearing heights of 30 feet. The process is much the same as a landward migration of the barrier/dune complex, although vegetation mortality is significantly reduced due to the absence of salt water intrusion.

By far the largest concentration of studies done on overwash process is confined to the realm of barrier islands, which comprise nearly 13 percent of the total coastline worldwide (Cromwell, 1971). This scope is further narrowed down to the U.S. Gulf and Atlantic coasts, with the majority of the literature based on studies done in this region. In a comprehensive paper on the 4 by 4 ¼ mile wide washover fan deposited by Hurricane Audrey on St Joseph Island, Texas, Hayes (1967) detailed the structure of the washover fan as semi-circular in plan view and wedge shaped in the vertical section, horizontally stratified with a progressively finer sand grain sequence toward the front end of the fan. Schwartz (1975) was the first to quantify washovers on an individual storm basis. He calculated that during a 1973 winter northeaster 300,000 m² of washover sedimentation was deposited along the outer banks of North Carolina. That is the equivalent of 12 m³ per meter of beach, highlighting the potential for sediment deposition during non-hurricane storms. Another study done on a winter northeaster at Assateague Island in 1947 (Leatherman et al., 1977b) again showed that there was significant deposition (20 m³ per meter of beach) in non-hurricane conditions. Based on this study Leatherman and Williams (1977a) suggested that the most important variable in determining the magnitude of an overwash is the storm tide height. Lu and Liu (2005) pioneered the use of phytolyths for validating the washover
origin of sand layers in paleotempestology. Their results help to support the fundamental interpretations that sand layers found in coastal lake sediments were formed by the erosion and subsequent deposition landward of barrier/dune sand during overwash caused by hurricane landfall and preceding storm surge. Their results support the previous work on washover sediment origins done by Kraft (1971).

During the last decade the literature has seen a rise in quantitative investigations on beach changes caused by coastal storms. Studies using light detection and ranging (LIDAR) technology (Zhang et al., 2005) are allowing for the large-scale mapping of beach and barrier erosion, overwash, and washover deposition, both before and after major storm events, with remarkable (sub-foot) detail. Morton and Sallenger (2003) demonstrated that the lateral landward extent of washover penetration could range from 100 to 1000 m with volumes in excess of 10 m$^3$ per meter of beach. They calculated this penetration distance as a function of a multitude of interconnected factors: “washover penetration distances are controlled primarily by the interactions among heights and durations of storm surge relative to adjacent land elevations, differences in water levels between the ocean and adjacent lagoon, constructive and destructive interference of storm waves, and alongshore variations in nearshore bathymetry”. They stated that the greatest overwash and washover deposition potential occurs when there is shallow water, confined flow and high wind stress, stressing the importance of macro vs. micro tidal influences on overwash deposits.

Fletcher et al. (1995) used a mix of empirical field data and theory to investigate both the meteorological and oceanographic components of overwash process, specifically concentrating on the right front quadrant of Hurricane Iniki that struck the island of Kauai in September of 1992. They found that “overwash was principally a function of eye-relative position and orientation of the coast, tan theta (slope), the friction-controlled wave run-up, and the wave set-up”. There has also been a movement to model the storm surge itself. Using computational grids Cheung et al. (2003), modeled ocean, coastal, and atmospheric parameters to hindcast the storm surges for Hurricanes Iwa and Iniki and found good correlation between storm surge levels and overwash debris lines.

In a report on Hurricane Ivan (Stone et al., 2005), the oceanographic and geologic impacts of the hurricane were examined in tandem. Using offshore buoy measurements of wind speed and sea level pressure (SLP) Stone et al. (2005) reinforce the theory put forth by Hsu et al.
(2000) that maximum wave height, concentrated in the northeast vector of the storm, is not solely dependent on wind speed but on a storm’s central pressure. Stone et al. (2005) found that buoy data indicating the highest amounts of storm surge (in excess of 16 feet) occurred concurrent with the lowest measured central pressure. The wind speeds at the time of highest storm surge were only measured at 27 m/s, well below that needed to generate a 16+ foot storm surge. This study provides an excellent reminder of the danger of using wind speed only to calculate maximum potential storm surge height.

Overwash and the resulting washovers coupled with rising sea levels have the effect of widening the barrier islands and barrier beaches, and perpetrating landward migration (Wilby, 1938; McKee, 1959; Kraft, 1971; Schwartz, 1975), though the extent of which seems to be regionally defined (Stone et al., 1997; Zhang et al., 2002; Peirce, 1969). The role of vegetation in reducing overwash/washover and scouring as well as its rapid recovery has been well-documented and seems to be fairly well-understood (Stoddard, 1962; Vermeer 1963; McGowen and Scott, 1975). The penetration or lateral extent of overwash and resulting washover, however, seems to be dependent on a large number of regional factors in addition to vegetation cover: the orientation of the hurricane’s path and eye-wall in relation to the coast (Perkins and Enos, 1968; Fletcher et al., 1995), hurricane wind speeds and central pressure (Hsu et al., 2000; Stone et al., 2005), offshore bathymetry and offshore water depth, as well as angle of shoreline and slope, and dune/barrier height, and tidal stage (Morton and Sallenger, 2003; Fletcher et al., 1995, Leatherman et al., 1977b).

Most work done on overwash and washover fans are concentrated on barrier island deposits, with limited work concentrated on estuarine and non-oceanic deposits such as coastal lakes. Nevertheless, the majority of overwash and washover studies are in concert with the practices and paradigms of paleotempestology. The interpretation of washover deposits found in coastal lake sediment cores that are interpreted to be hurricane-generated correlates well with the morphological characteristics described by Hayes (1967), Kraft (1971), Leatherman and Williams (1977a), and Van Straaten (1965), who all note that washovers consisted of clean, well-sorted sand, and that the source of the washover sands are the beach face, an observation further enhanced by the phytolith studies of Lu and Liu (2005).

While most overwash/washover studies focus on subareal deposition, the shape and structure of the deposits seems not to vary when deposited subaqueously. Subaqueous washover
deposits exhibit a fan shape when in plan view (due to lateral disbursal from unrestricted horizontal constraints) and a wedge shape from the vertical section with an upward fining sequence (Hayes, 1967). The crenulated margin identified by Howard (1939) could prove useful as an aid in identifying future research sites, as well as identifying a lake’s threshold to past overwash and washover events derived from historical air photos.

When interpreting the paleo-hurricane history of a coastal lake one must take into account the landward migration of barrier islands or beach barriers due to overwash processes and sea level changes (Kraft, 1971; McKee, 1959; Wilby et al., 1938). This quandary was addressed by Donnelly et al. (2004), who through the use of aerial photos and historical maps showed a 300-400 m migration of the barrier beach at Brigantine, NJ since 1869, due to overwash from hurricanes and winter storms. Donnelly et al. (2004) suggest that due to this landward migration of the barrier beach, prehistoric washovers found in sediment cores in the modern era would have to have been carried a greater distance, indicating perhaps storms of greater intensity than those seen today. Overwash and washover is a worldwide phenomenon and almost always occur on transgressive coastlines (landward migration of the shoreline) (Leatherman, 1981). However, hurricanes are not worldwide phenomena; only occurring between ~30° north/south latitudes. Prior overwash studies have shown that it is possible for a strong winter northeaster to move about significant amounts of sediment (Schwartz, 1975; Leatherman, 1977b). So the question begs to be asked: how are paleotempestologists certain that the washovers they have identified are indeed caused by hurricanes? Leatherman (1981) noted that even extremely high spring tides can produce overwash, but that these occurrences are not significant in terms of material transported. While strong winter storm and high spring tides may account on occasion for overwash, they are seldom strong enough to carry and deposit washovers to the lateral extent of hurricane-induced washovers. So lateral transects when coring would identify weak (nearshore only) washover events. While the above section differentiated between overwash and washover based on Leatherman’s (1981) definition, the remainder of this dissertation will use overwash to describe the deposition feature deposited by hurricanes in an effort to conform to the terminology used in all other paleotempestological studies.

**Tsunami**

In a region such as the Caribbean where both hurricanes and tsunami occur, it is important to have a good working understanding of their similarities and differences as they
relate to the proxy record. It is imperative that the stratigraphic signature of each event is distinguished in order to preserve the integrity of the hurricane strike chronology calculation. Due to its geological setting, the Caribbean region is susceptible to earthquakes, volcanic eruptions, and submarine landslides, each with the potential for tsunami genesis. Based on historical documents, the Caribbean has seen more than 88 tsunami over the last 500 years (Lander et al., 2002). However, physical evidence (depositional features) is surprisingly limited and has only been identified for a small percentage of tsunami (Scheffers et al., 2005). This could be attributed to the infrequency of the events, poor preservation potential (coastal deposition), or even misidentification (Tappin, 2007). This small percentage has been well documented with studies done on tsunami deposits spanning the pan-Caribbean region; Aruba, Bonaire, and Curacao (Scheffers, 2002), Venezuela (Schubert, 1994), Bahamas (Kelletat et al., 2004; Hearty, 1997), Puerto Rico (Moya, 1999), St Lucia, Grenada, and Guadeloupe (Scheffers et al., 2005), Bermuda (McMurty et al., 2007), and Grand Cayman (Jones and Hunter, 1992).

Obviously not unique to the Caribbean, hurricanes and tsunami are global phenomena as the geographic distribution of study sites indicates. Although deposits are scarce, there are studies dedicated to tsunami deposits outside of the Caribbean (Scheffers and Kelletat, 2003; Tappin, 2007; Dawson and Stewart, 2007; Dominey-Howes et al., 2006; Benson et al., 1997; Clague et al., 2000; Nanayama and Shigeno, 2006). Literature on paleotsunami is rare, with only 5 percent of available tsunami literature focused on evidence of tsunami within the geological record (Scheffer and Kelletat, 2003). Since 2000 there has been a large amount of literature focusing on comparing and contrasting hurricane deposits with tsunami deposits and it covers a large geographical area from Portugal (Kortekaas and Dawson, 2007), Japan (Nanayama et al., 2000), Australia (Switzer et al., 2005; Nott, 2004), New Zealand (Cochran et al., 2005; Goff et al., 2004; Goff et al., 2000) as well as an excellent summary paper by Morton et al. (2007). Not surprisingly given the paucity of paleotempestological studies in the vicinity, a dearth of papers exists comparing and contrasting the two events for the Caribbean.

The studies done along coastal British Columbia (Benson et al., 1997; Clague et al., 2000) found evidence of tsunami in low energy settings, ruling out depositional mechanism other than tsunami. Event deposits identified via $^{137}$Cs and $^{14}$C dating (1964, AD 1700, AD 1600) all showed similar structure: large sheets of sand and gravel preserved in sequences of peat and mud. The sand contained marine fossils and they thinned and fined landward. Results from a
study done on the 1993 Hokkaido tsunami (Nanayama and Shigeno, 2006) show that the resulting tsunami deposition consisted of mainly cobbles, pebbles, and pebbly coarse sands. The initial similarities to hurricane overwash deposits are apparent. As expected, the mechanisms for deposition are similar: generation by force of the disturbance of the water column, propagation of offshore waters landward, and inundation of onshore areas (Dawson and Stewart, 2007). For example, tsunami deposits for Vancouver Island (Benson et al., 1997) have many of the same characteristics as hurricane deposits: landward tapering of depositional layer, fining of grain size landward, and marine microfossils in the overwash layer. However that is where the similarities end. Figure 2-2 illustrates common global features of tsunami deposits. When compared with the prior section on hurricane deposits one need only glance at the table to see the discernable difference in the two deposit types.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Interpretation</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unusually coarse sediment compared with the overlying and underlying deposit</td>
<td>i.e. The bed is an ‘event horizon’</td>
<td>1, 4</td>
</tr>
<tr>
<td>The bed includes many exotic fragments (e.g. plants, coconuts, beachrock, corals) from beach environment, which are absent from the overlying and underlying deposit</td>
<td>An unusual influx from a subaerial source</td>
<td>2, 6</td>
</tr>
<tr>
<td>A liquefied zone below or in the lower part includes rip-up clasts, injection and deformation structures</td>
<td>Indicates erosion from shoreline and emergent coastal environments</td>
<td>4</td>
</tr>
<tr>
<td>Irregular undulating erosional base, and flat-lying top (tempestites mainly have mostly sharp, flat-lying bases and irregular upper surfaces)</td>
<td>Indicates very high dynamic pressures from vibration and rapid deposition</td>
<td>2, 5</td>
</tr>
<tr>
<td>Inversely-directed imbrications; palaeooverwash alternates between landward and seaward directions</td>
<td>Erosion by strong currents in the early upflow stage results in irregular infilling of a scoured substrate (rather than irregular aggradation under combined-flow conditions typical of tempestites)</td>
<td>6</td>
</tr>
<tr>
<td>Cross-stratification includes mud drapes</td>
<td>A long period of oscillatory current reversals</td>
<td>2, 3, 6</td>
</tr>
<tr>
<td>Bed geometry should be more ‘sheet-like’, (rather than the typical pinch-and-swell (hummock-and-swale) of tempestites)</td>
<td>Deposition from calm conditions during long-period oscillatory flows</td>
<td>2</td>
</tr>
<tr>
<td>Evaporite and mud</td>
<td>Widespread runout (rather than substrate mobilisation)</td>
<td>7</td>
</tr>
<tr>
<td>Reverse- to normally-graded coarse-grained,</td>
<td>Initial deposition via basal traction flow followed by late-stage settling of coarser material from a laminar, inversely-graded debris-flow</td>
<td>4</td>
</tr>
<tr>
<td>Condensed mud or organic bed in the upper part</td>
<td>Deposition from water with a high mud content and with large amount of organic debris washed from the land</td>
<td>4</td>
</tr>
<tr>
<td>Scour-and-grading structure</td>
<td>Stagnant and brisk flow velocities alternated repeatedly</td>
<td>6</td>
</tr>
<tr>
<td>Multiple upward-fining units</td>
<td>Deposition from relatively thin but high velocity backwash flows</td>
<td>7</td>
</tr>
<tr>
<td>Bioturbation is absent in the bed, although this is common in the overlying and underlying deposits</td>
<td>Transport energy decreases with time during deposition of the tsunamiite — multiple units reflect successive waves</td>
<td>4</td>
</tr>
<tr>
<td>Good—excellent preservation of fossils</td>
<td>Rapid deposition from strong currents</td>
<td>2</td>
</tr>
<tr>
<td>Indicates rapid deposition and minimal reworking by later storms, longshore currents and other processes</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-2. A summary of paleo-tsunami sedimentary signatures. Taken from Dawson and Stewart, 2007.

Tsunami events are unique and they exhibit four dramatically distinct characteristics in their sedimentation patterns:

1. The mechanism. The passage of tsunami waves involves the entire water
column. Open water tsunami differ from wind-generated waves as they can “feel” the deep ocean sea floor (Dawson and Stewart, 2007). This allows for the accumulation of un lithified sediments from continental shelves, meaning that tsunami can transport a full range of sediments from fine clays to boulders (Yeh et al., 1993; Nott, 2004). While the depositional signature would naturally conform to the source material available locally, Nanayama and Shigeno (2006) found that the source of most of the depositional material was derived from >5.5 m depth and that the sand sheet facies was eroded during the run-up. This “feeling” of the ocean floor also results in the accumulation of distinct macro and micro fauna embedded within the depositional layer. Tsunami layers were found to be embedded with fish remains, massive shell debris, and especially interesting, an abundance of deep seabed (benthic) foraminiferal species picked up during the tsunami run-up (Dawson and Stewart, 2007; Nanayama and Shigeno, 2006).

2. Tsunami waves exhibit traction, a seaward backwash current (Dawson and Stewart, 2007). This is totally unique to tsunami and produces a very distinctive and complex sedimentation style. With multiple waves common, tsunami often keep finer material suspended throughout the water column and this results in a coupled band of coarse/fine grain sizes. It is this unique mechanism that enables some researchers to identify specific incidences of run-up and backwash (Nanayama and Shigeno, 2006). This phenomenon often leaves the deposit topped with a final ‘low energy layer” or “mud cap” that settles out during the final moments of the tsunami (Dawson and Stewart, 2007). In comparison, hurricane overwash has a gradual return flow at the end of the initial event (Morton et al., 2007) and typically has little or no backflow reworking the resulting sediments do not exhibit couplets within the internal stratigraphy of the resulting deposition layer. The coupling of fine/coarse grain sizes in the internal stratigraphy is a good indication that these are not hurricane deposits.

3. Tsunami deposits are typically massive in size and extend landward far in excess of storm-induced deposits (Dawson, 1994; Goff et al., 2004). Nanayama et al. (2000) differentiates the two by noting that typhoon (hurricane) related deposits display foreset bedding and consist of well-sorted marine sands while tsunami deposits consist of chaotic deposits of both marine and landward derived sediments (i.e. terrestrial detritus) resulting from their deep landward penetration and resulting backflow. Length of coast impacted by tsunami also greatly exceeds that of hurricanes, with tsunami typically impacting 10-10,000 km of coastline and hurricanes
only impacting 100-600 km (Morton et al., 2007). Given that, evidence of a singular event over a large swath of coastline could indicate a tsunami deposit.

4. Tsunami deposits are typically erosional at the point of contact, compared with the sharp contact with underlying organics of hurricanes (Dawson and Stewart, 2007; Morton et al., 2007).

The tsunami deposits specific to the Caribbean region do not appear to be different from the generalized characteristics described previously. Scheffers et al. (2005) identified paleo-tsunami relics on St Lucia, consisting of a thick stratum of chaotic mixture, including fine particles, gravel, and large boulders and large chunks of coral, some weighing up to 10 tons. Scheffers et al. (2005) note that “because of the thickness of the stratum, the size of the boulders incorporated, and the chaotic setting, we exclude hurricane waves as transport mechanism”. On Guadeloupe tsunami deposits were found consisting of sand and shell debris with Pleistocene rock and living fragments from the living coral reefs with boulders of up to 100 tons moved but not uplifted, often deposited into boulder ridges (Kelletat et al., 2004; Scheffers et al., 2005). Kelletat et al. (2004) found that tsunami waves accumulate chaotic depositional features without stratification or sorting of the fragments. So while no published literature exists directly comparing and contrasting Caribbean tsunami deposits with Caribbean hurricane deposits, it seem fairly clear that the distinctions that exist globally also hold true for the West Indies. What is striking is how the vast array of tsunami deposits are (ranging from coupled sand sheets to chaotic boulder, coral, gravel, and shell debris) in stark contrast to the descriptions of hurricane induced washovers (e.g., Kraft, 1971; Hayes, 1967; Van Straaten, 1965; Leatherman and Williams, 1977a) as consisting of clean, well-sorted sand, characterized by typical horizontal stratification with an upward fining sequence toward the front end of the fan.

**Late-Holocene Caribbean Sea Level Change**

The islands of the Caribbean are organized into three groups: The Bahama Islands, the Greater Antilles, and the Lesser Antilles, which together form the West Indies. The Lesser Antilles, also known as the Caribbees, are further broken into groups. To the north are the Leeward Islands and to the south the Windward Islands (i.e. downwind to a sailing ship). The Lesser Antilles can also be divided into the inner arc or Volcanic Caribbees and the outer arc or Limestone Caribbees, based on the principal rock types (Fairbridge, 1975). The Caribbees form a “curvilinear archipelago” along the boundary of the North American Plate and the Caribbean
This archipelago is a result of the slow (2 cm yr\(^{-1}\) for the last 2.4 Ma) westward subduction of the North American plate below the Caribbean plate (Picard et al., 2006). Evidence suggests that during the Tertiary the development of the Bahamian platform was considerably influenced by tectonic activity (Mullins et al., 1992; Freeman-Lynde and Lohmann, 1992) but has been considered to be tectonically quiescent since the late Quaternary, showing no signs of tectonically-induced deformations (Mylroie and Carew, 1995). The Caribbean basin as a whole is assumed to have been tectonically stable over the Holocene with a low chance of tectonic disturbance on the Caribbean plate and no chance of volcanism on the outer arc (Toscano and Macintyre, 2003; Digerfeldt and Hendry, 1987; Picard et al., 2006; Fairbridge, 1975).

Coastlines mark the boundary between the sea and the land, and changes in the position of this boundary landward (transgressive) are considered to be periods of sea level rise and migrations of the coastline seaward (regressive) are considered to be periods of falling sea levels (Masselink and Hughes, 2003). Short-term changes in sea levels are averaged, giving a constant value termed mean sea level (MSL). MSL falls into one of two categories: eustatic and relative. Eustatic sea level change is global in scope, ignoring changes at the regional and local levels (topography, bathymetry, geology). Eustatic sea level is most often calculated by changes in total ocean water volume (Masselink and Hughes, 2003) and causal fluctuations are generally on the order of macro-scale: orbital forcings (Milankovich cycles), glacio-eustasy, and thermal expansion. Regional changes are due to more local-scale factors: isostatic balance/rebound, geologic subsidence, and tectonic activity. In this section only Caribbean-wide trends (eustatic) will be examined, regional or localized seal level will be looked at in further detail in the environmental history sections of Chapters 5, 6, and 7.

Sea level change can be interpreted via multiple proxies: corals, peat, as well as the geochemical analysis of ice and ocean cores (\(\delta^{18}\)O). Historically sea level high stands are relatively easy to locate (relict scarps and dunes, etc…), whereas sea level low stands are more difficult, as they are generally underwater and not easily accessible (Masselink and Hughes, 2003). In regions like the Caribbean, interpreting sea level low stands is often done through the interpretation and dating of corals (sclero-chronologic) and is a common technique used in the reconstruction of past sea level change (Toscano and Macintyre, 2003; Fairbanks, 1989; Mylroie and Carew, 1995; Taylor et al., 1985; Blanchon et al., 2002). Growing in horizontal bands, corals can be cored and dated chronologically, giving excellent records of historical sea level
change. Most often used is Acropora palmate, a fairly prolific species in reef crest communities of the West Indies. A. palmate is usually constrained to the upper five meters of water and has a known growth rate of up to 14 mm year\(^{-1}\). Thus, it can be used as a continuous proxy for sea level rise minima (Fairbanks, 1989). Corals, however, can only be used as an estimate for sea level minima as they are subaqueous in nature and cannot be used to reliably interpret sea level increases in excess of their growth rates. When using sclero-chronologic techniques, it is important to take into account the oceanic reservoir effect, a problem researchers often fail to consider (Toscano and Macintyre, 2003). The oceanic reservoir effect is a phenomenon that is common throughout the western tropical Atlantic and Caribbean and can lead to the underestimation of coral based dates by \(\sim 400\) years (Toscano and Macintyre, 2003). These erroneous dates need to be corrected in order to facilitate comparisons with terrestrial proxy data. “In order for \(^{14}\)C age data from mixed-layer marine samples (corals) to be comparable with terrestrial \(^{14}\)C chronologies and absolute chronologies from TIMS U-Th data, all \(^{14}\)C ages from shallow marine corals must be corrected for the \(^{13}\)C /\(^{12}\)C difference between atmospheric CO\(_2\) and the \(\Sigma\) CO\(_2\) of the mixed layer or surface ocean, which is not in isotopic equilibrium with (i.e. is older than) the atmosphere” (Bard, 1988).

For the reconstruction of sea level maxima, researchers look to mangrove peat (dendro-chronologic) which relies mainly on the interpretation of red mangrove (Rhizophora mangle) peats. Inter-tidal communities or swamp forests composed of Conocarpus erectus, Cladium jamaicense, and Rhizophora mangle all produce peat deposits that are useful for \(^{14}\)C dating and have a well-defined relationship to tidal range and sea levels (Toscano and Macintyre, 2003). These inter-tidal communities are formed at or within one meter of mean sea level (Digerfeldt and Hendry, 1987) and sea level curves based on the peats are considered a maximum estimate of sea level rise. Peat dating is not without problems. There is the age-reducing effects of root contamination on the peat sediment dates, and sediment compaction can also be a problem with downward displacement, both yielding samples that are too deep for their age (Digerfeldt and Hendry, 1987; Lighty et al., 1982). With coral levels restricted to heights below sea level and mangrove peat at inter-tidal or higher, reconstructed sea level curves bracketed by these two proxies should effectively delineate the positions of Holocene seas.

Sea levels in the Caribbean during the last glacial maximum are thought to have been \(~121 \pm 5\) meters below present levels (Fairbanks, 1989). Beginning around 18,000 ka the earth
was moving from a period of glacial dominance into an interstadial and the warming global temperatures released large amounts of water previously stored in ice sheets and glaciers into the world’s oceanic basins, resulting in a massive worldwide sea level rise. This ice melt and subsequent sea level rise, termed the Holocene transgression, was very rapid at the onset. During the early Holocene (~12,000 yr BP) the sea level rise was estimated to be around 2 cm per year. This rapid rate began to slow by the mid-Holocene (~6000 yr BP) as sea level rise began to slow dramatically with levels reaching near modern-day levels shortly after (MacKinnon and Jones, 2001; Diggerfeldt and Hendry, 1987). A study done by Toscano and Macintyre (2003) on sites around the Caribbean basin (Bahamas, Belize, Puerto Rico, Jamaica, Antigua, and Martinique) based on mangrove peats and coral proxies coincide well with the generally accepted model of the Holocene transgression for the Caribbean. Using Acropora palmata and Rhizopora mangle, Toscano and Macintyre (2003) reconstructed an 11 kyr sea level curve and found three distinct curve segments: From 10,000 to 7,700 yr BP sea level rose ~ 5.2mm yr$^{-1}$ followed by a decrease in rate from 7,700 - 2,000 yr BP to ~ 1.47mm yr$^{-1}$ and finishing up with a rate of ~ 0.93 mm yr$^{-1}$ from 2.0 –0.38 ka (400 years ago).

A deep core was taken from Barbados at 113.8 m below present sea level and was dated to 17,100 yrs BP (Fairbanks, 1989). Resulting oxygen isotope data ($\delta^{18}$O) indicted that during the last deglaciation there were two periods of rapid sea level rise contained within the Holocene transgression. A first meltwater pulse (MWP) event occurred at 14,200 cal yr BP, and a second one at 11,400 cal yr BP produced an overall sea level rise of 24-28 m 1000 yrs$^{-1}$ (Toscano and Macintyre, 2003; Fairbanks, 1989). Based on the data from Barbados (corals and $\delta^{18}$O), Fairbanks (1989) found that between 17,100 and 12,500 yr BP sea level increased rapidly by about 20 m (Fig 2-4). Sea level rise then stalled at around 11,000 yrs BP due to the Younger Dryas chronzone, and stayed minimal until around 10,500 yr BP before returning to a period of transgression. In a study of 55 samples from Jamaican peat sediment cores, Digerfeldt and Hendry (1987) found sea level changes for Jamaica to be in concert with the previous Caribbean studies as is apparent from their resulting sea level curve (Fig. 2-4). In a study from Black River and Negril, Jamaica, using 145 samples from both Rhizophora mangle and Acropora palmate Toscano and Macintyre (2003) define a sea level curve in concert with the majority of other studies (Fig 2.3). Nearly all Holocene sea level curves for the Caribbean adhere to the same trend and there is great uniformity within the literature. Following the last glacial maximum, a period
of rapid sea level occurred rise early in the Holocene following the melting of the ice sheets and a slowing occurred around mid-Holocene (~6000 yr BP) and continued to slow until reaching modern day levels. There is no published evidence of a sea level high stand during the Holocene found for the Caribbean.

All studies (Toscano and Macintyre, 2003; Fairbanks, 1989; Digerfeldt and Hendry, 1987; Mylorie and Carew, 1995; Taylor et al., 1985; Blanchon et al., 2002) show a minimal (>4 m) sea level rise for the last 4000 yr BP for the Caribbean. Obviously, local tectonic and geological features affect localized sea level reconstructions and site-specific studies are discussed in more detail in each study sites chapter.

![Graphs showing sea level changes](image)

Figure 2-3. Caribbean sea level changes throughout the Holocene compiled from various sources.

Late-Holocene Caribbean Climate Change

Holocene climate trends for the pan-Caribbean region is typified by a period of rapid amelioration following the last glacial maximum (18ka). This climatic warming was briefly interrupted by the onset of the Younger Dryas climatic reversal (12 ka) before resuming its prior warming trend (Fig 2-4). During the mid to late-Holocene there was a thermal maximum with temperatures warmer than today.

Localized studies indicate that prior to the Younger Dryas Caribbean climate was cool and dry (Higuera-Gundy et al., 1999r; Street-Perrott et al., 1993; Hodell, et al., 1991) reaching the lowest temperatures with the Younger Dryas. The Younger Dryas marked the peak of early-Holocene cooling and was followed in the mid-Holocene by a period of maximum warmth and moisture, the mid-Holocene thermal maximum (Higuera-Gundy et al., 1991; Haug et al., 2001). Following the thermal maximum temperatures began a slow but steady decline. Also following
the thermal maximum was a long period of decreasing precipitation for the entire pan-Caribbean region. Regional reconstructions reveal that a period of precipitation minima was reached throughout the Caribbean. However, the minima were experienced within different time frames depending on regional geographic location. Proxy records ($^{{18}}\text{O}$) established from cores taken from Lake Miragone, Haiti (Hodell et al., 1991), show this period of aridity to occur around 3,200 yr BP. Bertran et al. (2004) found the same period of aridity in cores from Grande Case, St Martin, but with a slightly different date (~4,200-2,300 yr BP) followed by a wet phase from 2300-1150 yr BP. Using palynological reconstruction on sediments from cores taken from a Blue Hole in the Bahamas, Kjellmark (1996) found that the Caribbean was wetter than present before 3200 yr BP but was followed by a late-Holocene dry period based on an increase in dry shrub taxa from 3200 to 1500 yr BP. Deep ocean cores taken from the Caricao basin (Higuera-Gundy et al., 1991) place the period of aridity around 3800-2800 yr BP. Based on proxy data from O, C, and Sr isotopes Peros et al. (2007) showed that during ~6,800-4,800, there were high rates of evaporation for Cuba, indicative of a period of aridity, but they make no claim as to a period of precipitation minimum. Localized differences notwithstanding, during the mid-to late-Holocene a pattern of climate change seems to be a circum-Caribbean occurrence and it might have affected the majority of the West Indies similarily. So ignoring high-frequency, localized variations, the general consensus was that there existed a period of reduced precipitation and an increase in aridity between 3200-1500 yr BP for seemingly the entire Caribbean (Brown and Cohen, 1985; Hodell et al., 1991; Burney et al., 1994; Kjellmark, 1996; Bertran et al., 2004; Higuera-Gundy et al., 1991). It is also the general consensus that this period of aridity was most likely due to a southward displacement in the ITCZ (Haug et al., 2001; Hodell et al., 1991, 2005). A second period of precipitation minima was found to have occurred for the Caribbean at
the onset of the Little Ice Age (LIA) spanning the mid 15th century from AD 1400-1500 (550-200 Cal yr BP). During the LIA the Caribbean experienced a period of aridity as well as sea surface temperature change as much as 3° C below today (Hodell et al., 2005). Haug et al. (2001) reporting on titanium concentrations in oceanic cores of the Cariaco Basin also found a period of reduced precipitation during the LIA (550-200 BP) during the same time frame as reported by Hodell et al. (2005) from the Yucatan Peninsula, Mexico.

This mid-Holocene aridity coincides well with the hypothesis of Liu and Fearn (2000a) who contend that there was a southward shift of the long-term position of the Bermuda High from 3,800-1000 yr BP. This hypothesized southward positioning of the Bermuda High correlates well with a period of increased aridity for the Caribbean region. The high pressure and its subsequent subsiding air and stabilizing effect on the atmosphere could well account for the warm, arid episode in the Caribbean.

The Bermuda High Hypothesis

To date paleotempestological studies have been concentrated on determining the temporal variability of catastrophic hurricanes along the U.S. Gulf coast (Liu, 2004; Liu and Fearn, 1993, 2000a, 2000b) and Atlantic coast (Scott et al., 2003; Collins et al., 1999; Donnelly et al., 2001a; Donnelly et al., 2001b; Donnelly et al., 2004). Preliminary comparisons of proxy records from both coasts seem to show an inverse relationship in terms of their hurricane landfall frequencies. Studies done along the U.S. Gulf coast have revealed a period of increased hurricane activity during ~3400-1000 14C yr BP, which is bracketed by periods of decreased activity during 5000-3400 14C yr BP and the past ~1000 years (Liu and Fearn, 2000a). The “hyperactive period” of 3400-1000 14C yr BP is evidenced by a dramatic increase in the frequency of hurricane-deposited sand layers found in coastal lake sediments along the Gulf coast (Liu, 2004). Conversely, studies done along the Atlantic coast seem to show the opposite pattern, with a period of increased activity over the last ~1000 yr BP, and a period of lessened activity during 2000-3000 14C yr BP. The hypothesis that seeks to explain this anti-phase relationship of hurricane landfall frequencies is termed the Bermuda High hypothesis. Liu and Fearn (2000a) hypothesize that during the Gulf coast’s hyperactive period of the late Holocene (3400-1000 14C yr BP) the Bermuda High was located southwestward of its present position due to neoglacial cooling and a southward shift in the jet stream. This southwesterly shift in the position of the Bermuda High would redirect the paths of hurricanes, leading to an increase in
hurricane landfalls along the Gulf of Mexico coast (Fig. 2-5). Conversely, when the Bermuda High is in a more northeasterly position, the Atlantic coast experiences more hurricane strikes. Paleotempestological studies for sites in Central America and the Caribbean are crucial to understanding these shifts in hurricane frequencies on a regional basis. Therefore, in an effort to test the Bermuda High hypothesis and remedy the paucity of data for Central America and the Caribbean region, a number of studies have been undertaken over the last two years in Central America. These ongoing studies include sites in western Honduras (Knowles, 2004), eastern Honduras-Miskito coast (Liu et al., 2006), and Belize (McCloskey, 2004). However, only two studies have been done for the Caribbean region—Turks and Caicos (Knowles, 2004), and Puerto Rico (Donnelly, 2005). The northern Caribbean, while unrepresented, is well-suited for this type of study with a multitude of low energy coastal lakes and ponds, well-situated to receive allochthonous sediments from tropical cyclone strikes (Donnelly, 2005).

Further work on this hypothesis (Knowles and Leitner, 2007 (Chapter 3)) investigates the modern relationship between the Bermuda High (BH) as interpreted from the North Atlantic Oscillation (NAO) index and its effect on hurricane tracks using spatial analysis and kernel density surface interpolation techniques in a geographic information system.

Figure 2-5. Illustration of the Bermuda High hypothesis. Taken from Knowles and Leitner, 2007.
Carbonate Sedimentation

Sedimentological research for the Caribbean region is unique and offers new challenges for the study of paleotempestology. A distinctive sedimentary environment, Caribbean salt ponds have received little scientific attention and the associated sedimentary regimes are poorly understood (Jarecki and Walkey, 2006; Mackenzie et al., 1995; Dix et al., 1999). The physical and chemical conditions of Caribbean lakes are mostly governed by a hydrologic balance of inputs (precipitation, groundwater, ocean overwash) and outputs (evaporation, groundwater seepage), as well as basin geology, biologic activity, and climate (Saenger et al., 2006). All of the research sites for this study were shallow (<1.5 m) hypersaline (>50‰) coastal lakes that are generally formed in isolated basins where outflow is nominal and evaporation exceeds inflow (Scoffin, 1987). The salinity in Caribbean hypersaline lakes is known to fluctuate from 50-300 ‰ (Pinckney et al., 1995), and these fluctuations are especially high in shallow water bodies where the high surface to volume ratio makes them especially sensitive to seasonal weather pattern and environmental changes (evaporation and dilution) (Jarecki and Walkey, 2006).

Hypersaline lakes and the surrounding mangroves are the dominant form of wetlands in the Caribbean region (Jarecki and Walkey, 2006). Given their position at or near sea level, hypersaline coastal lakes are excellent indicators of high-frequency events or changes, as their water balance and chemistry responds quickly to sea level or local climate (Dix et al., 1999). Saline lake deposits range from laminae of cyanobacterial mats or carbonate muds, to bulk carbonates (CaCO₃) and, where extremely saline, evaporites (gypsum (CaSO₄.2H₂O), halite (NaCl). Hypersaline ponds are dynamic systems and evolve through stages in a natural hydrological progression, from near-marine systems (lagoonal) to near-terrestrial systems and finally ending up as a terrestrial mangrove forest (Saenger et al., 2006). Therefore, sediment cores are expected to indicate an upward vertical succession, displaying a transition from grey sub-tidal mud with marine fossils to tan/brown inter-and supra-tidal algal laminations, with evidence of evaporates and eventual terrestrial sediments (Scoffin, 1987).

Falling sea levels or isolation of coastal lakes from marine or lagoonal connections allow for the formation of these hypersaline lakes and the subsequent deposition the first sediment regime-carbonate muds, and laminated cyanobacterial mats (Saenger et al., 2006). Laminated cyanobacterial mats are the primary producers in the nutrient cycle of hypersaline lakes and are dominated by prokaryotic (cyanobacterial) communities (Paerl et al., 2003). Growth of the
laminated cyanobacterial mats can exist in salinities ranging from saline to hypersaline, occasionally as far as gypsum saturation. However, laminated cyanobacterial mats tend to fare better when the lake salinities are reduced, as extreme salinities tend to decrease productivity and inhibit growth, in some cases to near dormancy (Bebout et al., 1993; Rouchy et al., 2001). This decrease in productivity under extreme salinities is most likely due to an increase in osmotic stress, where as laminated cyanobacterial mats in ideal salinities would be more governed by nutrient limitations (Pinckney et al., 1995). Favorable conditions for the growth of laminated cyanobacterial mats are high insolation and temperature, largely open to the atmosphere (read: shallow) and lack of carbon limitation (Trichet et al., 2001). The presence of these laminated cyanobacterial mats represents the transition of normal marine to evaporitic environments (Rouchy et al., 2001).

The second regime present in coastal saline lakes is deposition of bulk carbonate sediments. It is thought that these CaCO₃ mineral sequences are derived from authigenic precipitation, possibly related to climate changes and changes in lake chemistry or depth. Carbonate deposition generally occurs in salinities ranging from saline to hypersaline, even nearing halite precipitation levels, though mostly in and around 80‰ (Rouchy et al., 2001). Occurring in near-identical salinities to the laminated cyanobacterial mats, the major difference is water depth and the availability of source minerals for CaC0₃ precipitation. A tidal connection or frequent sea water inundations or large amounts of meteoric precipitation could bring in eroded minerals from the surrounding carbonate platforms. Trichet et al, (2001) found that after heavy rains or sea water inundation, the following high rates of evaporation could lead to the supersaturation of calcite and argonite and the eventual dissolution/precipitation of calcium carbonate, as well as suspended growth of the cyanobacterial benthic populations. The amount of carbonate deposited is dependent on the HCO₃/Ca + Mg ratio, which, when in molar equilibrium, can precipitate out CaCO₃ (Scoffin, 1987). In some cores the two regimes have been found in alternating sequences. In a study done on hypersaline lakes in the Republic of Kiribati, Saenger et al, (2006) found that bacterial mat layers were incorporated throughout sediments, not only at the surface: “Underlying the upper bacterial mat (consisting of red, green or brown sub-millimeter laminations) more laminated sequences extended continuously from the surface and were periodically separated by bulk mineral-mat amalgams”. As the salinity of the lakes increases past the threshold of the laminated bacterial mats, carbonate precipitation sequences
deposition are replaced by the accumulation of white evaporite deposits (Saenger et al., 2006). As salinities increase past 175‰, gypsum and halite are deposited, and once passing 300‰, sodium chloride (NaCl) will accumulate in the most hypersaline of lakes (Saenger et al., 2006).

In summary, hypersaline lakes have three distinctive alternating lithological regimes: carbonate, organic, and evaporitic. Laminated organic-rich cyanobacterial mats and carbonate muds typifying a wide range of salinities from brackish to hypersaline are mainly forming in shallow water conditions. A bulk carbonate depositional regime forms under marine/inter-tidal or deeper-water conditions as high rates of evaporation concentrate calcite and aragonite to the point of CaCO3 precipitation. And finally, an evaporitic regime persists in which extreme lake salinities facilitate the accumulation of salts (gypsum and sodium-chloride) to be deposited on the lake bottom. It is believed that the deposition of each regime or facies is controlled by changes in the lake’s physico-chemical makeup, which in turn is essentially controlled by climate and its effect on the hydrologic balance (Trichet et al., 2001). Therefore, it is possible to reconstruct the historical climate and hydrologic state of the lake through the interpretation of the depositional facies (Purdy and Imbrie, 1964).

These tropical Caribbean shallow lakes are perfect for paleotempestological studies, due to their chemical stratification and intense microbial activity, both of which help create anoxic conditions that limit bioturbation and help to preserve sedimentary facies (Bertran et al., 2004; Dix et al., 1999). A new and possibly useful area that is only beginning to be explored is the effect of hurricanes on the growth of the laminated cyanobacterial mats. Using the tidal overwash associated with hurricane Floyd (1999), Paerl et al. (2003) found in a study on San Salvador Island, Bahamas, that the familiar depositional sand layer deposited onto the mats could serve as a stratigraphic marker for the estimation of mat accretion rates. Paerl et al. (2003) found that the increased influx of meteoric precipitation in conjunction with the hurricane had a “freshening effect” on the lake, reducing salinities from 142 ‰ pre storm to 85 ‰ post storm, a trend that was independently documented in the British Virgin Islands by Jarecki and Walkey (2006). Several lines of evidence indicate that due to stimulation of photosynthesis and N2 fixation there was substantial mat growth and accretion following the so called “freshening” effects of the 1999 hurricanes. It was also determined that from mid-September to November 1999 tropical storm activity accounted for nearly 40% of the islands mean annual rainfall. Post storm mat accretions of 1.5 cm yr⁻¹ was far greater than prior measured accretion rates (0.2-0.4

Does good mat accumulation allow for the assumption of more storm impacts and/or a higher influx of meteoric precipitation? Could mat productivity become a possible proxy for determining periods of excess moisture or aridity? One can certainly assume the latter to be true. In general the results of Paerl \textit{et al.} (2003) show that the “freshening” events associated with hurricanes and major storms alleviate the stresses on primary productivity and N\(_2\) fixation that begins to take place in hypersaline waters exceeding 70 \%. Perhaps even the hurricane overwash (averaging in the Caribbean at 35 \%) could have the effect of “freshening” these hypersaline lakes? At any rate in the absence of overwash sand layers perhaps an increase in the mat accumulation could be used as a proxy indication of more frequent tropical storm activity to correlate to nearby lake with the familiar overwash fan deposition.

**Mollusks**

Any review of Caribbean carbonate sedimentation would be remiss without a brief review of the omnipresent mollusks. There are eight classes of mollusks; Aplacophora, Scaphoda, Polyplacophora, Monoplacophora, Scaphopoda, Cephalopoda, Gastropoda, and Bivalvia. The latter two are found in the sediments of the cores taken for this project. Gastropoda (univalves) which include snails, periwinkles, whelks and conchs, are numerically the largest and most diverse of the eight and range from aquatic (marine and fresh) to terrestrial. Bivalvia, (Pelecypoda), which include clams, mussels, oysters, scallops and cockles, are exclusively aquatic with the majority being marine in origin. Species diversity in Bivalvia is far less than the gastropods, but the bivalves outweigh all other classes in sheer number of individuals (Andrews, 1994; Morris, 1975). Shells are classified by family. Identification is determined by the anatomy of the mollusk (predominantly the external shell characteristics). Identification is a difficult task as there can be great variation in color and shape within a species (Andrews, 1994). There are many factors that contribute to the differences in shell

![Figure 2-6. Morphological features of a gastropod taken from Morris, 1975.](image)
characteristics: age, sex, stage of lifecycle, habitat, and diet (Abbot, 1974). *Gastropoda* (stomach footed) are identified by the morphology of their asymmetrical calcareous shell or univalve based on shape and size of the shell. The shell itself is broken up into numerous parts (Fig. 2-6). A heliocone, the shell is an expanding tube that increases in size from its original end (apex) or the nuclear whorl towards its anterior canal (Abbot, 1974). Size is measured at 90° from either axes to get width and length. Differences in whorls (color, spacing), spires, lips, and canal (size/shape) are all used in differentiating between genera. Through the identification of the gastropods and their associated ecological tolerances it should be possible to infer valuable environmental information governing their presence within the core.
CHAPTER 3 VISUAL REPRESENTATIONS OF THE SPATIAL RELATIONSHIP BETWEEN BERMUDA HIGH STRENGTHS AND HURRICANE TRACKS

Introduction

Hurricanes play a significant role in the lives of the people living in high-risk areas, negatively impacting on all scales from the personal to the national. The ever-increasing concentration of people and properties in coastal areas has raised a serious question regarding hurricanes: Are there changes in the periodicity or return periods of hurricanes, and, if so, what is causing these changes? Paleotempestology, allows us to look to the past to interpret long-term changes in hurricane landfall frequencies that far exceed the scope of modern instrumental data. By looking to the proxy record, paleotempestology allows for the interpretation of changes in hurricane landfall patterns spanning millennia.

Previous paleotempestological studies done on sediment cores taken from coastal lakes and marshes along the U.S. Gulf and Atlantic coasts show an anti-phase relationship in hurricane landfall frequencies between the two coasts. U.S. Gulf coast studies (Liu, 2004; Liu and Fearn, 1993; 2000a; 2000b) have shown that there was a period of increased hurricane activity during approximately 1000-3400 yr BP and decreased activity from 6000-3400 yr BP, as evidenced by a dramatic increase in the frequency of hurricane-deposited sand layers found in the lake and marsh sediments (Fig. 3-1). Studies completed along the Atlantic coast (Scott et al., 2003; Collins et al., 1999; Donnelly et al., 2001a; Donnelly et al., 2001b; Donnelly et al., 2004; Lu and Liu, 2005) indicate the opposite, a period of increased hurricane activity during the last 1000 yr BP and a period of relative inactivity during 1000-3400 yr BP.

The hypothesis that seeks to explain this anti-phase relationship in hurricane landfall frequencies is termed the Bermuda High hypothesis. Liu and Fearn (2000a) hypothesize that during the Gulf coast’s hyperactive period of the late Holocene (3400-1000 yr BP) the Bermuda High (also known as the Azores High or Atlantic Subtropical Anticyclone) was located southwest of its present position due to neo-glacial cooling and a southward shift in the jet
stream. This southwesterly shift in the position of the Bermuda High would redirect the paths of hurricanes, leading to an increase in hurricane landfalls along the Gulf of Mexico coast. Conversely, when the Bermuda High is in a more northeasterly position, closer to Bermuda, the Atlantic coast experiences more hurricane strikes (Fig. 3-2). The Bermuda High is thought to have a substantial influence on the direction and path of hurricanes (Liu, 2004; Elsner et al., 2000; Elsner and Kara, 1999), but to date this relationship has not been tested visually or quantitatively.

The purpose of this research is to investigate the effect the Bermuda High has on hurricane tracks, testing the Bermuda High hypothesis of Liu and Fearn (2000a). If the Bermuda High is indeed a factor in controlling the millennia-scale spatial shifts in hurricane landfall, a spatial relationship should be found between today’s Bermuda High strengths and today’s hurricane directions and tracks. Using different visualization techniques, this research seeks to explore, whether a spatial relationship exists between the modern-day Bermuda High strengths and the direction and path of modern-day hurricanes (Knowles, 2006). ArcView® GIS (ESRI, 1999), CrimeStat III (Levine, 2004), and Surfer (Golden Software, 2003) were used to visualize such possible relationships.

**Background**

Hurricane tracks are discrete linear features that have a starting and an end point. The logical map type to visualize such tracks is the so-called flow map, which shows linear movements between places. Hurricane tracks can be symbolized with flow lines of either uniform (no distinction is made between different hurricane strengths) or increasing line thickness to indicate differences in hurricane strengths (from tropical storms to Category 5 hurricanes). Flow maps became especially popular in economic geography for mapping patterns of distribution of economic commodities, people (passengers), and any number of measures of traffic densities (Dent, 1999). Only recently has software for automated flow mapping become
available. Examples include CrimeStat III (Levine, 2004), Tobler’s Flow Mapper (Tobler, 1987), ArcGIS® (ESRI, 2005), and generatelines.dll, a tool that generates lines between locations. CrimeStat III (Levine, 2004) and Tobler’s Flow Mapper (Tobler, 1987) can be downloaded from the following websites: http://www.icpsr.umich.edu/NACJD/crimestat.html/ and http://www.csiss.org/clearinghouse/FlowMapper/. The generatelines.dll tool is included in Groff and McEwen (2006), who also provide a detailed comparison of the three software packages. Unfortunately, flow maps are very poor at visualizing large amounts of flow lines that are spatially clustered, overlap, and criss-cross each other. Such a dense display of flow lines often masks any potential spatial patterns in the data.

An alternative method to visualize hurricane tracks is first to split them into equally short segments and then replace each segment with a point placed at the center of each segment. Points can then be summarized for each cell of a regular grid placed on top of the study area. Such point densities can then be easily visualized with a choropleth map, which is defined by the International Cartographic Association as “a method of cartographic representation which employs distinctive color or shading applied to areas other than those bounded by isolines. These are usually statistical or administrative areas” (Meynen, 1973). In general, the choropleth map is easily understood by map readers and is therefore a popular visualization method. However, very “different-looking” choropleth maps can be derived from the same data depending on the classification method, areal symbolization, and size of administrative areas used. Any introductory cartographic textbook will provide a detailed discussion of the pitfalls of choropleth mapping (Dent, 1999; Slocum et al., 2005; Campbell, 2001; Muehrcke et al., 2001; Robinson et al., 1995). In addition, the choropleth map assumes a uniform distribution within the same statistical area and can show rather abrupt density changes at the borders between an area and its neighbors.

This latter drawback can be avoided when the center points of all hurricane segments are visualized using the kernel density interpolation method. This method creates smooth transitions between different density values. The kernel density interpolation method has become a popular visualization method where the volume of incidents is relatively large and spatially clustered (Brunsdon et al., forthcoming). It has, for example, been applied to investigate spatial and temporal changes in the retailing sector (Leitner and Staufer-Steinnocher, 2002); the dynamics of fire incidents (Corcoran et al., 2005); infant health analysis (Curtis and Leitner, 2006); crime hot
spots (Eck et al., 2005); and concentrations of Foot and Mouth Disease in South America (Curtis et al., 2005). A detailed discussion of how the method works is provided below. In general, kernel density interpolation results can be visualized in the form of density maps (similar to choropleth maps but with smooth transitions between neighboring grid cells), isometric maps, or actual 3-D surfaces visualized with the popular fishnet (wire frame) structure. The isometric map is generated from data that occur at points and is one distinct form of the isarithmic map. Isarithmic mapping involves mapping a real or conceptual three-dimensional geographical volume with quantitative line symbols (Dent, 1999). Finally, an actual 3-D surface can be enhanced by draping additional information, such as the topography or shaded relief, over the original wire frame structure.

**Data and Study Region**

Hurricane data were downloaded from the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center website (http://hurricane.csc.noaa.gov/hurricanes/index.html). The data set consisted of every storm (ranging from extra-tropical depression to Category 5 hurricanes) that occurred during the last 150 years. Each storm consisted of a multi-vectored track, divided into 6-hour segments (over 35,000 records). The attribute data associated with each 6-hour segment included, among others: the storm’s name, wind speed, category, and pressure; the day, month, and year of the storm segment’s occurrence; and the segment’s location, expressed as x- and y-coordinates. For this project, a subset that included only hurricanes after 1947 (over 17,000 records) was also collected, since 1947 is considered to be the onset of reliable measured data. The 17,000+ records represented a total of 577 hurricanes.

In addition to hurricane tracks, data measuring the strength of the Bermuda High needed to be collected. While no direct measure of the Bermuda High exists, its strength can be interpreted from the North Atlantic Oscillation (NAO) index. The NAO is a coherent north-to-south seesaw pattern in sea-level pressures between Iceland and the Azores, and when pressures are low over Iceland (Icelandic Low), they tend to be high over the Azores (Azores High) and vice versa. Simply put, when the Icelandic Low is strong (low pressures), the Bermuda High is strong (high pressures), resulting in a positive NAO index. NAO index data were taken from Portis et al. (2001), who calculated such data as the difference in the normalized sea-level pressure anomalies at the locations of maximum negative correlation between the sub-tropical
and sub-polar North Atlantic Sea Level Pressure (SLP). This means that the stronger (more positive) the NAO index, the stronger the Bermuda High; and the weaker (more negative) the index, the weaker the Bermuda High. The Portis et al. (2001) NAO index values range from -3.51 to +3.51 and were manually added to the database of the 17,000+ hurricane vectors.

**Visualization of Hurricane Tracks**

Geographic visualization of all +17,000 storm vectors as line segments in the same map resulted in a very dense display, which hid any potential spatial patterns in the data (Fig. 3-3). For this reason, a subset of the NAO index data was created that separated a “weak” Bermuda High category, with NAO index values smaller than -2.51, from a “strong” Bermuda High category, with NAO index values larger than +2.51. This had the effect of removing any moderating data and leaving only storm tracks that were associated with very large or very small Bermuda High strengths. This subset resulted in 1,201 segments (47 hurricanes) associated with a “weak” and 825 segments (41 hurricanes) associated with a “strong” Bermuda High, respectively, for a total of 2,026 segments (88 hurricanes).

Geographic visualization of the subset of storm vectors associated with only the “weak” and “strong” Bermuda High categories resulted once again in a very dense map display that hid any spatial patterns. For this reason, each hurricane vector from this subset was converted into a point that was placed at the center of each 6-hour storm vector. This resulting point coverage was used in all subsequent visualization efforts.

**Figure 3-3. Visualization of all 577 hurricanes that have reached the Atlantic Ocean and the Gulf of Mexico since 1947.**
**Choropleth Map**

Visualizing the point coverage alone did not show any improvement over the previous two vector displays in terms of revealing any specific spatial patterns. However, overlaying a regular grid on top of the point coverage, counting the number of points falling into each grid cell, classifying the resulting “points-per-grid-cell” densities, and visualizing the densities with a sequential color scheme (Brewer, 1994) resulted in a much more useful visual display. This approach was carried out at three different grid cell sizes: 1° latitude/longitude, 2.5° latitude/longitude, and 5° latitude/longitude (Fig. 3-4). While spatial patterns started to emerge using this choropleth method approach, maps still lacked smooth transitions between grid cells at all three resolutions. To further improve the smoothness of the visualization, the kernel density interpolation method was applied to the original point coverage.

**Figure 3-4. Choropleth mapping of hurricane density within a 2.5° latitude / longitude grid cell size.**

**Kernel Density Interpolation**

The kernel density estimation is an interpolation technique that generalizes individual point locations or events, \( s_i \), to an entire area and provides density estimates, \( \hat{\rho}(s) \), at any location within the study region \( \mathcal{R} \) (Bailey and Gatrell, 1995; Burt and Barber, 1996; Fischer et al., 2001). Density estimates are derived by placing a symmetrical surface, called the kernel function, \( \kappa(\cdot) \),
over each event and summing the value of all surfaces onto a regular reference grid superimposed over the study region (Fig. 3-5). Typically, a symmetrical kernel function falls off with distance from each event at a rate that is dependent on the shape of the kernel function and the chosen bandwidth, \( b \). A number of different kernel functions have been used, including normal, triangular, quartic, negative exponential, and uniform. The bandwidth determines the amount of smoothing and, for the limited distance functions (triangular, quartic, negative exponential, and uniform), the size of the kernel’s search area. In the case of the normal kernel function, the bandwidth is the length of the standard deviation of the normal distribution. The normal kernel function produces a density estimate over the entire region (i.e., it is an unlimited distance function), whereas the other four functions produce estimates only for the circumscribed bandwidth radius. Kernel density calculations can be carried out for events that are weighted or unweighted.

\[ \text{Figure 3-5. Kernel density estimation of a point pattern using the quartic kernel function (courtesy of Fischer et al., 2001).} \]

Selecting an appropriate bandwidth is a critical step in kernel estimation; bandwidth affects the results to a much greater extent than cell size or type of kernel function. A larger bandwidth expands the kernel at the cell center and results in a smoothed and generalized map with low-density values. In contrast, a small bandwidth results in less smoothing, producing a map that depicts local variations in point densities. A very small bandwidth almost reproduces the original point pattern and is spiky in appearance.
2-D Kernel Density Representation

Using the mid-point for each 6-hour section of the storm tracks, a kernel density interpolation was calculated using CrimeStat III (Levine, 2004). Density calculations were based on a normal kernel function with a fixed bandwidth of 195 miles. This bandwidth selection is fairly conservative, considering that hurricane diameters range from 125 to 800 miles (Elsner and Kara, 1999). The normal kernel function was chosen because it is the most commonly used (Kelsall and Diggle, 1995).

The results from the kernel density interpolations show the highest and lowest density of storm tracks in the darkest and lightest red, respectively. In contrast to the previously-discussed vector methods, spatial patterns now emerge more clearly. Hurricanes occurring during periods concurrent with a weak Bermuda High (highly negative NAO index) show little or no track re-curvature, with nearly all storm tracks showing east-west movement (Fig. 3-6A). However, during periods concurrent with a strong Bermuda High (highly positive NAO index), hurricane tracks show large amounts or re-curvature along the western edge of the well-defined high pressure system (Fig. 3-6B). These results support a visual spatial correlation between modern-day Bermuda High strengths and modern-day hurricane tracks.

Figure 3-6. 2-D continuous surface display of hurricane tracks derived from kernel density estimations coinciding with a “weak” Bermuda High (6A) and a “strong” Bermuda High (6B).
3-D Kernel Density Representation

The final representation used the density values from the kernel interpolation method to create an enhanced 3-D display. This step was accomplished with the Surfer program (Golden Software, 2003). First, kernel density estimations were visualized in the form of a 3-D wire frame structure. This 3-D continuous surface was subsequently draped with (1) a simplified topographic map, showing only the outline of country boundaries and the land and water areas, (2) a shaded relief, and (3) an isometric map with hypsometric tints, but no contours (Fig. 3-7).

The final, enhanced 3-D surface (Figure 8) is an improved visual representation compared to the 2-D display and clearly distinguishes between regions of high activity concurrent with small and large Bermuda High strengths. For periods with weak Bermuda Highs a general east-west trend of hurricane tracks is visible, indicative of a weak system exhibiting little or no control over the steering of the hurricanes. During periods when the Bermuda High is strong, hurricane tracks clearly exhibit a distinct pattern of re-curvature (Fig. 3-8). The 3-D enhanced surface representation is also compelling in that it illustrates changing risks associated with varying Bermuda High strengths. For example, according to the last 50+ years of data, when the Bermuda High is weak, the Caribbean Antilles (depicted with
red circles in Fig. 3-8) have a much lower occurrence of hurricane strikes. Alternatively, when the Bermuda High is strong, the same region’s risk of hurricane strike increases dramatically.

![Figure 3-8.](image)

**Figure 3-8.** Enhanced 3-D continuous surface display of hurricane tracks derived from kernel density estimations coinciding with a “weak Bermuda High (8A) and a “strong” Bermuda High (8B) Note: Red circles encompass the Caribbean Antilles and highlight changing risk associated with Bermuda High strength.

**Conclusions**

The purpose of this research was to discover which visualization methods are best suited to detecting the spatial patterns of a large number of hurricane tracks collected for the Atlantic Ocean and the Gulf of Mexico since 1947. Specifically, the research visually tested the Bermuda High hypothesis. The results indicate that, for periods concurrent with a strong Bermuda High, hurricane tracks show large amounts of re-curved curvature along the western edge of the well-defined (Bermuda High) pressure system, which is indicative of the Bermuda High as a controlling agent of hurricane tracks and is consistent with the stipulations put forth in the Bermuda High hypothesis of Liu and Fearn (2000a). Hurricane tracks during periods concurrent with a weak Bermuda High are also in agreement with the Bermuda High hypothesis, with hurricane tracks showing little or no track re-curved curvature but rather dominant east-west movement.

Among the different visualization methods tested, the 2-D and especially the enhanced 3-D representation, which are both based on kernel density interpolations, proved to be most useful. The spatial patterns exhibited by both visualization methods seem to be in agreement with the Bermuda High hypothesis. To the best knowledge of the authors, this is the first time that hurricane tracks have been represented in terms of their association with the strength of the
Bermuda High using the kernel density estimation method. In general, the approach presented in this research should be useful for detecting spatial patterns in any large data sets that consist of linear features (e.g., migration patterns of birds or fish, urban traffic flows, patterns of drug trafficking or illegal immigration, and many others).

One drawback of the kernel density estimation is that its calculation is more complex and more time-intensive when compared to a traditional choropleth map that displays the density values for a regular grid. In addition, care must be taken when selecting the bandwidth used to calculate the kernel density values. Unfortunately, there is currently no agreement in the literature as to how wide a particular bandwidth should be (Environmental Systems Research Institute, 1999; Diggle, 1981; Williamson et al., 1998).

An alternative approach to the fixed bandwidth is to use different bandwidths in different parts of the study area, an approach known as adaptive kernel estimation (Bailey and Gatrell, 1995). Adaptive kernel estimation is based on sampling theory, giving the choice of bandwidth a consistent level of precision over the entire study region. This is achieved by increasing the bandwidth until a fixed number of points (i.e., minimum sample size) are counted. Accordingly, in areas of high density, small bandwidths are used to show detailed local variation, whereas in areas of low density larger bandwidths smooth the point pattern (Bailey and Gatrell, 1995). Although adaptive kernel estimation solves the problem of determining a value for $b$, it still leaves open the question of how to set an appropriate minimum sample size. In general, the higher the minimum sample size, the larger the bandwidth and the more the density surface will be smoothed. Suggestions concerning the determination of the appropriate minimum sample size are lacking in the literature.

Results indicate that the 2-D and especially the enhanced 3-D display derived from kernel density interpolation seem to visually support the Bermuda High hypothesis. This is in line with recent public safety (Eck et al., 2005; Brunsdon et al., forthcoming) and public health studies (Curtis et al., 2005; Curtis and Leitner, 2006) that preferred to visualize large geospatial data sets of discrete (point or line) features that are spatially clustered with the kernel density interpolation method rather than with the choropleth or alternative methods. Although this is one indication that the kernel density interpolation method can “better” visualize large geospatial data sets, no human subject testing has ever been carried out to objectively validate this assumption. Such user studies become increasingly necessary as the kernel density interpolation method is
implemented in spatial analysis software that becomes ubiquitously available (e.g., CrimeStat III).

With respect to this current study, a more objective analysis is needed to verify the kernel density interpolation method’s ability to visualize the relationship between Bermuda High strength and re-curvature of hurricane tracks. Such an analysis would be the next logical step in this research and can be accomplished either through human subject testing or statistical analysis (e.g., correlation or spatial regression modeling). With regards to user studies, the two main assumptions that should be tested are (1) whether maps derived from kernel density interpolation are indeed “better” (“clearer,” “more intuitive”) at visualizing this specific relationship as compared to flow, dot, or choropleth maps; and (2) which parameter settings (i.e., bandwidth and kernel function) for the kernel density interpolation method would best visualize the relationship between Bermuda High strength and re-curvature of hurricane tracks. Human subject testing of this relationship would continue the recent resurgence of a long-standing tradition of empirical research in map design as a paradigm for eliciting and formalizing cartographic design knowledge (Leitner and Buttenfield, 2000; Aerts et al., 2003; Leitner and Curtis, 2004; 2006).
CHAPTER 4 METHODOLOGY

The preferred sites for paleotempestological studies are coastal lakes or lagoons fronted by a sandy barrier, which provides a source of material for transportation and deposition as an overwash layer. The overwash sand layer becomes embedded in pre- and post-hurricane lacustrine sediments deposited under normal depositional environments. Assuming fairly stable geomorphological conditions, the thickness and horizontal extent of each hurricane-generated layer should roughly reflect the intensity of the storm (Liu and Fearn, 1993).

Field Methods

Cores were extracted in the field by a modified Livingstone piston corer, which consists of a clear-plastic tube of approximately 1.5 meters (5 feet) in length, with a stainless steel cutting shoe attached to the bottom and a core head at the top. The core was pushed into the sediments and a continuous sediment core was captured in the tube. Core tubes, with the sediments inside, were sealed and transported back to the LSU Global Paleoecology Laboratory in the Department of Oceanography and Coastal Sciences. Coring is done manually from a wood platform secured on two inflatable rubber boats. Salinity was measured in the field by means of a hand-held salinity meter. Beach sand samples were collected for comparison with the embedded overwash sand layers contained within the sediment cores. All sediment/water samples and coring sites were marked by use of a global positioning system (GPS Garmin 12) for site revisitation and for display on geo-referenced maps and remotely sensed imageries.
Laboratory Methods

After the cores were returned to the lab they were subjected to a number of analyses. Firstly the cores were sent through the Geotek Multi-Sensor Core Logger (MSCL), for measurements of ultrasonic P-wave, Gamma ray density (attenuation), and magnetic susceptibility (Keen et al., 2004). A visual analysis was performed once the cores were opened and changes in sediment color, lithology, and stratigraphy (e.g., presence of sand layers) were noted and diagramed. All cores were scanned and digital images captured. Following the visual inspection, loss-on-ignition (LOI) analysis was done to determine the lithology content (% water, % organic, % carbonate, and % silicate contents). Supporting evidence for the sedimentological data was derived from the analysis of invertebrate fossils (gastropods and bivalves) (Lozek, 1986). Age control was established via radiocarbon ($^{14}$C) and cesium ($^{137}$Cs) dating techniques. $^{14}$C was used for dating overwash layers and basal sediments as well as for calculations of sedimentation rates in sediments older than 200 yr BP (Bartlein et al., 1995; Talma and Vogel, 1993). Samples for $^{14}$C dating were all analyzed at Beta Analytic, Inc., in Miami, FL. $^{137}$Cs detection was done using a Germanium-Lithium crystal multichannel analyzer/detector to record gamma emissions of bulk sediment at 661 keV (Ritchie and McHenry, 1990; Graustein and Turekian, 1986). $^{137}$Cs analysis was done in-house in the laboratory of Dr. Ron Delaune and was used specifically for the identification of the stratigraphic signature left by Donna (1960). Once the peak was established results were used to infer the age of overwash layers for the last ~50 years (Ab Razak et al., 1996; Jaakkloa et al., 1983).
CHAPTER 5 ACKLINS ISLAND, BAHAMAS

Introduction

Acklins Island (22.38° N, 73.90° W), a long narrow island with low topography (43 m), lies at the southern end of the 29-island Bahamian Archipelago (Fig. 5-1). It has a total area of 137 mi² (355 km²). The climate is sub-tropical to tropical and has a mean summer temperature of 28.3 °C and a mean winter temp of 21.2 °C (Kjellmark, 1996), with precipitation averaging 1200 mm per annum (Keegan, 1992), mostly during the spring and summer seasons. The Bahamian platform sits just north of the Caribbean plate junction which borders the northern shore of Hispaniola.

Figure 5-1. Location of Palm Pond and Lake Kalik, Acklins Island, Bahamas.

Evidence suggests that during the Tertiary, development of the Bahamian platform was considerably influenced by tectonic activity (Mullins et al., 1992; Freeman-Lynnde and Lohmann, 1992). However, the platform has been considered to be tectonically inactive since the late Quaternary, showing no signs of tectonically induced deformations (Mylroie and Carew, 1995; Toscano and Macintyre, 2003; Digerfeldt and Hendry, 1987).

Acklins Island is specked with many shallow ponds and hypersaline coastal lakes common among the islands of the Bahamas (Paerl et al., 2003) with many of the small hypersaline lagoons containing well-developed benthic microbial mat communities (Pinckney et al., 1995). The large number of coastal ponds and lakes situated along the eastern edge of
Acklins Island are ideally situated to receive allochthonous sediments from hurricane-induced overwash. Although these hypersaline ponds are poorly understood (Jarecki and Walkey, 2006; Mackenzie et al., 1995), recent studies have shown that they are excellent sedimentary archives of local and regional paleoclimatic events of the late Holocene (Dix et al., 1999; Bertran et al., 2004). Due to their chemical stratification and intense microbial activities, anoxic conditions occur on their bottom which limit bioturbation and help preserve sedimentary facies.

The Bahamas has a well-documented sea level history, having not risen more than 0.5 m in the last 1500 years and only rising 3 m to its present level over the last 3000 years (Boardman et al., 1989). This is in good agreement with regional Holocene sea level reconstructions (Toscano and Macintyre, 2003; Fairbanks, 1989; Digerfeldt and Hendry, 1987; Mylorie and Carew, 1995; Taylor et al., 1985; Blanchon et al., 2002). A ~3500-yr record from Andros Island, Bahamas (Kjellmark. 1996) provides the first late-Holocene climate reconstruction focused on the Bahamian Archipelago.

Analysis of a 2 meter core indicates that Caribbean climate was wetter than present before 3200 yr BP followed by a period of aridity for Andros Island in concert with a period of widespread pan-Caribbean aridity from 3200-1500 yr BP (Brown and Cohen, 1985; Hodell et al., 1991; Burney et al., 1994). Modern hurricane activity (Neumann et al., 1999) for Acklins Island shows that since 1949 there have been seven hurricanes passing within 65 nautical miles of the shores of Acklins Island (Fig. 5-2): 1949 Not named (Cat 1), 1954 Hazel (Cat 2), 1954 Edna (Cat 1), 1956 Betsy (Cat 2), 1960 Donna (Cat 4), 1963 Flora (Cat 1), and 1985 Kate (Cat 1).

Methods

In October of 2006 a total of 15 cores were retrieved (9 from Lake Kalik and 6 from Palm Pond), all to bedrock, with no core exceeding 1 meter in length. The cores were taken using a
combination of Livingstone piston and Russian peat borer coring techniques. Cores were taken parallel to the barrier beach shoreline in order to best capture the potential overwash signature from Hurricane Donna and other storms. Cores were sealed and wrapped transported back to Louisiana State University for analysis. Once in the lab cores were split lengthwise and a mono filament wire was passed through the sediment to separate the sediments in half. One half (working) was used in the analysis and the other half was archived. Cores were scanned and a digital image was captured for each archive core. Visual analysis was performed to determine downcore changes in lithology, and changes in sediment color and stratigraphy were noted. Following the visual inspection, core stratigraphy (% water, organic, carbonate, and silicate) was determined at 1 cm$^3$ intervals continually using loss-on-ignition (LOI) techniques (Dean, 1974).

Age control was established via radiocarbon ($^{14}$C) and cesium ($^{137}$Cs) dating techniques. For Lake Kalik 4 samples were extracted from the center of core LK01 at 21, 35, 55, and 84 cm. For Palm Pond 5 samples were extracted from the center of core PP07 at 30, 72, 83, 104, and 126 cm, as well as one sample from PP03 (86 cm). The samples were sent to Beta Analytic Laboratories, Miami, FL for AMS $^{14}$C dating. Samples were selected so that approximate dates of the major stratigraphic boundaries could be determined. $^{137}$Cs analysis was done in house and used specifically for the identification of the stratigraphic signature left by Donna (1960), but is also used to do high-resolution dating of overwash layers for the last ~50 years (Ab Razak et al., 1996; Jaakkloa et al., 1983). Sediment samples were dried and crushed to insure uniformity and placed in 5 cm petri dishes. The individual samples were then placed in a Germanium-Lithium crystal multichannel detector for 4 hours while gamma emissions were measured and recorded (Ritchie and McHenry, 1990; Graustein and Turekian, 1986).

**Lake Kalik**

**Description of Study Site**

Lake Kalik (22° 31’ N, 73° 51’ W), located along the eastern coast of Acklins Island, Bahamas (Fig. 5-3), is a tranquil hypersaline lake with no riverine or tidal influences and an average depth of <1.5 m. Salinities of 75‰ were measured for Lake Kalik in early October, 2006, and were as expected for early fall with salinities expected to increase throughout the dry season. Typically Bahamian hypersaline lakes experience fluctuating salinities (seasonally) from 45-100 ‰ (Pinckney et al., 1995). Lake Kalik is located in a shallow depression fronted to the east by a partially vegetated large undulating relict reef barrier (40 ft/12 m) likely of Pleistocene
origin (Purdy and Imbrie, 1964). This large rocky barrier, running nearly the entire length of the lake, has a few small openings or breaches. The most prominent measures ~ 70m and is located near the southern end of the lake, giving direct access to the beach. To the west the lake is surrounded by a gently sloping fully vegetated hillside rising eventually to close in the basin (40 ft /12 m). Lake Kalik is a typical hypersaline lake for the Caribbean, a closed basin where outflow is restricted and evaporation exceeds inflow (Scoffin, 1987). The lake surface is estimated to be <1m from mean sea level with red mangroves (Rhizophora mangle) dominating the fringe of the lake and black mangrove (Avicennia germinans) mixing in the understory displaying a typical vegetation assemblage for hypersaline Caribbean lakes (Jarecki and Walkey, 2006). Sand samples were taken from the near shore beach for comparison to the overwash layers contained within the core.

**Lithostratigraphy, Biostratigraphy and Sediment Composition**

The cores taken from Lake Kalik reveal many abrupt down-core stratigraphic changes that were divided into lithological zones. Loss-on-ignition curves were used to identify and correlate these lithological zones within and between cores (Fig. 5-4, 5-5). The cores from Lake Kalik indicate the presence of four distinct stratigraphic zones. Cores LK01 and LK02 are examined in detail here. LOI analysis results for all cores can be found in Appendix 2.
Zone 4: The basal zone is a grey peat and marl matrix that progressively gets lighter in color upcore. This color transition is mirrored by a very gradual decrease in water and organic content (note the arrow on LK01, Fig. 5-4). Carbonates, however, show little overall change in this unit. This facies is believed to represent a period of higher lake levels and increases in average meteoric precipitation received (and associated influx of runoff material to the lake basin) resulting in a carbonate deposition. Zone 4 is not present in any of the shorter cores (LK03, 04, 06, 08, 09) most likely due to local variations in the lake bottom bathymetry or topography.

Figure 5-4. Results of loss-on-ignition and stratigraphic analysis for Lake Kalik core LK01.

Zone 3: This zone contains a shell hash consisting of gastropods and fragmented bivalves within a dark grey unconsolidated marly matrix. LOI analysis reveals little change in the layer’s sedimentological makeup in comparison to Zone 4, even though the zonation is quite distinct. Distinctly darker in color, Zone 3 indicates much reworking and/or mixing as evidenced by the
abundance of broken and fractured mollusks (both gastropods and bivalves). It is unlikely that this stratigraphic change is due to a shift in the environmental parameters of the lake as the lithologic contents of the sediments do not change. The only change is the addition of a highly reworked chaotic mollusk death assemblage. It is likely that this is either a tsunami deposit layer or a brief period of intertidal connection such as a sea level rise. The possibility that this event is a tsunami deposit is further enhanced by the fact that it is only present in cores taken near the lower parts of the undulating overwash barrier.

Zone 2: consists of highly organic mangrove peat (likely Rhizophora mangle or Avicennia germinans) and laminated organic carbonate mud facies. This facies occurs in all cores. This zone is indicative of a shallow water environment with the accumulation of laminated highly organic muds and peats. A shallower lake or reduced lake extent would account for the encroachment of mangroves into the previously submerged areas.
Zone 1: A jellified carbonate rich organic mud (~31% organic, 40% carbonate, 29% silicate), typifies the modern depositional environment of the lake under hypersaline and somewhat shallow conditions. There is evidence of mollusks (bi-valve and gastropods) living within this facies. This zone is absent in LK01.

These four distinct lithological facies are interrupted by 4 event horizons interpreted to be hurricane overwash deposits. Each deposit consists of a layer of pure fine-grained golden sand. The loss-on-ignition values of the overwash layers (~2.76% organic, 42.66% carbonate, 54.57% silicate) are nearly identical to that of the surface sand samples taken from the adjacent beach (~2.38% organic, 42.29% carbonate, with 55.33% residual).

**Mollusks**

It has been found that after a violent storm there are a multitude of death assemblages of a wide variety of freshly killed mollusks strewn along the beaches (Warmke and Abbott, 1961). In the sediments of Lake Kalik and Palm Pond there were numerous death assemblages found to be contained within the core sediments. The presence of these mollusk death assemblages seems to be correlated with that of the event layers. There are no mollusk death assemblages without the present of an event layer. Mollusks were sampled from the death assemblages in order to identify them to genera and where possible species. Prior studies for the Bahamas have identified a number of localized species. Kjellmark (1996) and Dix et al. (1999) found the gastropods (*Batillaria minima, Cerithidea costata*) as well as tellinid bivalves (*Cumingia antillarum*) in the core sediments from Andros and Lee Stocking Island, Bahamas, respectively. Using these prior studies as a starting point the mollusks were brought to the LSU Museum of Natural Science for comparison to preserved invertebrate fossil collections. Using mollusk identification keys (Warmke and Abbott, 1961; Morris, 1975; Andrews, 1994; Abbot, 1974) in conjunction with the fossil collections the mollusks present in both lakes were tentatively identified. Following preliminary identification, specimens were sent to Dr. Fred Thompson, the curator of malacology at the Florida Museum of Natural History to confirm the initial identifications. Following this procedure, most of the assemblage were of the family Cerithiidae (Fig. 5-6), which exhibit elongated many whorled shells with vertical ribs or groves, a round aperture and flaring lip and live in moderately shallow waters of the tropics or subtropical region (Morris, 1975). *Cerithidea costata, Cerithidea beattyi, Cerithidea costa, Cerithium eburneum*, and *Batillaria minima* were tentatively identified to the species level. These mollusks are typically found in large numbers on mud flats, mangrove...
swamps, and landlocked marine ponds, often occurring in huge numbers (Warmke and Abbott, 1961; Williams and Williams, 1998; Bertran et al., 2004). All are poikilohaline species with a very broad salinity tolerance ranging from 0.05-300‰ (Purdy and Imbrie, 1964). Also found in the assemblages were *Littorina* sp., a small white-shelled gastropod whose habitat ranges from intertidal rocks to well above high tide lines (Warmke and Abbott, 1961). One prominent small pinkish white individual was found in the middle of the top overwash sand layer in core LK01 and was identified as a member of the Helicinidae family, a family of small tropical terrestrial snails indigenous to the Caribbean. Some of the bivalves located in the death assemblages were *Cumingia antillarum*, a bivalve species that lives embedded on corals and at the base of sea fans. Absent are any fresh water mollusks indigenous to the area (e.g. *Amnicola forsythia*). Notably, only euryhaline species are found in the cores (Purdy and Imbrie, 1964).

Figure 5-6. Lake Kalik and Palm Pond mollusk assemblages.
Radiocarbon Chronology

Radiocarbon dating (Fig. 5-7) indicates a basal age of 1150 cal yr BP for the sediments recovered from Lake Kalik. A plot of the radiocarbon dates shows a constant depth-age relationship between the dates ($r^2 = 0.991$). There appears to be no hard water error in Lake Kalik. All radiocarbon dates were all single intercepts with the radiocarbon curve.

Figure 5-7. Plot of calibrated radiocarbon dates against sediment depth for core LK01.

When interpreting radiocarbon dates, it is important to note that variations in atmospheric $^{14}$C concentrations results in a nonlinear relationship to calendar time and often leads to multiple calendar age ranges for each radiocarbon age (Bartlein et al., 1995; Stuiver et al., 1998). Results from Beta Analytic indicated multiple possible age ranges for the Lake Kalik cores within the 1 sigma (1σ) 68% probability, and 2 sigma (2σ) 95% probability ranges and they are listed below.

- Beta-234610: 1σ calibrated results were Cal BP 310 to 280 and Cal BP 160 to 160, 2σ were Cal BP 420 to 390, Cal BP 320 to 270, 210 to 150, and 20 to 0.
- Beta-234611: 1σ calibrated results were Cal BP 510 to 460, 2σ were Cal BP 520 to 420 and Cal
- Beta-235772: 1σ calibrated results were Cal BP 670 to 640 and 590 to 570, 2σ were Cal BP 680 to 620 and 610 to 560.
Beta-234612: 1σ calibrated results were Cal BP 1080 to 1050 and 1040 to 990, 2σ were Cal BP 1170 to 960.

However, it is accepted that calendar ages with the highest probability occur at the radiocarbon intercept with the calibration curve (Donnelly et al., 2001a). All four Lake Kalik cores are single intercepts with the radiocarbon curve and correspond to the calibrated dates listed in Figure 5-7. These calibrated dates were used in the analysis.

**137Cs Chronology**

137Cs sediment samples were obtained from a 3” diameter core (LK13) that was collected specifically for use in cesium dating (LK13 was taken immediately adjacent to LK01) (Fig 5-8). Sampling was done at 2 cm intervals downcore for the top 8 cm until the top of the first overwash sand layer was reached. The sediment directly above this first event was a mixture of sand and organic sediments accompanied by a gastropod/bivalve death assemblage. Sampling was continued directly following the top sand layer event for 4 cm more. The peak of 137Cs activity occurs at 7 cm and would indicate a date of 1963 coincident with the 7 cm mark in the sediments.

Figure 5-8. Results of 137Cs analysis for Lake Kalik.
Environmental History

There appear to be four major transitions during the 1060 yr history of Lake Kalik with four sand layers deposited within the various stratigraphic zones of the lake (Fig.5-9). The alternating lithological facies are likely indicative of changes in the balance between rainfall, evaporation, and basin drainage (Dix et al., 1999). Sediment deposition began in the basin around 1000 years ago with the accumulation of a peat/marl facies (Zone 4). Loss-on-ignition analysis (Appendix 2) shows that from the bedrock of the lake there was the gradual accumulation of a dark peat marl matrix, high in water and organic content. This facies has a gradual transformation in the sediment, both in color (lighter/whiter upcore) as well as in water and organic content which both decrease slightly upcore. This is a typical lithologic deposition indicating higher lake levels and increased precipitation which bring in eroded minerals from the surrounding carbonate platform to enrich the lake waters in calcite and aragonite (Trichet et al., 2001). During the dry season as high rates of evaporation persist, there is the supersaturation of calcite and argonite in the water column and the eventual dissolution/precipitation of calcium carbonate (Trichet et al., 2001; Scoffin, 1987). This depositional regime ends at around 660 Cal BP and is replaced by Zone 3, consisting of massively fractured gastropod and bivalve accumulation within a dark grey unconsolidated marly matrix. LOI analysis reveals little lithological change in the layer in comparison to Zone 4. However, it is quite distinct, with a much darker grey color, and visual inspection indicates much reworking and or mixing as evidenced by the abundance of broken and fractured mollusks. It is unlikely due to an environmental factor given the continuous nature of the lithologic content of the sediments. It is highly likely that this zone was created by either a tsunami deposit layer or a brief period of intertidal connection such as a sea level high stand. This presumption becomes more likely given that Zone 3 is only present in the cores near the low parts of the overwash barrier. A review of the regional sea level history does not indicate any evidence of a late Holocene sea level rise, but Facies 3 is well-positioned stratigraphically to coincide with the tsunami deposits found by Kelletat et al., (2004) from Long Island, Bahamas occurring at ~500 yr BP. The deposits of Zone 3 are chaotic and display no stratification or sorting to the fragments. There is a badly fractured mollusk assemblage and evidence of much reworking, all characteristic of tsunami deposits (Morton et al., 2007; Dawson and Stewart, 2007; Nanayama and Shigeno, 2006; Kelletat et al.,
Figure 5-9. Stratigraphic correlations for Lake Kalik.
The deposit itself is not very large in depth or in spatial extent, so it is assumed that the impact of this tsunami was relatively minor for Lake Kalik.

Following the assumed tsunami deposition, the lake transitioned into Zone 2 around 490 Cal BP. This zone of high organic depositions and peat encroachment into the previous lake is indicative of a period of aridity and/or reduced precipitation. Reducing both lake levels and extent, there is the encroachment of mangrove and the accumulation of cyanobacterial mats, both typical features of shallow water levels (Saenger et al., 2006; Paerl et al., 2003; Rouchy, 2001). Many of the older cyanobacterial mats have lost their prominent laminations, which is to be expected as they tend to decay over time liberating large amounts of carotenoid (pigments resulting in less prominent or even non-visible laminations within the organic rich strata (Trichet et al., 2001). This interpretation of a period of aridity, roughly 490 to 290 yr BP, coincides well with the Little Ice Age which occurred around 550-200 yr BP. It has been well-documented that the LIA had a reducing effect on precipitation for the Caribbean (Hodell et al., 2005; Haug et al., 2001) and would fully account for the reduced lake levels and mangrove encroachment apparent in Zone 2.

Following 290 yr, the lake enters its current modern-day depositional environment, Zone 1. Zone 1 is typified by a jellified carbonate mud facies topped by waters 1-2 meters deep with salinities that presumably span the typical range of hypersalinity for the Bahamas (45-100‰). This was a period of much more precipitation than what was available during the LIA period of Zone 2.

**Hurricane History**

There are four sand layers deposited within the sediments of Lake Kalik. The sand layers are distinct in both color and lithological content from the surrounding facies. The layers are upward fining, clean well sorted-beach sand and are interpreted to be allochthonous marine-derived sediments presumably transported by hurricane storm surge. It was assumed that the top layer (E4) would be deposited by Hurricane Donna as it was the only Category 4 storm to hit Acklins Island in the modern record. The path of Hurricane Donna aligns perfectly for maximum impact at or near Lake Kalik, located directly in the right front quadrant of the storm.

$^{137}$Cs analysis indicates that E4 could possibly be Hurricane Donna as the peak in cesium activity (1963) is found directly above the E4 event, indicating that the event was deposited shortly before 1963 (Fig. 5-9). However, based on the position in the sediment stratigraphy
(7cm) it seems unlikely. $^{14}$C dating gives an average sedimentation rate for all zones of 0.08 cm per annum. Using that calculation (0.08 x 48yrs) the storm signature for a deposit in 1960 should be no deeper than 3.8 cm within the stratigraphy. Calculations for 7cm at 0.08 cm per annum yield a date of ~87 years ago or 1921 far too old for the $^{137}$Cs peak to be accurate. The cesium peak at 7 cm in this core must be erroneous. However this is not completely unexpected. The $^{137}$Cs readings (pCi/g) were very in low abundance. This is most likely due to not enough sediment available for the analysis due to the low sediment accumulation rate of the lake. There simply was not enough sediment available in the narrow diameter cores. The high sedimentation rates in conjunction with the low $^{137}$Cs readings could very likely lead to contamination of the readings due to fluctuations in background counts on the germanium lithium counter. Given the uncertainty here, it seems more prudent to rely on $^{14}$C dates.

E4 was deposited into Lake Kalik around 290 Cal BP. A dramatic event E4 came in through the southern breach in the barrier and exhibits the typical landward thinning associated with hurricane overwash extending and thinning toward the southern end of the lake all the way to core LK10 (Fig 5-9). Given that there is no signature deposited by Hurricane Donna it stands to reason that E4 was an event of Category 5 magnitude or greater. This is further enhanced by the amount of sediment deposited; a massive amount of sand was deposited in conjunction with this storm with nearly 20 cm recovered in core LK01.

E3 dated to 490 Cal BP may have been deposited over a low point in the undulating overwash barrier, and perhaps is an extension of the sub-areal crenulated margin directly to the east of the coring locations of LK06 and LK04. The overwash layer is most prominent in cores LK04 and LK06 (nearly 20cm of sand) and thins out horizontally to the north and south of the lake. Again, this likely represented a very large storm perhaps of Category 5 strength.

It is likely that the mollusk death assemblages associated with E3 and E4 were direct results of the hurricane overwash. It is unlikely that the majority of the mollusk shells were transported in, as there is no significant damage to the shells. More likely it was an in situ population that was killed by burial from the resultant overwash fan. The presence of some marine/beach mollusks ($Littorina$, $Cumingia antillarum$) and terrestrial mollusks (Helicinidae) mixed into the assemblage certainly help indicate transport of marine origin.

The sand layers E2 and E1 (660 and ~950 Cal BP respectively) are only recorded in the longer cores, again presumably due to the changes in lake bottom bathymetry topography. Much
smaller events E2 and E1 are only a few centimeters each. E2 most distinct in core LK08 likely came in through both low points in the barrier, appearing in LK01, LK02 and LK07, LK08 only.

Taken as a whole, the four events deposited in Lake Kalik over the last 1060 yr BP gives a return period of 265 yrs or an annual strike probability of 0.0037% for the island. This calculation is based only on extremely strong storms as Hurricane Donna, a Category 4 storm, failed to leave any stratigraphic signature within the sediments.

**Palm Pond**

*Description of Study Site*

Palm Pond (22° 38' N, 73° 52' W) also located along the eastern coast of Acklins Island, Bahamas (Fig. 5-10) is similar to Lake Kalik, a tranquil hyper-saline (80‰) lake with an average depth of <1.5m. Palm Pond differs, however, as it is completely enclosed in a carbonate depression fronted on the east side by a large (60 ft/18 m) continuous relict reef barrier also likely of Pleistocene origin, with no outlets or breach at all. The west side of Palm Pond is a steep partially vegetated limestone cliff rising up 80 ft (24 m). Both red mangrove (*Rhizophora mangle*) and black mangrove (*Avicennia germinans*) are present at Palm Pond. However, the mangroves do not encroach the edges of the lake as they do in Lake Kalik. Also as the name indicates there are a large number of palm trees mixed in with the scrub vegetation.

**Lithostratigraphy, Biostratigraphy and Sediment Composition**

Following the same methodology used for Lake Kalik, the sediments from Palm Pond were divided up into four zones based on lithological content derived from visual and loss-on-ignition analysis (Fig 5-11).

Zone 1 consists of compact thin stromatolite cap of the underlying carbonate facies not exceeding 5 cm in any area. Stromatolites generally form in shallow waters in areas of inorganic precipitation, often forming a thin lithified crust a few centimeters thick (Scoffin, 1987).
Figure 5-11. Results of loss-on-ignition and stratigraphic analysis for Palm Pond Core 07.

Zone 2 is a facies of carbonate deposition (39% carbonate, 7% organic, 54% silicate). This is a typical depositional environment for higher water levels with high rates of aragonite and calcite influx, likely in this case to be derived from the steep limestone cliffs surrounding the lake.

Zone 3 consists of highly organic mangrove peat (*Rhizophora mangle* or *Avicennia germinans*) and organic carbonate mud facies. This facies is similar to Unit 2 in Lake Kalik. However, in this case there is limited organic mud and no laminations; the unit is dominated almost entirely by mangrove peat. This period most certainly corresponds to a period of shallower or reduced lake extent, also most likely in conjunction with extreme hypersalinity.

Zone 4 is comprised of a peat/marl matrix with a gradual transition toward organic sedimentation eventually turning into peat deposition. The facies is identical to Zone 4 in the Lake Kalik cores and most likely represents a climate with high rates of precipitation.

**Radiocarbon Chronology**

Palm Pond $^{14}$C dates were also done by Beta Analytic, Miami, FL, and indicate a preliminary basal date of ~3800 yr BP for Palm Pond. All of the material extracted for sampling
was in stratigraphic order and was sampled from the middle of the core in order to avoid being disturbed during coring. All radiocarbon dates from Palm Pond were all single intercepts with the radiocarbon curve. A plot of the radiocarbon dates (Fig. 5-12) shows good correlation between date continuity ($r^2 0.926$) and excellent depth-age relationship between the dates.

![Plot of calibrated radiocarbon dates against sediment depth for core PP07.](image)

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<th>$^{13}$C/12C</th>
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<td>PP07-83cm</td>
<td>2560 +/- 40</td>
<td>-26.4%</td>
<td>Organic material (peat)</td>
<td>Cal BP 2740</td>
</tr>
<tr>
<td>Beta-223212</td>
<td>PP07-104cm</td>
<td>3510 +/- 40</td>
<td>-26.6%</td>
<td>Organic material (peat)</td>
<td>Cal BP 3560</td>
</tr>
<tr>
<td>Beta-223213</td>
<td>PP07-126cm</td>
<td>3390 +/- 40</td>
<td>-26.4%</td>
<td>Organic material (peat)</td>
<td>Cal BP 3820</td>
</tr>
<tr>
<td>Beta-234613</td>
<td>PP03-86cm</td>
<td>3310 +/- 40</td>
<td>-25.7%</td>
<td>Organic material (peat)</td>
<td>Cal BP 3640</td>
</tr>
</tbody>
</table>

**Figure 5-12. Plot of calibrated radiocarbon dates against sediment depth for core PP07.**

Results from Beta Analytic indicated multiple possible age ranges for the Palm Pond cores within the 1 sigma ($1\sigma$) 68% probability, and 2 sigma ($2\sigma$) 95% probability ranges. These are listed below.

- Beta-235773: $1\sigma$ calibrated results were Cal BP 1090 to 1000, $2\sigma$ were Cal BP 1150 to 950.
- Beta-223210: $1\sigma$ calibrated results were Cal BP 2350 to 2320, $2\sigma$ were Cal BP 2360 to 2300 and Cal BP 2260 to 2160.
- Beta-223211: $1\sigma$ calibrated results were Cal BP 2750 to 2720, $2\sigma$ were Cal BP 2760 to 2710 and Cal BP 2630 to 2500.
- Beta-234613: $1\sigma$ calibrated results were Cal BP 3580 to 3470, $2\sigma$ were Cal BP 3640 to 3450.
- Beta-223212: 1σ calibrated results were Cal BP 3840 to 3710, 2σ were Cal BP 3880 to 3680.
- Beta-223213: 1σ calibrated results were Cal BP 3680 to 3580, 2σ were Cal BP 3710 to 3550.

As stated earlier it is accepted that calendar ages with the highest probability occur at the radiocarbon intercept with the calibration curve (Donnelly et al., 2001a). All six Palm Pond cores are single intercepts with the radiocarbon curve and correspond to the calibrated dates listed in Figure 5-9. These calibrated dates were used in the analysis.

**137Cs Chronology**

Palm Pond 137Cs sampling was done continuously for the top 10 cm of the 3” diameter core. This core was sampled specifically for use in cesium dating (PP08 taken directly adjacent to PP01), stopping at the top of the first sand layer in an effort to identify the event as Hurricane Donna. Once again sampling was done at 2 cm intervals downcore for the top 10 cm until the top of the presumed overwash event layer was reached. The peak of 137Cs activity was reached at 8 cm, indicating the date of 1963 (Fig 5-13).

**Figure 5-13. Results of 137Cs analysis for Palm Pond.**
Environmental History

Three major depositional transitions occur during the ~4000 yr history of Palm Pond with as many as five sand layers deposited within the various stratigraphic units of the lake (Fig.5-14). The alternating lithological facies are likely indicative of changes in the climate and water depth, as there is no open ocean connectivity of the lake. However, limited connectivity via seepage thorough the porous Pleistocene coral barrier is possible. Sediment deposition began in Palm Pond around ~4000 yr BP with the accumulation of a peat/marl facies. This zone is indicative of a period of steady precipitation and not shallow water depths similar to peat/marl (Zone 4) facies in Lake Kalik with. This coincides very roughly with a period of increased precipitation prior to 3200 yr BP found for Andros Island, Bahamas (Kjellmark, 1996). Loss-on-ignition analysis of core PP07 (Fig 5-11) shows a gradual increase in water and organic content upcore finally transitioning over to complete organic deposition (Zone 3) at 3560 yr BP. Zone 3, representing a period of organic deposition (almost entirely peat accumulation), lasts until 2340 yr BP and is likely indicating of a period of greatly reduced precipitation leading to reduced lake levels and lake extent. The timing of Zone 3 (3560-2340 yr BP) coincides well with the period of Pan-Caribbean aridity spanning 3200-1500 yr BP (Brown and Cohen, 1985; Hodell et al., 1991; Burney et al., 1994; Kjellmark, 1996). Around 2340 yr BP the lake transitions to a period of carbonate deposition that exists up until modern conditions. This is most likely due to precipitation returning to above arid levels. Higher amounts of precipitation are reflected in the stratigraphy by increased rates of surface and hillside erosion (Dix et al., 1999). This should lead to the seasonal precipitation out of carbonates out of the water column to the lake surface (Trichet et al., 2001; Scoffin, 1987). The modern sediments are capped by a thin layer of stromatolites that are common in shallow areas with inorganic precipitation (Scoffin, 1987; Dix et al., 1999).

Hurricane History

Interspersed within the history of Palm Pond are five hurricane-induced overwash sand layers and gastropod death assemblages. The deposition of the sand layers appears to be the cause of the mollusk death assemblages as was the case in Lake Kalik, as there are no mollusk death assemblages without a concurrent sand layer. The first sand layer deposited was E1, having been deposited around ~3300 yr BP. The largest of all sand layers, it is present in all cores save PP02 which, due to changes in the lake bottom did not record the event. A second sand layer
Figure 5-14. Stratigraphic cross core correlations for Palm Pond.
was deposited around 2340 yr BP and is only found in cores PP04 and PP06. It is unclear why it is only present in these two cores as there are no low points in the beach barrier fronting the lake to the sea. A third sand layer (E3) was deposited around 2340 yr BP and is present in all cores. Following E3 there is the deposition of E4 and E5 within the sediments of Palm Pond. Given the lack of stratigraphic variation in Zone 2, cross-core correlation is difficult and it is unclear whether the top sand layer in core PP07, dated to 1050 yr BP, is the sand event as E4 or E5. It is likely, however, based on stratigraphic position and $^{14}$C calculated sedimentation rates that it is the same event as E4.

The sand layers located within the sediments of Palm Pond, while distinct from the surrounding sediments, are not nearly as prominent as they are in Lake Kalik. The sand is not as continuous a layer or unit as is found in Lake Kalik. Perhaps due to the high unbroken beach barrier, the volume of sand being transported is as great. Mollusk death assemblages occur simultaneously with the sand layers and are the same mélange of in situ poikilohline Cerithiidae gastropods and *Cumingia antillarum* bivalves (Warmke and Abbott, 1961; Morris, 1975).

$^{137}$Cs analysis again indicates that the top event could possibly be Hurricane Donna, although, yet again it seems unlikely given the depth of the cesium peak. The same issues apply here as in Lake Kalik, namely low sedimentation rate, small sediment samples, and very low near background readings (pCi/g) for the $^{137}$Cs analysis. With a $^{14}$C calculated average sedimentation rate of 0.035 cm/yr for Palm Pond it is exceedingly unlikely that the $^{137}$Cs analysis is correct. Eight centimeters would yield a date of ~240 yr BP. Once again this indicates that Donna, a Category 4 hurricane with a very close landfall to the lake, failed to generate any overwash deposit. Palm Pond had a maximum of five events over 3820 yrs, giving a return period of 764, or an annual strike probability of 0.13%.

**Discussion and Conclusions**

A ~4000 year late Holocene record of lacustrine carbonate and peat sedimentation was deposited in two shallow hypersaline coastal lakes on Acklins Island, Bahamas. Climate change and hurricane history are interpreted from litostratigraphy, biostrigraphy, and $^{14}$C AMS radiocarbon chronology. Analyses indicate that several dramatic changes have occurred on Acklins Island over the last ~4000 yr BP. The sedimentary sequences contain carbonate and organic deposition of varying proportions. Facies were identified based on their biota and sediment characteristics. The two lakes display remarkable variability in sediments. This
disparity in sediments of closely situated lakes is not unusual; Trichet et al. (2001) found that each lake behaves as a spatially independent system with a variety of biogeochemical conditions even under similar climatic conditions.

Both lakes have seemingly remained closed basins with no permanent or long term intertidal or marine connections. There is no evidence to suggest any close connection to the sea, as lagoons or intertidal ponds display sediments with no mats, dominated by shell cements and little fine grained material (Saenger et al., 2006). Nor is there evidence that the lakes were ever dominated by fresh water. Absent from either lake are the presence of any fresh water mollusks indigenous to the area (i.e Amnicola forsythia); only euryhaline species (Purdy and Imbrie, 1964) are found. It appears that the transitions in the lake sediments result from changes in the precipitation and evaporation balance of the basin and its associated effect on the depositional regimes of the lakes (Dix et al., 1999). The sensitivity of each lake varies tremendously. Lake Kalik, the younger of the two lakes, has a much higher sensitivity threshold as it is dramatically affected by the Little Ice Age drying as evidenced by the changes to its sedimentation regime. Palm Pond, however, shows no indication of the Little Ice Age having any effect on its depositional regime. Palm Pond is undoubtedly a much more stable system, only responding to dramatic long-term changes such as the ~1200 yr pan-Caribbean drying of the late-Holocene.

The paleotempestological sensitivity between the two lakes also differs. Lake Kalik, less isolated than Palm Pond due to its undulating beach barrier, received twice as many storms overwash during the same time period (Lake Kalik has four sand layers in ~1000 yrs to Palm Pond’s two). These events are almost certainly hurricane overwash deposits. Given the tectonic stability of the Bahamian platform during recent time, the only likely explanation for these deposits is a high-order eustatic sea level change or the incursion of marine-derived sediments from a hurricane overwash (Dix et al., 1999). Good regional sea level reconstructions (Mylroie and Carew; 1995, Fairbanks, 1989) show no indication of these high-order variations. The presence of overwash marine derived sediments (sand) alongside in situ indigenous biota are in agreement with the study done by Dix et al. (1999) who found similar events, typified by their similar texture to the loose sediments occurring along present day beaches, deposited in an apparent century-scale return period. Dix et al. (1999) found four “marine derived sediments” over 3000 yrs for Lee Stocking Island, Bahamas. This matches up well with the results from Palm Pond, where five events were deposited over 3820 yrs.
The presence of the mollusk death assemblages also indicates a dramatic deposition for the beach-derived sand layers. With all of the in situ biota having euryhaline salinity tolerances, it is exceedingly unlikely that the death assemblages were caused by fluctuations in salinity (Rouchet et al., 2001). Instead it appears that the in situ mollusks were likely killed by burial, as there are no mollusk death assemblages without a sand layer present. This coupled with the presence of offshore bivalves and terrestrial gastropod species mixed in with the in situ population all buried in beach sand certainly enhances the idea of marine-derived transport of the overwash sand layers.

Of the seven hurricanes passing Acklins Island, Bahamas, since 1949 not one has left a discernable signature within the stratigraphy of the lake sediments. With multiple storms (Categories 1-4) passing the island within the modern record, and Hurricane Donna making a direct hit, the fact that none have left a stratigraphic signature indicates that for an event to be recorded in the sediment record of these two lakes it would have to be a very large Category 5 event. This would suggest a Category 5 event or greater paleotempestological sensitivity for these two lakes. Taken as a whole, the events deposited within the sediments of Acklins Island, Bahamas, over the last 3820 yr BP reveal a clear pattern of temporal variability (Fig 5-15), beginning with a period of low/no activity spanning from 3800-3360 yr BP. This is followed by a period of increased activity from ~3300 to 2300 yr BP followed by a period of relative inactivity spanning ~2300-1100 yr BP and a return to increased activity from ~1100 to 300 yr BP. This record, in conjunction with the results of the other two islands in this study, will be used to ascertain what, if any, temporal patterns can be found and how they relate to the establishment of a discernable basin-wide spatial shift in hurricane activity.

Figure 5-15. Temporal variations in catastrophic hurricane strikes for Acklins Island, Bahamas.
CHAPTER 6 ANGUILLA

Introduction

Anguilla, British West Indies (18°05”N, 63°05”W), is the northernmost of the Leeward Islands, 146 miles (235 km) east of Puerto Rico and six miles (10 km) north of St. Martin (Fig 6-1). Anguilla is a long narrow island, 16 miles by three miles at the widest point with a total area of 73.7 km² (35 mi²). A low-lying island composed of coral and limestone, it has a low topography with its highest point (Crocus Hill) at a little over 62 m (203 ft) (Christman, 1953).

Figure 6-1. Location of Rendezvous Pond and Gull Pond, Anguilla.

The north shore is composed of sea cliffs nearly 100 ft high and the south shore is low-lying coastal plains interspersed with numerous natural salt ponds (Christman, 1953), two of which (Gull Pond and Rendezvous Pond) were cored during May 2006. Many of the coastal ponds on Anguilla were used as salt ponds for the collection of raw salt and this offers a potential source of contamination for paleoenvironmental studies done on cores from the coastal ponds of Anguilla. The last bag of salt from Sandy Ground was taken in 1985 (Scott, 2005).

The Leeward Islands are located near the junction of two geological plates, the Caribbean Plate and North Atlantic plates (Fink and Fairbridge, 1975). Divided into two distinct groups, the inner (western) belt of islands that are of recent volcanism in origin (Monserrat, Nevis, St. Christopher, St. Eustace, and Saba) and the outer (eastern) belt, termed the “limestone Caribbees” which include Anguilla, St. Martin, St. Bartholomew, Sombrero, Barbuda, Antigua, Grand Terre of Guadeloupe, Desirade, and Marie Galente (Christman, 1953). Anguilla sits on the outer limestone arc which was tectonically active from the Eocene to the Oligocene (Foster and Johnson, 1988). However, Anguilla is now considered tectonically quiet and there has been no volcanic activity in the Limestone Caribbees since the early-Oligocene (Fairbridge, 1975). Very
limited paleoclimatic data exist for this region of the West Indies and especially sparse are the records for Anguilla (Bertran et al., 2004; Higuera-Gundy et al., 1999). The only regional reconstruction comes from a study on Grande Case St. Martin (Bertran et al., 2004).

Rainfall for Anguilla is seasonal and dominated by the northeast trade winds. There are two distinct seasons, a dry season extending from January to July and a wet season peaking in September/ October with an average annual rainfall of 116 cm (Bertran et al., 2004). Bertan et al., (2004) found that a period of mid-Holocene aridity occurring around ~4,200-2,300 followed by a wet phase from 2300-1150 yr BP. Although this period of precipitation minima appears in the St Martin record slightly earlier than the basin wide trends (3200-1500 yr BP) (Brown and Cohen, 1985; Hodell et al., 1991; Burney et al., 1994; Kjellmark, 1996) there is little other evidence that the environmental history of St Martin and Anguilla differs significantly from that of the rest of the northeastern West Indies. There is a severe lack of fresh water (no surface streams) and the island is dominated by thin in-arable soils that support only scrub brush vegetation.

Anguilla is vulnerable to hurricanes from June to November, with peak hurricane activity running from August to mid-October. A subtropical climate, temperatures for Anguilla range from 27 °C (80 °F) in December to 30 °C (86 °F) in July (Bertran et al., 2004). The modern hurricane history for Anguilla has been well-documented (Neumann et al., 1999) and relatively active with 11 hurricanes passing within 65 nautical miles of its shores post 1947 (Fig. 6-2): 1950 Dog (Cat 3), 1951 Alice (Cat 1), 1960 Donna (Cat 4), 1996 Bertha (Cat 1), 1966 Faith (Cat 1), 1989 Dean (Cat 1), 1995, Luis (Cat 4) 1998, Georges (Cat 3), 1999 Jose (Cat 1), 1999 Lenny (Cat 3), and 2000 Debbie (Cat 1).

Figure 6-2. Tracks of hurricanes passing within 65 nautical miles of Anguilla since 1947 (Neumann et al., 1999).
Methods

Cores were taken using a modified Livingstone piston corer made of clear plastic PVC tubing. Sealed and capped in the field, the sealed cores were returned to LSU for laboratory analysis. In the laboratory cores were examined to determine changes in lithology, sedimentology, and biostratigraphy. The Livingstone cores were passed horizontally through an automated Geotek multi-sensor core logger to measure sediment density, a measurement used to interpret changes in grain size. Gamma density was measured from a beam of gamma rays emitted from a $^{137}$Cs source (10mCi) with energies principally at 661 keV (Keen et al., 2004), which is used to estimate bulk density. By measuring the number of unscattered gamma photons that pass through the core unattenuated (at 661 keV), the density of the core material can be determined (http://www.geotek.co.uk/ftp/manual.pdf). A function of grain size, mineralogy, and water content, gamma density is an ideal measurement for the identification of overwash sand layer found within the core sediments. Following the Geotek analysis, cores were split lengthwise and one half (the “working” half) was used for the rest of the analysis and the other half was archived. Cores were scanned and a digital image was captured for each archive core. Visual analysis was performed to determine downcore changes in lithology and changes in sediment color and stratigraphy were noted. Following the visual inspection, core sediment stratigraphy (% water, organic, carbonate, and silicate) was determined at 1 cm$^3$ intervals continually using loss-on-ignition (LOI) techniques (Dean, 1974). Age control was established via interpretation of radiocarbon ($^{14}$C) and cesium ($^{137}$Cs) decay curves. Six samples were sent to Beta Analytic Laboratories, Miami, FL, for AMS $^{14}$C dating. $^{137}$Cs was done in-house with the assistance of Dr. Ron Delaune, and was used specifically for the identification of the stratigraphic signature left by Donna (1960), as well as high resolution dating of overwash layers for the last ~50 years (Ab Razak et al., 1996; Jaakkloa et al., 1983).

Gull Pond

Description of Study Site

Gull Pond (Fig. 6-3) is a hyper-saline (69.0 ‰) lake located along the southeastern coast of Anguilla (local ocean salinity 41.5 ‰). A tranquil lake with no riverine or tidal influences and a large sandy beach, Gull Pond is an ideal study site for paleotempestological research. It is a southwestern-facing lake and is located perfectly to receive allochthonous marine-derived
sediments. In May 2006 a total of seven cores were extracted from Gull Pond with none longer than 40 cm.

**Lithostratigraphy, Biostratigraphy, and Sediment Composition**

The sediments currently accumulating in Gull Pond are delicate (¼ to 1 mm thick) laminations of cyanobacterial mats exhibiting sharp chromatic stratification interspersed with numerous (between 3 and 6) golden sand layers identified by the LOI analysis. Due to unforeseen complications, Gull Pond was the only set of cores run through the Geotek. However, this presented little problem as further analysis of the Geotek data did not add anything significant to the analysis. Comparison of the bulk density parameter with LOI techniques revealed that the two analyses were yielding the same information and there was nothing to be gained by using both measurements (Appendix 3). Two transects were taken landward from the beach barrier order to determine the extent of the sand layers: Transect 1 (GP01, 02, 03, 05), and Transect 2 (GP06, 07). Examination of LOI results for GP02 (Fig 6-4) shows that the only departure from the fairly stable accumulation of the cyanobacterial mats occurs when the regime is interrupted by the deposition of golden sand layers. These sand layers are typified by much lower water and organic contents as well as an increase in carbonates and they show up as easily identifiable pronounced dips and peaks on the LOI figures. In core GP02 (Transect 1) interspersed within the laminated cyanobacterial mats were a maximum of seven golden sand layers occurring at 2-6 cm, 14 cm, 16 cm, 18 cm, 20 cm, 25 cm, and 28-38 cm, all sandwiched by sediments with an average LOI content of 6.45 % organic, 40.30% carbonate, and 53.24% silicate (Fig 6-4). Comparisons of the sand layers to the beach sand samples collected show that they are very similar in both lithology (2.85 % organic, 41.55% carbonate, 55.60% silicate) and in color and texture. Analysis was done for all cores along both transects and cross-core correlations were established to determine the spatial extent of each sand layer within the lake. All seven cores ended in the same poorly-sorted coarse-grained gastropod-laden sand layer (Fig 6-5a). This bottom layer differs from all other sand layers as it has a chaotic pattern of deposition.
Figure 6-4. Results of stratigraphic and loss-on-ignition analysis for Gull Pond cores GP02 and GP07.
(no fine sorting), and a very fine sediment layer on top as indicated in the dramatic dip in water and organic percentages (Fig 6-4).

**Mollusks**

In all cores from Gull Pond and Rendezvous Pond a prominent death assemblage occurs within the bottom sand layer (Fig 6-5). Sporadic individuals were found throughout the core sediments but with no significant accumulation larger than one or two individuals. Mollusks were sampled from the death assemblage in the bottom layer to identify genus, and where possible, species. Prior studies for hypersaline ponds in the Bahamas have identified a number of localized species. Kjellmark (1996) and Dix *et al.* (1999) found gastropods (*Batillaria minima*, *Cerithidea costa*) as well as tellinid bivalves (*Cumingia antillarum*) in the core sediments from Andros and Lee Stocking Island, Bahamas, respectively. Species identified from a study in Barbuda (Brasier and Donahue, 1985) included *Batillaria minima, Bulla striata*, and *Cerithium eburneum*, whereas another study from St. Martin (Bertran *et al.*, 2004) found *Batillaria minima* and *Anomlocardia brasiliiana* (bi-valve). There was no bi-valve assemblage present in the Anguilla cores only gastropods. The mollusks were brought to the LSU Museum of Natural Science for comparison with specimens in preserved fossil collections. Using mollusk identification keys (Warmke and Abbott, 1961; Morris, 1975;

![Figure 6-5](image)

**Figure 6-5.** Gastropod assemblages for Gull Pond and Rendezvous Pond. Inset (A) is field photo of gastropod laden bottom layer.
Andrews, 1994; Abbot, 1974) in conjunction with comparison to specimens in the fossil collections, the mollusks present in both lakes were tentatively identified. Following preliminary identification, specimens were sent to Dr. Fred Thompson, the curator of malacology at the Florida Natural History Museum, to confirm the initial identification. The assemblage was dominated by members of the family Cerithiidae which exhibit elongated, many-whorled shells with vertical ribs or groves, a round aperture and flaring lip, and live in moderately shallow waters of the tropics or subtropical region (Morris, 1975). *Cerithidea costata*, *Cerithium eburneum*, and *Batillaria minima*, tentatively identified to the species level, are all endemic to mud flats, mangrove swamps, and landlocked marine ponds, often occurring in huge numbers (Warmke and Abbott, 1961; Williams and Williams, 1998; Bertran et al., 2004). All are poikilohaline species with a very broad salinity tolerance ranging from 0.05-300‰ (Purdy and Imbrie, 1964). No freshwater mollusks indigenous to the area (e.g. *Amnicola forsythia*) were found in the cores only euryhaline species (Purdy and Imbrie, 1964).

**Radiocarbon Chronology**

Chronological control was based on AMS radiocarbon dating of organic material (peat or organic detritus), organic matter in bulk sediments, or mollusk (gastropod) shells.

![Graph of radiocarbon dates against sediment depths in GP02 and GP07 cores.]

**Figure 6-6.** Plot of calibrated radiocarbon dates against sediment depths in GP02 (left) and GP07 (right), selected calibrated dates are in bold.
A plot of age against depth shows that the radiocarbon chronology for Gull Pond is good (Fig 6-6). Dating on separate cores (GP02, GP07) shows very similar dates, as well as good depth to age correlation ($r^2$ of 0.99 each). All dates had multiple intercepts with the radiocarbon curve except for Beta-228636 which had a single intercept. When interpreting radiocarbon dates variations in atmospheric $^{14}$C concentrations results in a nonlinear relationship between radiocarbon age and calendar time and often leads to multiple possible age ranges (Bartlein, et al., 1995; Stuiver et al., 1998). Results from Beta Analytic indicated multiple age ranges for the Gull Pond cores within the 1 sigma (1σ) 68%, and 2 sigma (2σ) 95% probability ranges and they are listed below (Table 6-1).

It is generally accepted that calendar ages with the highest probability occur at the radiocarbon intercept with the calibration curve (Donnelly et al., 2001a). There were multiple intercepts for the Gull Pond dates. The basal date (Beta-228636) is single intercept and has a calibrated age of Cal BP 250, and is used as a basis for selection of the other radiocarbon dates. The later dates in cores Beta-228633 and Beta-228634 (280 and 260 respectively) were discarded as they were both sampled higher up on the core and could not yield an older date than the basal sample, allowing for the selection of Cal BP 180 and 170 respectively. Selected calibrated dates (symbolized in bold) were used in the analysis (Table 6-1).

**Table 6-1. Radiocarbon dates and calibrated calendar years for Gull Pond, Anguilla.**

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<td>Cal BP 20 to 0</td>
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**137Cs Chronology**

Sediment for $^{137}$Cs dating was sampled from Cores GP11 (taken directly adjacent to GP10) and GP04 (taken directly adjacent to GP05), both 3” diameter aluminum cores taken solely for geochemistry analysis. The top 2 cm of laminated cyanobacterial mats was sampled to the top of the sand layer presumed to be Hurricane Donna. The remaining sediment was sampled from directly under the presumed Donna layer in GP04 at 1 cm intervals from 3-8 cm, stopping above the 2nd sand layer. The $^{137}$Cs peak is located at 6 cm (Fig 6-7). With the $^{137}$Cs peak
(corresponding to 1963) directly below the layer assumed to be Hurricane Donna (1960) initial indications are that the sand layer in question is unlikely to have been deposited from Hurricane Donna.

Figure 6-7. $^{137}$Cs results for Gull Pond.

Summary

Radiocarbon dating indicates an average age of 250 yr BP for the sediments accumulating in Gull Pond. The stratigraphy of Gull Pond consists of gelatinous laminated cyanobacterial mats, a common feature of Caribbean hypersaline ponds (Saenger et al., 2006), underlain by a large coarse-grained sand layer that contains a substantial gastropod death assemblage (Fig 6-8). In Transect 1 there are seven sand layers deposited in the near shore core, GP02, and only three sand layers in the cores farther away from the beach (GP03 and GP05). The sand layers are dramatically distinct from the surrounding sediments and are consistent in content (%water, organic, carbonate) as well as in grain size and color with that of the beach sand fronting the lake, indicating the beach as the source of the deposit. This interpretation is further enhanced by the surrounding landscape, which is composed of relic corals and limestone with little or no soils, leaving the beach face as the only possible source for the deposited sand. These sand layers are determined to be the result of hurricane overwash based on the following
Figure 6-8. Gull Pond stratigraphic and lithological correlations.
characteristics: (1) visual inspection of the sand layers shows an upward fining sequence; (2) the sand layers are a homogenous golden color; and (3) overall, the layers tend to thin and dissipate landward (as indicated by more event layers in the near shore cores). These are all typical characteristics of hurricane overwash deposits as described in Chapter 2. These allochthonous marine-derived sediments are visually and sedimentologically distinct from the normal depositional regime of the lake and have a very sharp contact with the underlying sediment indicating a rapid deposition, like that associated with hurricane storm surges.

$^{137}$Cs analysis indicates that the top sand layer was deposited by a storm after 1963. Sedimentation rate based on the $^{14}$C dating (calculated without the sand layer deposit accumulations) is $\sim$0.07 cm/yr. The calculated sedimentation rate based on the $^{137}$Cs analysis is $\sim$0.09cm/yr, which is very similar. Based on its position in the core stratigraphy as well as its positive correlation with the radiocarbon-calculated sedimentation rates, it is probable that the $^{137}$Cs dating (peak) is correct here. If the analysis is indeed correct then the top event layer could not have been deposited by Hurricane Donna. Given a sedimentation rate of $\sim$0.07- 0.09 cm/yr, and the top event occurring at $\sim$1 cm below the modern surface, that event would most likely be Hurricane Luis (Cat 4, 1995). This correlates well with estimates from sedimentation calculations which would put 1995 at 0.84 - 1.08 cm. Given that the top overwash layer was likely deposited by Hurricane Luis, it has left the largest and most significant deposit in the lake. The rest of the overwash layers found within the cores are much thinner, and do not extend into the lake any great distance, indicating overwashes from smaller storms or a large storm with a more distant passing.

The origin of the bottom sand layer is intriguing. It demonstrates a general upward fining sequence and likely suggests a large catastrophic event. The bottom of the deposit was never penetrated so the lower extent cannot be known. This layer differs from the other hurricane-generated sand layers in the cores as the sediments are chaotic (not clean and poorly-sorted) and there is an abrupt very fine sand layer near the top of this bottom sand layer, as seen in the drastic dip shown by percent water at the top of each layers in the LOI values (Fig 6-4). These sedimentary features (chaotic, poorly-sorted) would seem to suggest a tsunami deposit, as would the fine top layer, characteristic of the final “low energy layer” or “mud cap” that settles out during the final moments of a tsunami (Dawson and Stewart, 2007; Nanayama and Shigeno, 2006). This is in direct contrast to features resulting from hurricane overwash that has a gradual
return flow at the end of the initial event (Morton et al., 2007) with little or no backflow reworking, resulting in the lack of internal stratigraphy. The coupling of fine/coarse grain sizes in the internal stratigraphy of this bottom layer is an indication that these are not hurricane deposits or at least not typical hurricane deposits. However, the gastropod assemblages are very well preserved and there is no breakage and damage (similar to those associated with the hurricane overwash deposits on Acklins Island, Bahamas), which is not typical of an abrupt event with a large amounts of run up and backflow. The mechanism behind this large deposit is unclear.

**Rendezvous Pond**

**Description of Study Site**

Rendezvous Pond (Fig. 6-9) is 4.8 km (2.89 mi) northeast of Gull Pond, also facing the southwest, partially isolated in a horseshoe-shaped cove. Nearly identical to Gull Pond in environmental setting, Rendezvous Pond has a salinity of 59.5 ‰ and also has no riverine or tidal influences. Fronted on the seaward side by a sandy beach, Rendezvous Pond also has great potential to receive and preserve marine-derived overwash sediments. In May 2007, eight cores were retrieved from Rendezvous Ponds, none longer than 55 cm.

**Figure 6-9. Rendezvous Pond coring**

Two transects were taken landward, away from the barrier: Transect 1 (RP01, 02, 03) and Transect 2 (RP07, 08). Cores RP05 and RP06 were taken between the two transects to expand coring coverage. The sediments from Rendezvous Pond also consist mainly of thin laminae of cyanobacterial mats. This is the only lithological facies accumulating within the lake. The cyanobacterial mat accumulation is periodically interrupted by the deposition of several golden sand layers. Similar to Gull Pond, the sand layers are drastically distinct from the surrounding cyanobacterial mats, both visually and lithologically. Easily identified both visually and by LOI analysis, sand layers show up as dips in both water and organic content and peaks in carbonates.
(Fig 6-10). Also in concert with Gull Pond, all of the cores taken from Rendezvous Pond end in the same coarse chaotic sand layer mixed with copious amounts of gastropods and are capped by a fine-grained layer. Transects 1 and 2 have three large sand layers contained within the core sediments in addition to the large impenetrable bottom layer. Cores RP05 and RP06 have five sand layers in each core.

Radiocarbon Chronology

A plot of the age to depth relationship between the two radiocarbon dates from Rendezvous Pond shows a poor correlation (Fig 6-11). The two $^{14}$C dates are stratigraphically reversed and are both rejected. The sample from 13 cm in RP06 (Beta-228637) had a single intercept and a calibrated date of Cal BP 650. This date is far too old to be considered. Beta-228638 had multiple intercepts and possible calibrated dates of: Cal BP 60, and Cal BP 40; both dates are too young to be possible. So due to the inconsistencies in the radiocarbon dating for
Rendezvous Pond, age correlations were done based on cross-correlation with the stratigraphy of Gull Pond.

![Graph showing age correlation for Rendezvous Pond]

Figure 6-11. Plot of calibrated radiocarbon dates against sediment depths for RP06.

**137Cs Chronology**

Sediment was sampled for the presence of $^{137}$Cs from the top 1 cm from core RP04 (taken adjacent to RP02). The event layer presumed to be Hurricane Donna went from 2 – 7 cm. Sampling continued at 1 cm intervals from 7-13 cm. The $^{137}$Cs peak is found at 1 cm (Fig. 6-12)

![Table showing $^{137}$Cs analysis for Rendezvous Pond]

Figure 6-12. Results of the $^{137}$Cs analysis for Rendezvous Pond.
indicating a date of 1963. This would indicate that the sand layer deposited immediately below it could possibly be Hurricane Donna.

**Summary**

The stratigraphy of Rendezvous Pond mirrors that of Gull Pond, and consists of the same laminated cyanobacterial mats interspersed with a few golden sand layers underlain by a large coarse-grained sand layer containing a large gastropod death assemblage. Radiocarbon dating is poor for Rendezvous Pond so the basal date from Gull Pond will be used as there is excellent stratigraphic correlation between the two with the large basal layer contained in the sediments of both lakes. Given that, it is further assumed that the basal layer here was deposited at the same time as the layer in Gull Pond, indicating that the sediments in Rendezvous Pond have been accumulating for the same time period, ~250 years. Further correlations *i.e.* depth *vs.* age, or correlation between individual sand layers between lakes, would be tenuous at best as the accumulation rate of the laminated cyanobacterial mats differ vastly based on the localized hydrostatic budget of the individual basins (Paerl *et al.*, 2003; Trichet *et al.*, 2001).

Transects 1 and 2 (Fig. 6-13) in Rendezvous Pond identify three prominent sand layers deposited within the 250 years of sediment accumulation. RP05 and RP06 taken between the two transects contain four and five sand layers, although not nearly as prominent as the sand layers in the two transects. Here again, these sand layers are assumed to be hurricane overwash deposits based on the same rationale stated in the Gull Pond summary. $^{137}$Cs dating of the Rendezvous Pond sediments indicates that the top sand layer was deposited prior to 1963. This presents a problem for correlation with Gull Pond. If the $^{137}$Cs peak is correct, it would indicate that the sediments of Rendezvous Pond are accumulating at a rate of 0.02 cm/yr, a rate that is fully four times lower than that of Gull Pond at 0.08 cm/yr. Given the relatively stable modern climate for Anguilla, this seems unlikely. If the bottom event in Rendezvous Pond was deposited at 250 yr BP, that would indicate a sedimentation rate of 0.08 cm/yr for RP02, a rate in sync with the Gull Pond record. It is likely that the $^{137}$Cs peak here is incorrect. Given a 0.08 cm/yr accumulation rate it is likely that the top event would most likely again be Hurricane Luis (Cat 4, 1995) in direct correlation to Gull Pond. Continuing on in that logic, at 3 cm below the assumed Hurricane Luis layer is a second sand layer that, if using the 0.08cm/yr accumulation rate would correlate to the date of ~1958, possibly deposited by Hurricane Donna. Storms were both Category 4, with similar paths and similar depositional features. A third hurricane overwash is
Figure 6-13. Stratigraphic and lithologic correlations for Rendezvous Pond.
deposited before the deposits of Hurricane Donna and Luis and is roughly the same size and extent, possibly indicating another strike by a Category 4 hurricane around ~1895 (or 112 yr BP.

At any rate, poor dating control for Rendezvous Pond only allows for speculation. While it is strongly believed that the Rendezvous Pond summary is accurate, the lack of sufficient dating control makes it difficult to determine accurately, and parsimony dictates that it be presented as speculation.

Discussion and Conclusions

Analysis of both Anguillan lakes shows remarkable stratigraphic similarity. There are no apparent changes to the depositional regime for the lakes of Anguilla that reflect any environmental shifts. For the last ~250 yr BP there has only been the accumulation of laminated cyanobacterial mats, indicating that the hydrologic budget of each lake has remained within the tolerances suitable for the survival of cyanobacterial, i.e. salinities less than 175‰ (Bebout et al., 1993, Rouchet et al., 2001). There is no evidence of extreme aridity, and no accumulation of peats or the evaporitic deposition of halite or NaCl (Saenger et al., 2006). It appears that based on the stability of the sediments found accumulating in the Anguillan lakes that for at least the last 250 years, the climate and hydrological budget of Anguilla has not fluctuated dramatically.

During those 250 yrs three to six layers were deposited within the sediments that are interpreted to be hurricane overwash deposits. Radiocarbon and cesium dating for Gull Pond indicates that the top event layer in each core was deposited by Hurricane Luis, a Category 4 hurricane that struck Anguilla in 1995. This would indicate that Gull Pond has only recorded one Category 4 storm in the last 250 yr and that the other overwash sand layers were the result of smaller storms or larger storms passing farther away. Rendezvous Pond has three prominent event layers of roughly the same size and extent. If the assumed correlations between Gull Pond’s basal date and sedimentation rates are correct, the top two deposits were from Hurricane Luis and Donna with a third possible Category 4 hurricane, indicating that Rendezvous Pond has recorded three Category 4 storms over its 250 yr history.

Disparity in the number of event layers found in each lake is not unusual. It is well known that not every storm is accompanied by supra-tidal deposits (Perkins and Enos, 1968). Numerous factors determine whether an overwash fan is generated, differing paleotempestological sensitivity of each lake (barrier height, facing direction), differing approaches of the storm overwash in relation to the lake, the path of storm, and position of the
eye wall in relation to the lake at landfall (Fletcher et al., 1995). So even though the two lakes were a mere 4.8 km apart, they exhibited different sensitivities to hurricane strike and recorded different hurricane histories for the same time period.

Cores from both lakes, however, did end in the same large chaotic gastropod-laden sand layer. It is unclear whether this layer is the result of a tsunami or a hurricane deposit, as the depositional signature has elements of both and could possibly be attributed to either. The nature of this deposit cannot be resolved without further coring and penetration of the full extent of the layer.

Once again there are discrepancies in $^{137}$Cs peak between the sediments of the two lakes. This is most likely a function of the low readings of pCi/g in the soil due to the low sedimentation rates of the lakes, as well as the limited amount of sediment available for analysis. Future studies of these hypersaline lakes (or any low sedimentation lakes) will need larger diameter core samples > 3″, to be used specifically for $^{137}$Cs analysis. Despite being used in some capacity as a salt pond, it appears that both lakes (at least near the coring sites) have not been disturbed as indicated by the presence of undisturbed laminations.

Working on the assumption that only Category 4 or greater storms left a depositional signature in the lakes past the nearshore cores, a return rate for catastrophic hurricane landfall for Anguilla can tentatively be placed at 83 years, or an average annual strike probability of 1.2%. This calculation does not take into account the bottom unknown event layer. The bottom of this event was never penetrated, so an accurate deposition date cannot be calculated. A review of the tsunami studies for the Caribbean (Scheffers, 2002; Schubert, 1994; Kelletat et al., 2004; Hearty, 1997; Moya, 1999; Scheffers et al., 2005; McMurty et al., 2007; Jones and Hunter, 1992) does not reveal any tsunami deposits younger than 500 yr BP for the region, so in all likelihood this is a very large hurricane deposit. It is also possible (although unlikely) that this event could in fact be a basal sand layer. Future work on Anguilla may reveal the mystery of the bottom event. It is quite possible that the bottom event layer could be penetrated with the right equipment such as a vibra-corer and then the extent of this large layer could be determined and a much longer environmental and hurricane history determined.

Given that every storm is not recorded in the sediment record, a caveat must be stated that, at best, the records determined from a paleotempestological study are a very conservative estimate of hurricane landfall frequency. The record from Anguilla only gives a 250 yr history of
hurricane strikes (Fig 6-14) and environmental change, a period too short to detect any low-frequency or millennial-scale shifts. However, the preliminary return interval of 83 years (three Category 4 hurricanes over the last 250 years) helps to add valuable data to a region where none existed previously.

Figure 6-14. Hurricane landfall frequency for Anguilla.
CHAPTER 7 BARBUDA

Introduction

The Caribbean Island of Barbuda (17.35º N, 61.49º W) is the outermost island of the Leeward island arc, 40 km north of Antigua (Fig. 7-1). It has a total area of 174 km² with nearly 20 percent of that dominated by shallow lagoons and tidal ponds (Wigley, 1973). The majority of the island is relatively low-lying (< 7 m) with an elevated portion to the east locally known as the eastern highlands (maximum elevation of 39 m). Covered in scrub woodlands with poorly developed soils, the lowlands are characterized by minimal topography and flat limestone pavement (Wigley, 1973). Often regarded as part of the limestone Caribbees, Barbuda is actually somewhat of an anomaly, existing 100 km east of the active volcanic Caribbees and 50 km northeast of the limestone Caribbees arc (Brasier and Donahue, 1985). Situated on an “anomalous block”, the low-lying island of Barbuda is made up of limestone of Tertiary age (Fairbridge, 1975; Wigley, 1973; Martin-Kaye, 1969). Subsequent studies of Barbuda’s geology have shown that in contrast to the Caribbean islands of the volcanic arc, Barbuda has remained relatively level and stable throughout the Pleistocene (Brasier and Donahue, 1985). Barbuda has many coastal lakes perfect for this type of study and in conjunction with the relative geological stability post-Pleistocene, Barbuda has the potential to yield excellent undisturbed Holocene sediments. Rainfall averages are low and there is a high rate of evaporation. Annual precipitation for Barbuda ranges between 790 and 990 mm, distributed during two seasons--a wet season.

Figure 7-1. Location map of Barbuda and field research site.
running from October to December and a dry season from March to June (http://www.antiguamet.com).

A look at the modern hurricane history of Barbuda (Fig 7-2) reveals that since 1947 Barbuda has had a busy hurricane history with twelve hurricanes passing within 65 nautical miles of the island: 1950 Dog (Cat 2), 1950 Baker (Cat 2), 1954 Alice (Cat 1), 1960 Donna (Cat 4), 1966 Faith (Cat 2), 1989 Hugo (Cat 4), 1990 Klaus (Cat 1), 1995 Luis (Cat 4), 1996 Bertha (Cat 1), 1998 Georges (Cat 3), 1999 Jose (Cat 2), 2000 Debbie (Cat 1), including direct hits on the island by Donna and Luis, both of Category 4 intensity (Neumann et al., 1999).

**Methods**

In August 2006 a total of eleven cores were retrieved from Barbuda Salt Pond, all to bedrock, with no core exceeding one meter in length. Cores were taken using a modified Livingstone piston corer and were sampled in three transects landward from the sand barrier in an effort to ascertain the extent of the overwash deposits from Hurricane Donna. Core tubes and their sediments were sealed and transported back to Louisiana State University for analysis. In the laboratory, cores were split lengthwise and a mono-filament wire was passed through the sediment to separate the sediments in half. One half was used in the sediment analysis and the other half was archived in storage. All cores were scanned and a digital image was captured. Visual analysis was performed to determine down-core changes in sediment stratigraphy and color. Following the visual inspection, core lithology (% water, organic, carbonate, and silicate) was determined at 1 cm³ intervals continually using loss-on-ignition (LOI) techniques (Dean, 1974).

Core chronology was established by means of radiocarbon (¹⁴C) and cesium (¹³⁷Cs) dating. Six samples (bulk sediments) were taken from cores BSP10 and BSP13. The samples were sent to Beta Analytic Laboratories, Miami, FL, for AMS ¹⁴C dating. The samples were selected stratigraphically to ascertain the dates of lithological changes and to identify presumed
storm events and any changes found in periods of activity. $^{137}$Cs analysis was done at LSU in the lab of Dr. Ron Delaune and was used specifically for the identification of the stratigraphic signature left by Donna (1960), but will also be used to identify overwash layers for the last ~50 years (Ab Razak et al., 1996; Jaakkloa et al., 1983).

**Barbuda Salt Pond**

**Description of Study Site**

Located at the southeastern corner of Barbuda, Barbuda Salt Pond (17° 33’ N, 61° 45’ W), is a tranquil hypersaline (81.3 ‰) coastal pond with an average depth of < 1 m and no fluvial input. Located along a flat coastal plain, the lake basin has little source material for lacustrine deposition. During August 2006, eleven cores were extracted from Barbuda Salt Pond along three transects (Fig.7-3). The lake itself is fronted to the seaward side by a low sand barrier (> 1 m) with very sparse scrub vegetation, mostly mangroves. To the northeast of the lake, along the seaward edge, there is a large subaerial overwash fan deposit. The lake surface is estimated to be <.5 m above sea level with a solid fringe of red mangroves (*Rhizophora mangle*) dominating the edges of the lake, a typical mangrove swamp community for hypersaline Caribbean lakes (Jarecki and Walkey, 2006).

**Lithostratigraphy, Biostratigraphy, and Sediment Composition**

Analysis of core lithology shows that the sediments are typically pale white to dark grey carbonate marls interspersed with a large number of sand layers (Appendix 5). No major lithological changes appear to be associated with the sediments of the Barbuda Salt Pond cores. Slight color changes are visually apparent in the sediments, beginning with dark grey marl at the bottom, gradually shifting to lighter grey marl, and returning to darker grey marls toward the top.
of the cores. This trend is not apparent in Transect 1, which only reflects the dark grey marl in the top section of the cores. A look at the LOI analysis results for core BSP10 (Fig. 7-4) indicates

Figure 7-4. Results of loss-on-ignition and sedimentological analysis for BSP10, Barbuda.

that the sedimentary history of Barbuda Salt Pond has been relatively stable. There are no major lithological changes to the sediments associated with the subtle but distinct color changes. The dark marls are slightly higher in organic content and display a slight reduction in organic content when transitioning to/from the white marl facies (Fig 7-4, see arrows at 70 cm and 17cm). The only major disruption to the seemingly stable regime of carbonate accumulation is the intrusion of the sand layers. The sand layers, distinct in lithology, are clearly identified by dips in the water and organic contents of the cores (highlighted by the gray bars in Fig 7-4) and for the most part slight increases in carbonate content, while not as distinct as in other lakes presumably due to the already high carbonate content of the sediments. While there are no abrupt changes to the sediments of Barbuda Salt Pond, there is a steady transition toward increasing carbonate concentration up-core. A look at the changing lithological trends for Barbuda Salt Pond created
from the LOI results of BSP10 (Fig. 7-5) clearly indicates that as the lake has aged there has been a noticeable decrease in organic content and an increase in carbonate content up-core.

![Figure 7-5. Plot of carbonate and organic contents for BSP10. Trend lines were added to highlight the gradual change in content of the sediments.](image)

**Radiocarbon Chronology**

![Figure 7-6. Plot of radiocarbon ages vs. depth for cores BSP10 (left) and BSP13 (right).](image)
A plot of the radiocarbon dates (Fig. 7-6) shows good consistency among the dates in each core ($r^2 = 0.933$ and 0.964). However, the depth-age relationship is slightly off, intercepting the y axis at depths below zero. This is likely due to the inclusion of the many sand layers, which, as an abrupt event, would have the effect of artificially increasing the sedimentation rates and thereby accounting for the misaligned age-to-depth ratio.

Again, when interpreting radiocarbon dates it is important to become conscious of the continual variations in atmospheric $^{14}$C concentrations that leads to a nonlinear relationship with radiocarbon ages and calendar time, frequently resulting in multiple calendar age ranges (intercepts) for each radiocarbon age (Bartlein et al., 1995; Stuiver et al., 1998). Results from Beta Analytic indicated multiple possible age ranges for the Barbuda Salt Pond cores within the 1 sigma (1σ) 68% probability, and 2 sigma (2σ) 95% probability ranges and they are listed in Table 7-1. It is accepted that calendar ages with the highest probability occur at the radiocarbon intercept with the calibration curve (Donnelly et al., 2001a). All but two of the BSP dates were single intercepts, and the two samples that had multiple intercepts were essentially the same dates (<40 yrs); so the middle date was used. The selected calibrated dates used in the analysis are listed in bold in Table 7-1.

$^{137}$Cs Chronology

Sediment was sampled for the $^{137}$Cs analysis from core BSP14 (taken adjacent to BSP10) at 1 cm intervals for the first 3 cm, stopping at the top sand layer, assumed to be Hurricane Donna. Sampling resumed following the sand layer from 10-12 cm. The peak in cesium activity, corresponding to 1963, occurs here at 2 cm depth, indicating that the sand layer immediately
following the activity peak was deposited before 1963, which is consistent with the age of Hurricane Donna.

### Summary

A ~5000 year history of increasing/decreasing carbonate/organic sedimentation was recorded in a shallow hypersaline coastal lake in Barbuda. Analyses show three color transitions and many overwash sand layers contained within the ~5000 yr history for Barbuda Salt Pond (Fig 7-8). A chronology for the sediments was created using $^{14}$C AMS radiocarbon and $^{137}$Cs dating techniques. Sediments began accumulating in the lake around 4970 Cal BP, and are composed of dark grey marls interspersed with many numerous sand layers. At ~2300 Cal BP the sediments changed from the dark grey marl to a light grey almost white marl with a slightly lower organic content. This depositional phase continues until ~500 yrs ago when the sediments changed back to a dark marl. There is little reflection of the color changes in the sediment lithology other than a slight decrease in organic content with the white marl. Studies of Caribbean sea level change (Toscano and Macintyre, 2003; Fairbanks, 1989; Digerfeldt and Hendry, 1987; Mylorie and Carew, 1995; Taylor et al., 1985; Blanchon et al., 2002) show a
Figure 7-8. Results of stratigraphic and lithologic changes for transects 1, 2, and 3, Barbuda Salt Pond.
minimal (> 4 m) sea level rise for the last 4000 yr BP for the Caribbean in general. Localized records for Barbuda show that Holocene sea levels reached modern levels around 4085 yr BP (Brasier and Donahue, 1985), so it is unlikely that the color changes result from sea-level changes.

A period of pan-Caribbean aridity existed from ~3200-1500 $^{14}$C yr BP (Brown and Cohen, 1985; Hodell et al., 1991; Burney et al., 1994; Kjellmark, 1996; Bertran et al., 2004; Higuera-Gundy et al., 1991) and it is likely that this period of aridity is what is being reflected within the sediments of Barbuda Salt Pond. While occurring slightly later for Barbuda (2300-500 yr BP), the basin-wide period of aridity would undoubtedly have affected this shallow Caribbean pond. It is known that high sea levels or frequent inundation tends to result in large-scale extraction of CaCO$_3$ in shallow waters and thereby increased calcareous deposition (Scoffin, 1987). Barbuda Salt Pond has a very low overwash barrier and likely receives input from the sea, either as flooding events or via an underground porous connection. A frequent influx of sea water would allow for the enrichment of calcite and aragonite into the pond, and as the climate dried and evaporation rates increased there would be an increase CaCO$_3$ deposition at the expense of organic production, accounting for the change in sentiment color (Trichet et al., 2001). There is no accumulation of peats or evaporite accumulation within the sediments of Barbuda Salt Pond, indicating that the lake never dried completely and that salinities probably never exceeded 175 ‰ (Jarecki and Walkey, 2006). Seawater incursions would account for the lack of peats and evaporitic materials. While mineral saturation increased in the water column to the point of CaCO$_3$ precipitation (Scoffin, 1987), the sea water intrusions kept water levels high enough to limit mangrove encroachment, and salinities low enough that it never reached the point of evaporitic deposition. The return to darker grey marls around ~500 yr BP may be indicating the return to the original depositional regime.

During this ~5000 yr history of Barbuda Salt pond, a large number of overwash sand layers were deposited into the lake (Fig 7-8). Transect 1, taken directly out from the subaerial overwash fan, has 12 sand layers in the nearshore core (BSP01) and 9 in the core taken farthest from the beach (BSP03), 130 meters from the shoreline. Of the 12 sand layers none is more prominent than the third event, believed to be Hurricane Donna. This is the largest and by far most prominent sand layer in the transect. Transect 2 has more sand layers deposited in the landward cores than in the nearshore cores; BSP10 has seven sand layers and BSP13 has
The reason for this is twofold. First, radiocarbon dating indicates that BSP13 is 900 years older than BSP10 and hence would have likely recorded more events. Second, the nearshore sand layers can potentially represent multiple storm deposits. Transect 3 has ten sand layers in the nearshore core (BSP15) and five sand layers in core BSP17 taken 130 meters into the lake away from the shore. Here again the top layer presumed to be Hurricane Donna is the largest and most prominent sand layer in the cores.

\(^{137}\text{Cs}\) analysis indicates a peak in activity at 2 cm for Barbuda Salt Pond. This indicates that there is a high likelihood that the event immediately below the 1963 \(^{137}\text{Cs}\) peak was deposited by Hurricane Donna in 1960. This first large sand layer is easily the most prominent sand layer in every transect. Its thickness decreases as the fan extends into the lake. Assuming the \(^{137}\text{Cs}\) analysis is correct it would appear that for transects 2 and 3 there have been no event layers deposited since 1963, despite direct hits from three hurricanes: Luis, 1995 (Cat. 4), Bertha, 1996 (Cat. 1), and Debbie, 2001 (Cat. 1). Despite its low beach barrier there appears to be no deposition from the weaker storms that made direct landfall on the island. There seems to be no evidence for Hurricane Luis (Cat. 4, 1995) in transects two or three. It is possible, however, that the large subareal fan extending into the northeast corner of the lake was deposited by Hurricane Luis and one of the top thinner sand layers in Transect 1 is the stratigraphic expression of that fan.

Given the lack of stratigraphic markers within the sediments of Barbuda Salt Pond it is difficult to correlate the sand layers across cores to any great extent. The correlation of cores along the transects is also tenuous without good stratigraphic markers and it is difficult to account for differing numbers of sand layers throughout the cores. This is likely explained by differing storm surge approaches. When taking transects it is assumed that the overwashes are arriving at a 90° angle to the lake front, and this of course is almost certainly not the case. Overwash fans deposited from storm surges from different angles can account for the presence of more event layers in cores farther along the transects and without good stratigraphic markers it is difficult to determine correlations. This complication is can be addressed when there are distinct visible or lithological changes and by taking more transects and having good dating control on multiple cores.

What is intriguing and ultimately most noteworthy from the results of Barbuda is the noticeable disparity as to the frequency of the depositional layers. The changes in frequency are
quite plain and occur in three distinct phases; two periods of hyperactivity bracketing a period of relative quiescence. From around ~4970 to 3500 yr BP there is a large amount of hurricane overwash layers deposited within the sediments of Barbuda Salt Pond, indicating a period of hyperactivity. This period of high activity is dramatically reduced at 3500 when there is a dramatic reduction in the deposition of overwash layers. This period of quiescence lasts until around 1500 yr BP when there is a transition back to the active period lasting until the modern record.

Discussion and Conclusions

The driving mechanism behind the color transitions occurring in Barbuda Salt Pond likely revolves around the slight changes in organic concentration of the sediments. The timing of the changes indicates that the changes are reflecting regional patterns of well-documented pan-Caribbean aridity (Brown and Cohen, 1985; Hodell et al., 1991; Burney et al., 1994; Kjellmark, 1996; Bertran et al., 2004; Higuera-Gundy, et al., 1991). The difference in timing is likely due to a time lag based on northeasterly geographical positioning of Barbuda in relation the rest of the Caribbean. As mentioned before, frequent sea water inundation leads to increased calcareous deposition (Scoffin, 1987) and this is likely what is being reflected in the sediments. Its closeness to the sea must allow for partial connection either through seepage or occasional flooding events that have kept water levels sufficiently high so as not to reach evaporite deposition or drying completely and allowing for the mangrove encroachment during the period of increased evaporation. This steady source of seawater probably accounts for a bit of the time lag as the lake may not be as sensitive to change as other water limited coastal ponds.

It is likely that the event found directly below the $^{137}$Cs peak is indeed Hurricane Donna. It is the largest layer deposited in the 5000 yr history of the lake. Hurricane Luis is likely responsible for the subareal overwash fan deposited in Barbuda Salt pond. It left no prominent stratigraphic signature within the sediments of the lake other than a thin sand layer in cores BSP01 and BSP02. These two Category 4 storms had very similar approaches with both making direct landfall on Barbuda. It appears that the slight difference in landfall angle and approach resulted in very different stratigraphic signatures. Donna made an enormous impact with overwash sand layers still apparent in the sediments 130 meters into the lake. Luis, however, made little impact. The contrasting signature of two storms of similar strength highlights that the proxy records recreated from the sediments provide only a conservative estimate of storm
strengths. Given the impacts from Donna and Luis, and the absence of any sedimentological evidence of the weaker storms contained in the sediment record, it is presumed the other sand layers found within the cores are likely to have resulted from similarly large hurricanes giving Barbuda Salt Pond a threshold of category four or greater.

There is significant noise in the Barbuda cores. The lack of stratigraphy makes it difficult to cross correlate each sand layer in the transects. The difference in basal dates between Cores BSP10 and BSP13 (~900 yrs) indicates differing rates of sedimentation throughout the lake so landfall probabilities can only be calculated based on cores with good dating control. With that in mind, it seems prudent to look at trends being displayed in the most landward cores only, as they are likely to represent the largest storms in the record furthermore, these are most likely a clearer indication of individual storms, rather than multiple events in a single layer. When looking at the last core of each transect the trends become even clearer (Fig 7-8). There are three distinct periods: two active regimes from 0-1500 and 3500-5000 yr BP bracketing an inactive regime from 1500-3500 yr BP. BSP13 is the only landward core that was dated but the results show that the temporal frequency shifts are apparent and landfall probabilities can be broken up into active and inactive regimes (Fig. 7-9). The record from BSP13, a 4970 yr history, contains 14 overwash deposits. That would give Barbuda a return annual landfall probability for Category four or larger hurricanes of 355 yrs, or an average landfall probability of 0.28% for the entire record.

If broken up into active vs. inactive regimes the probabilities change dramatically. For the active regimes: six storms in the first 1500 years gives an average return rate of 250 yrs (0.40%) and five storms in the last 1500 years gives an average return rate of 300 (0.33%). Calculations for the inactive regime: three storms over 2000 yrs gives an average return rate of 666 (0.15%). The average annual return period is roughly double that of the inactive regimes.

This 5000-year record clearly highlights the dramatic reduction in landfall probability coincident with the inactive period. This inactive period also coincides well with the active
period from the U.S. Gulf coast, indicating that these millennial-scale temporal shifts in hurricane activity likely align to the theory of the Bermuda High hypothesis. When the Gulf coast is active due to a southerly shift in the Bermuda High, there is suppressed hurricane activity along the northern Caribbean and U.S. Gulf coasts. When the Bermuda High is in a more northerly position, there are more hurricanes directed along the northern Caribbean and U.S. Atlantic coast.

This pioneer study from Barbuda is very exciting and the results retrieved from it exacerbate the importance of paleoempestological studies. This record adds a 5000 yr hurricane history to a region where none existed previously, and positively identifies millennial-scale shifts in hurricane frequency in line with the dominant paradigm of paleotempestology, the Bermuda High hypothesis. It is clear that for Barbuda there are shifting regimes of risk to hurricane strikes, further highlighting the need to understand the forcing mechanisms behind these millennial-scale shifts in hurricane activity. The results from this study are an excellent addition to the arsenal of paleotempestological studies that over time will be instrumental in formulating a basin-wide Holocene hurricane history and deciphering the causal reasons behind these spatial and temporal shifts in hurricane landfall.
CHAPTER 8 DISCUSSION

One of the primary objectives of this dissertation is to examine the genesis and depositional mechanism behind the sand layers found in the coastal lake sediment cores that are interpreted to be hurricane overwash layers. Each study site for this dissertation was a Caribbean hypersaline coastal lake with salinities ranging from 60 to 80‰, consistent with expected seasonal variations (Pinckney et al., 1995). The sediments were typified by alternating lithologies of organic and inorganic regimes unique to each island. A common feature among these cores from different islands, however, is the presence of golden beach sand contained within the various sediments of every coastal lake cored. Whether laminated cyanobacterial mats or white marls, the overwash deposits were visibly and lithologically distinct from all of the in situ sediments accumulating in all of the lakes. All lakes were located on low-lying carbonate platforms with little or no soils topping relic Pleistocene platforms leaving little doubt as to the source of the overwash layers. Comparisons of the overwash deposits’ lithological composition and color to the surface samples taken from the barrier beaches of each lake clearly indicate the genesis of the overwash sand layers. Interestingly, a comparison of the beach sands from each site shows remarkable similarity, and LOI analysis shows that they are nearly identical in lithological content (Fig. 8-1). So no matter the variety of depositional regimes located in the 5 lakes cored for this study, the beach sand from each site was homogenous and completely distinguishable from the localized in situ accumulating sediments. There can be no question as to the source of these overwash materials other than the barrier beaches fronting the study sites. This assumption is perfectly in line with previous overwash studies by Leatherman and Williams (1977a) and Van Straaten (1965), who all note that the source of the washover sands are the beach face. This observation is further supported by the phytolith studies of Lu and Liu (2005).

With the genesis of the overwash sand layers fairly clear the question of depositional mechanism needs to be addressed. A question often asked is “How can the researcher be certain that the sand layers found within coastal lake sediments are indeed deposited from hurricane storm surge overwash and not the result of some other catastrophic event such as a tsunami”. This question is especially pertinent to studies done in the West Indies, a region vulnerable to both hurricanes and tsunami.

The question of misidentifying hurricane deposits with tsunami deposits was addressed in Chapter 2. While there are some similarities between tsunami and hurricane deposits, the
Figure 8-1. Lithological comparisons of sand surface samples from the barrier beach located in front of each coastal lake.

differences are glaring. Hurricane deposits are typically fan-shaped and sub-aqueously they are often extensions of the sub-areal crenulated margins (Howard, 1939). These overwash fans display upward fining sequences (Hayes, 1967) of clean, well-sorted sand with horizontal stratification, and the source of the washover sands are the beach face (Hayes, 1967; Kraft, 1971; Leatherman and Williams, 1977(a); Van Straaten, 1965; Lu and Liu, 2005).

This is in stark contrast to deposits of tsunamis, whose sedimentological signature is typified by a full range of grain sizes from fine clays to boulders (Yeh et al., 1993; Nott, 2004). Tsunami waves exhibit traction with multiple seaward backwash currents that results in the coupling of fine/coarse grain sizes in the internal stratigraphy (Dawson and Stewart, 2007; Nanayama and Shigeno, 2006). The stratigraphy is usually topped off with a low-energy layer or mud cap (Morton et al., 2007). Tsunami deposits are chaotic deposits composed of both marine and terrestrial sediments resulting from deep landward penetration (Nanayama et al., 2000). Tsunami deposits are typically erosional at the point of contact, compared with the sharp contact with underlying organics of hurricanes (Dawson and Stewart, 2007; Morton et al., 2007).

Given the stark differences in the nature of the two deposits, it can be confidently inferred that the event layers identified in this study are indeed deposited from hurricane overwash processes. The sand layers found in this study are characterized by clean well-sorted sands displaying an upward fining sequence and horizontal stratification, features typical of hurricane
overwash deposits. Further supporting this interpretation are the results of the modern analog study done with $^{137}$Cs analysis. The identification of an overwash sand layer deposited immediately before the $^{137}$Cs peak of 1963 indicates that there is a high likelihood of that event being attributed to Hurricane Donna (1960). These results from the modern analog study suggest that the clastic event layers are indeed generated by hurricanes.

The presence of mollusk death assemblages that contain near-shore marine and terrestrial species within the layers further adds credence to the interpretation that these sand layers are indeed hurricane-generated overwash deposits whose source material is derived from the near-shore beach sand. There is no evidence of any in situ death assemblages other than those that accompanied the overwash sand layers.

Only one event layer may not conform to all the characteristic features of hurricane deposits. This is the clastic layer found at ~500 yr BP for Lake Kalik. This layer displayed some characteristics suggestive of tsunami deposits and was different from the typical hurricane layers found within the same sediments.

There is, however, room for overlap. As was shown in the basal sand layer found in Anguilla (~250 yr BP), an event can display characteristics of both events and thereby become indistinguishable as to the nature of the deposit. This problem for the basal layer in Anguilla would likely be rectified if the entire layer could have been evaluated. However, since the event could not be penetrated with current coring methodologies, the depositional mechanism remains unclear. However, analysis of all event layers fully retrieved showed uniquely distinguishable characteristics that conform to an overwash origin.

Given the above reasons, there is little doubt that the event layers in question were indeed deposited via hurricane overwash and hence can be used in concert with radiometric dating to determine a pattern of temporal and spatial distribution of hurricane landfall for the northern West Indies.

- Acklins Island, Bahamas

Taken as a whole the overwash layers deposited within the sediments of Acklins Island, Bahamas, over the last 3820 yr BP reveal a clear pattern of temporal variability of hurricane strikes (Fig. 8-2). It began with a period of low/no activity spanning from ~4000-3300 yr BP, followed by a period of increased activity from ~3300 to 2300 yr BP. After that, there was a period of relative inactivity spanning ~2300-1100 yr BP, and a return to increased activity from
~1100 -300 yr BP. Superimposed on these results is the possibility of a tsunami event that may have hit the island at around ~500 yr BP, although the identification of this potential tsunami deposit remains to be confirmed.

- **Anguilla**

  The record from Anguilla gives a ~250-yr history of hurricane strikes (Fig. 8-2), a period too short to detect any low-frequency or millennial-scale shifts in hurricane activity. However, the initial return interval of three presumed Category 4 hurricanes (including one believed to be deposited by Hurricane Donna) for Anguilla over the last 250 yr BP could conceivably be seen as an active period. However, given that there were no older records retrieved from Anguilla this has to be considered with caution.

- **Barbuda**

  Analysis of the ~5000-yr record of hurricane deposits for Barbuda also indicates a clear pattern of temporal variability (Fig. 8-2). A period of high landfall frequency existed from ~5000-3500 yr BP. This was followed by a period of low activity from ~3500-1500 yr BP. The last 1500 years seems to be a transition back to an active period. With these results in mind the stated hypotheses for this dissertation are examined.

- **Hypotheses**

  Hypothesis 1. A basic assumption in paleotempestology is that catastrophic hurricanes leave a distinct stratigraphic record in coastal lake sediments in the form of overwash sand layers, and sand layer thickness is generally proportional to hurricane intensity (Liu, 2004). This hypothesis is tested by examining the sedimentary signature left by a Category 4 storm (Hurricane Donna) in five Caribbean lakes. This recent storm deposit is used as a modern analog to compare with the depositional signature of other hurricanes in an effort to calibrate the intensity of the prehistoric storms. Based on the modern historical record it is anticipated that there will be two prominent sand layers within the sediments from Barbuda and Anguilla representing the two catastrophic hurricanes strikes from Donna (1963) and Luis (1995) and one prominent sand layer for Acklins Island representing Donna only. It is expected that none of the other weaker hurricanes in the modern record will have left any sedimentological evidence.

  The signature deposited by Hurricane Donna was anticipated to be the largest and most prominent signature in the stratigraphic record and indeed it was. Using the $^{137}$Cs peak as a stratigraphic marker, the overwash deposit from Hurricane Donna was identified and the results
produced from analysis of the lake sediments conform well with the second part of the hypothesis. For Anguilla there was evidence of both Hurricane Luis and Donna located in the sediment record, with none of the other weaker storms in the modern record making an impact on the lake. This was also true for Barbuda, which had evidence of both storms, although only Donna was prominent. Both lakes on Acklins Island, Bahamas, did not have any sedimentological evidence of Hurricane Donna, likely due to the high barriers fronting the lakes. In other words, these lakes had a threshold too high to record the storm surge from even a Category 4 hurricane, so there was no evidence in the sediments from Hurricane Donna.

As stated above, catastrophic hurricanes do indeed leave a distinct stratigraphic record. A good modern analog, such as Hurricane Donna, once identified, can give a good idea of the site-specific paleotempestological threshold of a coastal lake, but it would only be establishing a threshold of minimum intensity. Given the litany of factors controlling the penetration or lateral extent of overwash deposits—namely, vegetation cover, orientation of the path and eye-wall in relation to the coast (Perkins and Enos, 1968; Fletcher et al., 1995), wind speeds and central pressure (Hsu et al., 2000; Stone et al., 2005), offshore bathymetry and offshore water depth, angle of shoreline and slope, dune/barrier height, and tidal stage (Morton and Sallenger, 2003; Fletcher et al., 1995; Leatherman et al., 1977b), it would be difficult to correlate one sand layer to another within the sediment record. Also, it is not possible to equate every hurricane with supratidal deposition as storms of equal strength may have differing overwash deposit patterns (Perkins and Enos, 1968). While it is impossible to calibrate each individual layer, one can establish a threshold level of minimum paleotempestological sensitivity for the lake with the modern analog, i.e., the deposits in the lake must have been laid down by a storm stronger than a minimum intensity category. Therefore, once the threshold of a lake has been established, it can be assumed that the sand layers located within the sediments of the lake are above that threshold.

Hypothesis 2. It is hypothesized that many past catastrophic hurricanes, like Donna, that passed through the northern Caribbean would also recurve to affect the U.S. Atlantic coast. This implies that, in terms of the temporal patterns of hurricane activities, proxy records from the northern Caribbean record will be positively correlated with those from the Atlantic coast and negatively correlated with those from the Gulf coast. Therefore, based on the Bermuda High hypothesis it is anticipated that in the longer sediment cores, there will be more hurricane-
induced overwash sand layers occurring in the upper parts of the cores (<1000 yr BP) than in the lower parts (2000-3000 yr BP).

The results from this dissertation are consistent with the second hypothesis. The 5000-year records of hurricane strikes from the lake sediments of the Northern Caribbean are in agreement to show an apparent anti-phase pattern with the U.S. Gulf coast. Results from Acklins Island, Bahamas, and Barbuda indicate an uneven distribution of events throughout the cores with a definite pattern of temporal variation (Fig 8-2). The Anguillian results are too short to determine any long-term variation, although there is a large number of overwash sand layers in the 250 years recovered, tentatively in agreement with the active portion of the top parts of the core. It is reasonable to expect that once the large basal sand layer is penetrated and a long-term record recovered, Anguilla would reflect the same pattern of landfall frequency as Barbuda given the close geographical proximity. However, in the absence of a longer record, we will only examine the two longer records from Acklins Island and Barbuda.

A period of increased activity appears in the upper portions of the cores spanning ~0 to 1500 yr BP for Barbuda and ~300 to 1000 yr BP for the Bahamas. This active period of frequent hurricane landfall is followed by a period of relative inactivity from 1500-3500 yr BP for Barbuda and ~1000 to 2300 yr BP. Activity picks up again around ~3500 yr BP for Barbuda and 2500 yr BP for the Bahamas. There is a discrepancy in the timing between the cores, as the active phase for Barbuda starts earlier and lasts longer, as does the inactive period, while the record for the Bahamas starts later and lasts a much shorter time. Regardless, there is a marked correlation between the northern West Indian record and the U.S. Atlantic coast, and as postulated in Hypothesis 2, an anti-phase relationship with the U.S. Gulf coast in agreement with the Bermuda High hypothesis. McCloskey and Knowles (in press) they expounded on the Bermuda High hypotheses, postulating that the north/south spatial migrations of the Bermuda High set forth by Liu and Fearn (2000a) are resultant from long term migrations of the Intertropical Convergence Zone (ITCZ), which in turn is controlled by the pole-equator pressure gradient. They describe the North Atlantic circulation system as a series of “stacked belts” with a “hurricane zone” fitting between the ITCZ and the Bermuda High. As this entire system moves north/south, so does the primary region of hurricane landfalls.

When looking to the geographical extremes of the system this hurricane region can be grouped into two distinct zones (Fig 8-3). Zone 1 is typified by a period of polar cooling,
Figure 8-2. Summary of temporal variation in hurricane landfall for the West Indies compared to U.S. Atlantic and Gulf coast records. Barbuda, Anguilla, and Bahamas records are from this study, with black lines indicating actual hurricane strikes, and grey shading indicating periods of increased activity. Other records are from previous studies: U.S. Gulf coast (Liu, 2004), Nobska Pond, Massachusetts (Liu and Lu, 2007).

displacing the ITCZ southward. There is a concurrent southward displacement of the Bermuda High resulting in a drier West Indies. This position directs more hurricane tracks along the western edge of the Bermuda High into the Caribbean Sea, the Greater Antilles, Central America, and the U.S. Gulf coast.

Zone 2: A weaker polar equatorial gradient allows for the northward displacement of the ITCZ and concurrent northern movement of the Bermuda High. This phase directs more hurricane tracks along the western edge of the Bermuda High and into the Northern Antilles and Bahamas, and the U.S. Atlantic coast.
As the “hurricane zone” shifts so does the landfall probabilities of the geographical regions falling under the different phases, often changing dramatically as seen in the Barbuda results, which show a twofold increase from zone 2 to zone 1. Of course zones 1 and 2 are broad scale generalizations and represent only the extreme ends of the scenario. There is likely a gradual migration along the entire N/S track, and it is this period of migration that likely accounts for the time discrepancy in activity periods from the Barbuda and Bahamas cores. As the entire system shifts, there is likely to be overlap between shifting periods of activity, especially in the West Indies, which lie in the middle of the extreme ends of the two theorized phases.

A second factor that may be further complicating the record is the high-frequency interaction between the Inter-tropical Convergence Zone (ITCZ) and the Bermuda High. McCloskey and Knowles (in press) argue that while the millennial-scale distribution in hurricane landfall throughout the Holocene is primarily due to the latitudinal migration of the ITCZ, controlled by the pole-equator temperature gradient, there are high-frequency variations in the dynamic play between the Bermuda High and the ITCZ superimposed on the system (Fig 8-4).
The effect of a strong Bermuda High on hurricanes has been shown to be an important factor in controlling hurricane tracks (Knowles and Leitner, 2007; McCloskey and Knowles, in press; Elsner et al., 2000) and the high frequency variation of Bermuda High stages (strong/weak) can also contribute to shifting hurricane landfall patterns. These changes are manifested in a bi-modal sequence. When the Bermuda High is strong it tends to move in a northeasterly direction and exhibit a significant control over storm tracks (Fig. 8-4). When the high is weak it moves to the southwest and exhibits little control over storm tracks. This high-frequency oscillation superimposed on the large-scale migration of the ITCZ (zones 1 and 2) would in effect “blur” the record based on years of extremely strong or weak Bermuda Highs. For example, when the system is in zone 2, the majority of storm tracks would be directed along the northern Caribbean and U.S. Atlantic coast. However, if there was a weak Bermuda High there would be a slight southwestward migration of the tracks and there would not be much
control exerted over the steering of storms tracks, allowing for storms to devastate to the U.S. Gulf coast. This phenomenon could serve to complicate the identification of regional patterns of shifting landfall frequencies.

With that in mind it becomes clear that in order to distinguish a clearer pattern of spatial and temporal variation in hurricane landfalls and reduce the “blurring” effect of the high-frequency variations, one needs to look to the extreme reaches of the hurricane zone. It is imperative that future studies should concentrate on these geographic extremes of the system such as the northern U.S. Atlantic coast and the southern Caribbean (Aruba, Bonaire, and Curacao) as well as southern Central America. The coring of these geographic extremes may reveal a clearer pattern and better able research to pinpoint the timing of the phase shifts.

While the Bermuda High hypothesis is the dominant paradigm for paleotempestology and the records from this dissertation certainly add credibility to that theory showing a distinct anti-phase relationship between the US Gulf coast and the Northern Caribbean, it is not without its detractors. Recent results from Long Island, NY (Scileppi and Donnelly, 2007), show an in-phase relationship with the results of the U.S. Gulf coast. The authors postulated that there is no spatial migration associated with the temporal changes in hurricane activity. They speculated that the in-phase relationship between the Long Island, NY, record and the U.S. Gulf coast implies a basin-wide synchronous increase/decrease in hurricane activity. They cite the Puerto Rico record of Donnelly and Woodruff (2007) to augment their speculation further, as it too is in line with both previous records. Donnelly and Woodruff (2007) also postulated a North-Atlantic-wide decrease in hurricane activity from 1000 yr BP, and that there is “no change in the prevailing hurricane tracks as has been postulated by Liu and Fearn, (2000a)”.

Results from this study do not support the contentions of Donnelly et al. (2007). The results presented here show definite phases of shifting hurricane activity in direct contrast to a “synchronous basin-wide” pattern to hurricane activity. The results presented here also seem to indicate that there is indeed an anti-phase relationship in hurricane activity based on geography as put forth by Liu and Fearn (2000a) with the Bermuda High hypothesis.

Figure 8-5 is represents of all paleotempestological records in the region to date and leaves little doubt that there is indeed non-synchronous changes in hurricane landfall activity, both temporally and spatially. Interestingly all records, save the Long Island, NY, record, can be correlated to the Bermuda High hypothesis. Barbuda, Anguilla, Bahamas, and Cape Cod all
Figure 8-5. Pan-Caribbean trends of shifting hurricane landfall frequencies. (Barbuda, Anguilla, and Bahamas records are from this study, black lines indicate actual hurricane strikes, grey shading indicates periods of increased activity. Other records are from previous studies: St. Martin (Betran et al., 2004), U.S. Gulf coast (Liu, 2004), Nobska Pond, Massachusetts (Liu and Lu, 2007), Puerto Rico (Donnelly and Woodruff, 2007), and Long Island, NY (Scileppi and Donnelly, 2007).

correlate with increased activity for the last 1000 yrs, and the U.S. Gulf coast and Puerto Rico both exhibit increased activity from 1000-2500 yr BP. The record from Puerto Rico was taken from the southern island of Vieques and is likely affected by the same phasing as the U.S. Gulf coast (zone 1). The only outlier to the trends is the Long Island, NY, core. The disparity between the U.S. Atlantic coast records (Cap Cod and Long Island, NY) needs to be addressed as there is an irreconcilable difference in the timing of recorded event for each core.

Interestingly, there appears to be a significant basin wide-trend to the data. An examination of all of the records together indicates that there are three major transition periods apparent in nearly all cores, a transition at ~1000 yr BP, ~2,500 and ~3,500 yr BP. These transitions vary slightly among cores (due most likely to a gradual ITCZ migration and the superimposed high-frequency oscillation) but they all show that there are indeed transitions
happening around three axes points. This new discovery has not before been seen and may add significant insight to the interpretation of basin-wide shifts as it is unlikely that these three axes points are arbitrary. To understand these axes points better more studies need to be done in the extreme reaches of the migrating hurricane zone. Core taken for this study are positioned in the geographic middle, or overlap region, of the hurricane zone and have marginally different timings to the active and inactive phases. To isolate the timing of these migrations better, studies done in the extremes of the hurricane zone (U.S. Atlantic coast and southern Caribbean) have the potential to better pinpoint the movement of the hurricane zone over time which in turn may lead to a better understanding and correlation between regional records.
CHAPTER 9 CONCLUSIONS

Storm intensity is very difficult to correlate between individual overwash sand layers. Too many site specific variables exist regarding the deposition of overwash fans. Each storm signature is unique and the individual signature of each storm is ultra local and varies vastly for each site. Therefore, it is critical that modern analog studies are undertaken to establish a storm intensity “threshold” for each site. While the individual layers cannot be calibrated, a modern analog can set a threshold of minimum intensity for each site and allow for a minimum intensity estimate for each storm layer. Also, it should be noted that not all storms leave overwash deposits. Consequently, the geological method of paleotempestology must be considered to be a conservative estimate of hurricane frequency.

The results from this dissertation have identified definitive temporal and spatial shifts to hurricane landfall frequencies in the Northern Caribbean. These millennial-scale shifts are likely due to a migrating ITCZ and correlate well to the Bermuda High hypothesis. Regional variations in the timing and length of these active and inactive regimes varies geographically. There appears to be an overriding basin-wide period of transition in hurricane activities based around three apparent time frames, or pivot axes, transitioning between active and inactive phases at ~1000 yr BP, ~2,500 and ~3,500 yr BP respectively.

To better understand these newly discovered pivot axes’s, more studies need to be done in the far north and south reaches of the hurricane zone. These studies should aim to avoid the blurring effect of being in the geographic middle, or overlap region of the hurricane zone to better isolate the timing of these north/south migrations. Studies done in the extremes, far north U.S. Atlantic coast, Nicaragua and very southern Caribbean islands (e.g. the Dutch Islands of Aruba, Bonaire, and Curacao) have the potential to help pinpoint the movement of the hurricane zone over time, which in turn may lead to a better understanding and correlation between for regional records.

The importance of paleotempestology cannot be overstated. The realized and potential information gleaned about millennial-scale hurricane climate cannot be gathered from any other source. An invaluable scientific tool, paleotempestology far outreaches the scope of the modern instrumental record and is helping to reveal important long-term regional trends. These trends are only just now beginning to emerge and indicate large-scale changes in frequency. Understanding the timing and causation of these changes is paramount. There is much work left to be done.
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APPENDIX 1 RESEARCH PERMITS

GOVERNMENT OF ANGUILLA
Office of the Chief Minister and
Minister of Immigration, Labour, Lands, Physical Planning, Environment, Human Rights, Gender Affairs & Information

Telephone: (264) 497-2518/3618 or 497-2451 Ext 2400
Facsimile: (264) 497-3389
E-mail: chief.minister@gov.ai

Ref: MHA/ENV/1/1

23rd February, 2006

TO WHOM IT MAY CONCERN

The Government of Anguilla, through the Ministry of Home Affairs and Environment hereby grants Mr. Jason T. Knowles, PhD candidate at the Louisiana State University, Department of Geography and Anthropology permission to carry out his proposed PhD research on coastal ponds of Anguilla. Mr. Knowles’ research will aid in the reconstruction of catastrophic hurricanes strikes based on sedimentological evidence found within coastal pond sediments. Additionally this will provide invaluable data on the impacts of climate change on Anguilla’s coastline, which has significant bearing for disaster and environmental management.

A study of this nature would be invaluable to Anguilla as it is presently developing its disaster and environmental management capabilities. The study will also assist us in better understanding the science of hurricanes and the potential risk Anguilla now faces with this active cycle. This information would enable us to be more proactive and better prepared to implement disaster planning with greater accuracy.

Mr. Knowles is tentatively planning to arrive in Anguilla during the month of April and will be departing Anguilla at the end of April 2006. The Government of Anguilla, through the Ministry of Home Affairs and Environment will facilitate Mr. Knowles in getting his research work completed during his stay in Anguilla.

The Ministry of Home Affairs and Environment hereby informs Mr. Knowles that most of the coastal ponds on Anguilla are in private ownership and that he should seek formal permission from such persons to carry out this research if necessary. Additionally, the Ministry also wishes to remind Mr. Knowles that he has to leave a preliminary report of his findings here in Anguilla and upon completion of his analysis, a final report must be supplied to the Ministry in addition to copies of all publications, which may contain data from Anguilla.

Regards,

Mr. Foster Powell
Permanent Secretary

CC: Mr. Gifford Connor - Director, Lands and Survey
Mr. Wycliffe Richardson - Director, Disaster Management
Barbuda Local Government

THE BARBUDA COUNCIL
Codrington Village Barbuda,
Via St. John's Antigua W.I.
Tel. (268) 460-0877/260-1921
Fax: (268) 460-0440/460-0801
E-Mail: barбудacouncil@islandnet.com

BC/120A/06

5th May 2006

Jason T. Knowles
Department of Geography & Anthropology
Louisiana State University
227 Howe-Russell Geoscience Complex
Baton Rouge, LA 70803-4005

Dear Sir,

The Barbuda Council is in receipt of your correspondence and we would like to apologize for not responding sooner.

However, the Council would be honored to have you conduct the research on the island and to collect samples for your dissertation.

The Permanent Secretary in the Ministry of Agriculture should be contacted though to seek any further permits that may be needed. They may be contacted at 268-462-1213 or 268-462-1007, or the Director of Agriculture at 268-460-9818 or facsimile 268-462-4962.

We would like to interject that your findings are to be submitted in a report at the completion of your dissertation.

Anticipating your arrival,

Respectfully,

[Signature]
Dorothy Symister (Mrs.)
Secretary
Barbuda Council
Mr. Jason T. Knowles  
Department of Geography and Anthropology  
227 Howe Russell Geoscience Complex  
LOUISIANA STATE UNIVERSITY  
Baton Rouge  
Louisiana 70803-4105  
U.S.A.  

Dear Mr. Knowles,

Re: **MARINE SCIENTIFIC RESEARCH PERMIT**

Further to your e-mail transmission of 22nd August 2006, I have been directed to say that approval for your scientific research trip to The Bahamas next month has been granted.

Therefore, please find enclosed the necessary permit for your study entitled "Tracking Donna Across the Northern Caribbean: Developing a Modern Analog Methodology for Palaeoceanography" to be conducted at Acklins Island from 01-07 September 2006.

Additionally, please note that we have notified the relevant authorities of your proposed marine scientific research activities in The Bahamas during that time.

Please take careful note of the conditions that govern the permit. If I may be of further assistance, do not hesitate to call on me.

In the meantime, I remain:

Enc. (1)

Yours Sincerely,

Roland Albury  
for Director of Marine Resources
APPENDIX 2 BAHAMAS LOI
# APPENDIX 5 RADIOCARBON RESULTS

Dr. Kam-biu Liu/Jason Knowles  
Louisiana State University  
Report Date: 11/7/2007  
Material Received: 10/10/2007

<table>
<thead>
<tr>
<th>Sample Data</th>
<th>Measured Radiocarbon Age</th>
<th>Δ13C/12C Ratio</th>
<th>Conventional Radiocarbon Age(*)</th>
</tr>
</thead>
</table>
| Beta - 235770  
SAMPLE: BSP10-72  
ANALYSIS: AMS-Standard delivery  
MATERIAL/PRETREATMENT: (organic sediment): acid washes  
2 SIGMA CALIBRATION: Cal BC 750 to 690 (Cal BP 2700 to 2640) AND Cal BC 660 to 640 (Cal BP 2610 to 2590)  
Cal BC 590 to 400 (Cal BP 2540 to 2340) | 2310 +/- 40 BP  
-19.2 o/oo | 2410 +/- 40 BP |
| Beta - 235771  
SAMPLE: BSP10-92  
ANALYSIS: AMS-Standard delivery  
MATERIAL/PRETREATMENT: (organic sediment): acid washes  
2 SIGMA CALIBRATION: Cal BC 2190 to 2170 (Cal BP 4140 to 4120) AND Cal BC 2150 to 1950 (Cal BP 4100 to 3900) | 3560 +/- 40 BP  
-17.6 o/oo | 3680 +/- 40 BP |
| Beta - 235772  
SAMPLE: LK01-55  
ANALYSIS: AMS-Standard delivery  
MATERIAL/PRETREATMENT: (peat): acid/alkali/acid  
2 SIGMA CALIBRATION: Cal AD 1270 to 1330 (Cal BP 680 to 620) AND Cal AD 1340 to 1400 (Cal BP 610 to 560) | 670 +/- 40 BP  
-24.7 o/oo | 670 +/- 40 BP |
| Beta - 235773  
SAMPLE: PP07-30  
ANALYSIS: AMS-Standard delivery  
MATERIAL/PRETREATMENT: (shell): acid etch  
2 SIGMA CALIBRATION: Cal AD 800 to 1000 (Cal BP 1150 to 950) | 1100 +/- 40 BP  
-1.2 o/oo | 1490 +/- 40 BP |
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -19.2; lab. mult = 1)

Laboratory number: Beta-235770

Conventional radiocarbon age: 2410 ± 40 BP

2 Sigma calibrated results: Cal BC 750 to 690 (Cal BP 2700 to 2640) and Cal BC 660 to 640 (Cal BP 2610 to 2590) and Cal BC 590 to 400 (Cal BP 2540 to 2340)

Intercept of radiocarbon age with calibration curve: Cal BC 410 (Cal BP 2360)

1 Sigma calibrated result: Cal BC 530 to 400 (Cal BP 2480 to 2350)

(68% probability)

References:

Database used

INTCAL04

Calibration Database

INTCAL04: Radiocarbon Age Calibration


Mathematics

A Simplified Approach to Calibrating C14 Dates


Beta Analytic Radiocarbon Dating Laboratory

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = 17.6; lab. mult = 1)

Laboratory number: Beta-235771

Conventional radiocarbon age: 3680±40 BP

2 Sigma calibrated results: Cal BC 2190 to 2170 (Cal BP 4140 to 4120) and
(95% probability)
Cal BC 2150 to 1950 (Cal BP 4100 to 3900)

Intercept data

Intercepts of radiocarbon age
with calibration curve: Cal BC 2110 (Cal BP 4060) and
Cal BC 2100 (Cal BP 4050) and
Cal BC 2040 (Cal BP 3990)

1 Sigma calibrated result: Cal BC 2130 to 2020 (Cal BP 4080 to 3970)
(68% probability)

References:
- Database used
  - IntCal04
- Calibration Database
  - IntCal04: Radiocarbon Age Calibration
- Mathematics
  - A Simplified Approach to Calibrating C14 Dates
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -24.7; lab. mult = 1)

Laboratory number: Beta-235772

Conventional radiocarbon age: 670±40 BP

2 Sigma calibrated results: Cal AD 1270 to 1330 (Cal BP 680 to 620) and
(95% probability) Cal AD 1340 to 1400 (Cal BP 610 to 560)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal AD 1290 (Cal BP 660)

1 Sigma calibrated results: Cal AD 1280 to 1310 (Cal BP 670 to 640) and
(68% probability) Cal AD 1360 to 1380 (Cal BP 590 to 570)

References:

Database used
INTCAL04

Calibration Database
INTCAL04. Radiocarbon Age Calibration

Mathematics
A Simplified Approach to Calibrating C14 Dates

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=1.2; Delta-R=-5±20; Glob res=-200 to 500; lab. mult=1)

Laboratory number: Beta-235773

Conventional radiocarbon age: 1490±40 BP

(1500±40 adjusted for local reservoir correction)

2 Sigma calibrated result: Cal AD 800 to 1000 (Cal BP 1150 to 950)
(95% probability)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal AD 900 (Cal BP 1050)

1 Sigma calibrated result: Cal AD 860 to 960 (Cal BP 1090 to 1000)
(68% probability)

References:

Database used:
MARINE04

Calibration Database

INTCAL04: Radiocarbon Age Calibration


Mathematics:

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<table>
<thead>
<tr>
<th>Sample Data</th>
<th>Measured Radiocarbon Age</th>
<th>13C/12C Ratio</th>
<th>Conventional Radiocarbon Age(*)</th>
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</thead>
<tbody>
<tr>
<td>Beta - 234610</td>
<td>240 +/- 40 BP</td>
<td>-25.0 o/oo</td>
<td>240 +/- 40 BP</td>
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<tr>
<td>SAMPLE: LK01-21</td>
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<tr>
<td>ANALYSIS: AMS-Standard delivery</td>
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<tr>
<td>MATERIAL/RETREATMENT: (peat): acid/alkali/acid</td>
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<tr>
<td>2 SIGMA CALIBRATION:</td>
<td>Cal AD 1530 to 1560 (Cal BP 420 to 390) AND Cal AD 1630 to 1680 (Cal BP 320 to 270)</td>
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</tr>
<tr>
<td></td>
<td>Cal AD 1740 to 1800 (Cal BP 210 to 150) AND Cal AD 1940 to 1950 (Cal BP 20 to 0)</td>
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<td></td>
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<tr>
<td>Beta - 234611</td>
<td>410 +/- 40 BP</td>
<td>-25.4 o/oo</td>
<td>400 +/- 40 BP</td>
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<td>SAMPLE: LK01-35</td>
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<td>ANALYSIS: AMS-Standard delivery</td>
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<tr>
<td>MATERIAL/RETREATMENT: (peat): acid/alkali/acid</td>
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<tr>
<td>2 SIGMA CALIBRATION:</td>
<td>Cal AD 1430 to 1530 (Cal BP 520 to 420) AND Cal AD 1560 to 1630 (Cal BP 390 to 320)</td>
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</tr>
<tr>
<td>Beta - 234612</td>
<td>1160 +/- 40 BP</td>
<td>-25.8 o/oo</td>
<td>1150 +/- 40 BP</td>
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<td>SAMPLE: LK01-84</td>
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<td>ANALYSIS: AMS-Standard delivery</td>
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<tr>
<td>MATERIAL/RETREATMENT: (peat): acid/alkali/acid</td>
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<tr>
<td>2 SIGMA CALIBRATION:</td>
<td>Cal AD 780 to 980 (Cal BP 1170 to 960)</td>
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<tr>
<td>Beta - 234613</td>
<td>3320 +/- 40 BP</td>
<td>-25.7 o/oo</td>
<td>3310 +/- 40 BP</td>
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<td>SAMPLE: PP03-86</td>
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<td>ANALYSIS: AMS-Standard delivery</td>
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<td>MATERIAL/RETREATMENT: (peat): acid/alkali/acid</td>
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<tr>
<td>2 SIGMA CALIBRATION:</td>
<td>Cal BC 1690 to 1500 (Cal BP 3640 to 3450)</td>
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</tbody>
</table>
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-25; lab. mult=1)

Laboratory number: Beta-234610

Conventional radiocarbon age: 240±40 BP

2 Sigma calibrated results: Cal AD 1530 to 1560 (Cal BP 420 to 390) and Cal AD 1630 to 1680 (Cal BP 320 to 270) and Cal AD 1740 to 1800 (Cal BP 210 to 150) and Cal AD 1940 to 1950 (Cal BP 20 to 0)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal AD 1660 (Cal BP 290)

1 Sigma calibrated results: Cal AD 1640 to 1670 (Cal BP 310 to 280) and Cal AD 1780 to 1790 (Cal BP 160 to 160)

References:

Database used
INTCAL04

Calibration Database
INTCAL04 Radiocarbon Age Calibration

Mathematics
A Simplified Approach to Calibrating C14 Dates

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -25.4, lab. mult = 1)

Laboratory number: Beta-234611

Conventional radiocarbon age: 400±40 BP

2 Sigma calibrated results: Cal AD 1430 to 1530 (Cal BP 520 to 420) and Cal AD 1560 to 1630 (Cal BP 390 to 320)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal AD 1460 (Cal BP 490)

1 Sigma calibrated result: Cal AD 1440 to 1490 (Cal BP 510 to 460) (68% probability)

References:

Database used: INTCAL04

Calibration Database: INTCAL04: Radiocarbon Age Calibration


Mathematics:

A Simplified Approach to Calibrating C14 Dates


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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -25.8; lab. mult = 1)

Laboratory number: Beta-234612

Conventional radiocarbon age: 1150±40 BP

2 Sigma calibrated result: Cal AD 780 to 980 (Cal BP 1170 to 960)
(95% probability)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal AD 890 (Cal BP 1060)

1 Sigma calibrated results: Cal AD 870 to 900 (Cal BP 1080 to 1050) and
(68% probability) Cal AD 920 to 960 (Cal BP 1040 to 990)

References:

Data used

INTCAL04

Calibration Database

INTCAL04: Radiocarbon Age Calibration


Mathematics

A Simplified Approach to Calibrating C14 Dates


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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variability: ~C13/C12 = 25.7: lab. mult = 1)

Laboratory number: Beta-234613

Conventional radiocarbon age: 3310 ± 40 BP

2 Sigma calibrated result: Cal BC 1690 to 1500 (Cal BP 3640 to 3450)

(95% probability)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal BC 1610 (Cal BP 3560)

1 Sigma calibrated result: Cal BC 1630 to 1520 (Cal BP 3580 to 3470)

(68% probability)

References:

Database used
INTCAL04

Calibration Database
INTCAL04: Radiocarbon Age Calibration

Mathematics
A Simplified Approach to Calibrating C14 Dates

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<table>
<thead>
<tr>
<th>Sample Data</th>
<th>Measured Radiocarbon Age</th>
<th>13C/12C Ratio</th>
<th>Conventional Radiocarbon Age(*)</th>
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<tbody>
<tr>
<td>Beta - 228633</td>
<td>NA</td>
<td>NA</td>
<td>190 +/- 40 BP</td>
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<tr>
<td>SAMPLE : GP02-15cm</td>
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<tr>
<td>ANALYSIS : AMS-Standard delivery</td>
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<tr>
<td>MATERIAL/PRETREATMENT : organic material: acid/alkali/acid</td>
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<tr>
<td>2 SIGMA CALIBRATION : Cal AD 1650 to 1700 (Cal BP 300 to 250) AND Cal AD 1720 to 1820 (Cal BP 230 to 130) Cal AD 1840 to 1880 (Cal BP 110 to 70) AND Cal AD 1920 to 1950 (Cal BP 40 to 0)</td>
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<tr>
<td>COMMENT : the original sample was too small for a 13C/12C ratio measurement. However, a ratio including both natural and laboratory effects was measured during the 14C detection to derive a Conventional Radiocarbon Age, suitable for applicable calendar calibration.</td>
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<td>Beta - 228634</td>
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<td>SAMPLE : GP02-21cm</td>
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<td>ANALYSIS : AMS-Standard delivery</td>
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<tr>
<td>MATERIAL/PRETREATMENT : organic material: acid/alkali/acid</td>
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</tr>
<tr>
<td>2 SIGMA CALIBRATION : Cal AD 1660 to 1960 (Cal BP 290 to 0)</td>
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<td>Beta - 228635</td>
<td>220 +/- 40 BP</td>
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<td>180 +/- 40 BP</td>
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<td>SAMPLE : GP07-18cm</td>
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<tr>
<td>MATERIAL/PRETREATMENT : organic material: acid/alkali/acid</td>
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<td>2 SIGMA CALIBRATION : Cal AD 1650 to 1710 (Cal BP 300 to 240) AND Cal AD 1710 to 1880 (Cal BP 240 to 60) Cal AD 1910 to 1950 (Cal BP 40 to 0)</td>
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<td>Beta - 228636</td>
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<td>-0.9 o/oo</td>
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<td>SAMPLE : GP07-24cm</td>
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<td>ANALYSIS : AMS-Standard delivery</td>
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<tr>
<td>MATERIAL/PRETREATMENT : (shell): acid etch</td>
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<tr>
<td>2 SIGMA CALIBRATION : Cal AD 1660 to 1840 (Cal BP 280 to 110)</td>
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<tr>
<td>Beta - 228637</td>
<td>790 +/- 40 BP</td>
<td>-6.9 o/oo</td>
<td>1090 +/- 40 BP</td>
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<tr>
<td>SAMPLE : RP05-13cm</td>
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<tr>
<td>ANALYSIS : AMS-Standard delivery</td>
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<tr>
<td>MATERIAL/PRETREATMENT : (carbonate sediment): none</td>
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<tr>
<td>2 SIGMA CALIBRATION : Cal AD 1250 to 1340 (Cal BP 700 to 610)</td>
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</tbody>
</table>
Dr. Kamin Liu  

<table>
<thead>
<tr>
<th>Sample Data</th>
<th>Measured Radiocarbon Age</th>
<th>13C/12C Ratio</th>
<th>Conventional Radiocarbon Age(*)</th>
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<tbody>
<tr>
<td>Beta-22863B</td>
<td>100 +/- 40 BP</td>
<td>-25.6 o/oo</td>
<td>90 +/- 40 BP</td>
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</table>

**SAMPLE**: RP05-22cm  
**ANALYSIS**: AMS-Standard delivery  
**MATERIAL/PRETREATMENT**: (organic material): acid/alkali/acid  
**2 SIGMA CALIBRATION**:  
  - Cal AD 1680 to 1770 (Cal BP 270 to 180) AND Cal AD 1800 to 1940 (Cal BP 150 to 10)  
  - Cal AD 1950 to 1960 (Cal BP 0 to 0)
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

Variables: C13/C12 = -25.4ab. mult=1

Laboratory number: Beta-228633

Conventional radiocarbon age: 190±40 BP

2 Sigma calibrated results: (95% probability)
- Cal AD 1650 to 1700 (Cal BP 300 to 250) and
- Cal AD 1720 to 1820 (Cal BP 230 to 130) and
- Cal AD 1840 to 1880 (Cal BP 110 to 70) and
- Cal AD 1920 to 1950 (Cal BP 40 to 0)

Intercept data

Intercepts of radiocarbon age with calibration curve:
- Cal AD 1670 (Cal BP 280) and
- Cal AD 1780 (Cal BP 170) and
- Cal AD 1800 (Cal BP 150) and
- Cal AD 1950 (Cal BP 0) and
- Cal AD 1950 (Cal BP 0)

1 Sigma calibrated results: (68% probability)
- Cal AD 1660 to 1680 (Cal BP 290 to 270) and
- Cal AD 1740 to 1810 (Cal BP 210 to 140) and
- Cal AD 1930 to 1950 (Cal BP 20 to 0)

References:

- IntCal04
- Calibration Database INTCAL04 Radiocarbon Age Calibration
- Mathematics
- A Simplified Approach to Calibrating C14 Dates

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-27.8; da.b. mult=1)

Laboratory number: Beta-228634
Conventional radiocarbon age: 140±40 BP
2 Sigma calibrated result: Cal AD 1660 to 1960 (Cal BP 290 to 0)
(95% probability)

Intercept data

Intercepts of radiocarbon age with calibration curve:
Cal AD 1690 (Cal BP 260) and
Cal AD 1730 (Cal BP 220) and
Cal AD 1810 (Cal BP 140) and
Cal AD 1930 (Cal BP 20) and
Cal AD 1950 (Cal BP 0)

1 Sigma calibrated results:
Cal AD 1670 to 1710 (Cal BP 280 to 240) and
Cal AD 1710 to 1770 (Cal BP 240 to 180) and
Cal AD 1800 to 1880 (Cal BP 150 to 60) and
Cal AD 1910 to 1940 (Cal BP 40 to 10) and
Cal AD 1950 to 1950 (Cal BP 0 to 0)

References:

Database used
INTCAL94

Calibration Database
INTCAL94: Radiocarbon Age Calibration

Mathematics:
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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -27.5; $\Delta_{14} \text{C} = 0$)

Laboratory number: Beta-228635

Conventional radiocarbon age: 180 ± 40 BP

2 Sigma calibrated results:
- Cal AD 1650 to 1710 (Cal BP 300 to 240) and
- Cal AD 1710 to 1880 (Cal BP 240 to 60) and
- Cal AD 1910 to 1950 (Cal BP 40 to 0)

(95% probability)

Intercept data

Intercepts of radiocarbon age with calibration curve:
- Cal AD 1670 (Cal BP 280) and
- Cal AD 1770 (Cal BP 180) and
- Cal AD 1800 (Cal BP 150) and
- Cal AD 1940 (Cal BP 10) and
- Cal AD 1950 (Cal BP 0)

1 Sigma calibrated results:
- Cal AD 1660 to 1690 (Cal BP 290 to 260) and
- Cal AD 1730 to 1810 (Cal BP 220 to 140) and
- Cal AD 1930 to 1950 (Cal BP 20 to 0)

(68% probability)

References:
- Database: INTCAL04
- Calibration Database: INTCAL04 Radiocarbon Age Calibration
- Mathematics: A Simplified Approach to Calibrating $\Delta^{14}C$

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

Variables: C13/C12 = -0.9; Delta-R = -5 ± 20; Glob res = -200 to 500; lab. mult = 1

Laboratory number: Beta-228636

Conventional radiocarbon age: 560 ± 40 BP

(570 ± 40 adjusted for local reservoir correction)

2 Sigma calibrated result: Cal AD 1660 to 1840 (Cal BP 280 to 110)
(95% probability)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal AD 1700 (Cal BP 250)

1 Sigma calibrated result: Cal AD 1680 to 1810 (Cal BP 270 to 140)
(68% probability)

References:

Database used: MARINE04

Calibration Database

INTCAL04: Radiocarbon Age Calibration


Mathematics:

A Simplified Approach to Calibrating C14 Dates


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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-6.9;Delta-R=0;Glob res=-200 to 500;lab. mult=1)

Laboratory number: Beta-228637

Conventional radiocarbon age: 1090±40 BP

(local reservoir correction not applied)

2 Sigma calibrated result: Cal AD 1250 to 1340 (Cal BP 700 to 610)
(95% probability)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal AD 1300 (Cal BP 650)

1 Sigma calibrated result: Cal AD 1280 to 1320 (Cal BP 670 to 630)
(68% probability)

References:

Database used

Calibration Database

INTCAL04 Radiocarbon Age Calibration


Mathematics:

A Simplified Approach to Calibrating C14 Dates


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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -25.6; delta 13C = -1)

Laboratory number: Beta-228638

Conventional radiocarbon age: 90 ± 40 BP

2 Sigma calibrated results:
Cal AD 1680 to 1770 (Cal BP 270 to 180) and
(95% probability) Cal AD 1800 to 1940 (Cal BP 150 to 10) and
Cal AD 1950 to 1960 (Cal BP 0 to 0)

Intercept data

Intercepts of radiocarbon age
with calibration curve:
Cal AD 1890 (Cal BP 60) and
Cal AD 1910 (Cal BP 40) and
Cal AD 1950 (Cal BP 0)

1 Sigma calibrated results:
Cal AD 1690 to 1730 (Cal BP 260 to 220) and
(68% probability) Cal AD 1810 to 1920 (Cal BP 140 to 30) and
Cal AD 1950 to 1960 (Cal BP 0 to 0)

References:
- Database used: INTCAL04
- Mathematics: A Simplified Approach to Calibrating C14 Dates

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<th>Sample Data</th>
<th>Measured Radiocarbon Age</th>
<th>13C/12C Ratio</th>
<th>Conventional Radiocarbon Age(?)</th>
</tr>
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<tbody>
<tr>
<td>Beta - 223210</td>
<td>2330 +/- 50 BP</td>
<td>-26.8 o/oo</td>
<td>2300 +/- 50 BP</td>
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<tr>
<td>SAMPLE : PALMPOND7-72cm</td>
<td>ANALYSIS : AMS-Standard delivery</td>
<td>MATERIAL/PRETREATMENT : (peat): acid/alkali/acid</td>
<td>2 SIGMA CALIBRATION : Cal BC 410 to 350 (Cal BP 2360 to 2300) AND Cal BC 310 to 210 (Cal BP 2260 to 2160)</td>
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<td>Beta - 223211</td>
<td>2580 +/- 40 BP</td>
<td>-26.4 o/oo</td>
<td>2560 +/- 40 BP</td>
</tr>
<tr>
<td>SAMPLE : PALMPOND7-83cm</td>
<td>ANALYSIS : AMS-Standard delivery</td>
<td>MATERIAL/PRETREATMENT : (peat): acid/alkali/acid</td>
<td>2 SIGMA CALIBRATION : Cal BC 810 to 760 (Cal BP 2760 to 2710) AND Cal BC 680 to 550 (Cal BP 2630 to 2500)</td>
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<tr>
<td>Beta - 223212</td>
<td>3540 +/- 40 BP</td>
<td>-26.6 o/oo</td>
<td>3510 +/- 40 BP</td>
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<tr>
<td>SAMPLE : PALMPOND7-104cm</td>
<td>ANALYSIS : AMS-Standard delivery</td>
<td>MATERIAL/PRETREATMENT : (peat): acid/alkali/acid</td>
<td>2 SIGMA CALIBRATION : Cal BC 1940 to 1730 (Cal BP 3880 to 3680)</td>
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<td>Beta - 223213</td>
<td>3410 +/- 40 BP</td>
<td>-26.4 o/oo</td>
<td>3390 +/- 40 BP</td>
</tr>
<tr>
<td>SAMPLE : PALMPOND7-126cm</td>
<td>ANALYSIS : AMS-Standard delivery</td>
<td>MATERIAL/PRETREATMENT : (peat): acid/alkali/acid</td>
<td>2 SIGMA CALIBRATION : Cal BC 1760 to 1600 (Cal BP 3710 to 3550)</td>
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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12= -26.8; lab. mult=1)

Laboratory number: Beta-23210
Conventional radiocarbon age: 2300±50 BP

2 Sigma calibrated results:
- Cal BC 410 to 350 (Cal BP 2360 to 2300) and
- Cal BC 310 to 210 (Cal BP 2260 to 2160)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal BC 390 (Cal BP 2340)

1 Sigma calibrated result:
- Cal BC 400 to 370 (Cal BP 2350 to 2320)

References:

Database used
INTCAL98
Calibration Database
Editorial Comment
INTCAL98 Radiocarbon Age Calibration
Mathematics
A Simplified Approach to Calibrating C14 Data

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -26.4 ± 1.0, mult = 1)

Laboratory number: Beta-223211
Conventional radiocarbon age: 2560±40 BP

2 Sigma calibrated results:
Cal BC 810 to 760 (Cal BP 2760 to 2710) and
Cal BC 680 to 550 (Cal BP 2630 to 2500)

Intercept data
Intercept of radiocarbon age with calibration curve: Cal BC 790 (Cal BP 2740)
1 Sigma calibrated result:
Cal BC 800 to 770 (Cal BP 2750 to 2720)
(68% probability)

References:

Database used:
INTCA1995
Calibration Database
Editorial Comment
INTCA1983 Radiocarbon Age Calibration
Mathematics:
A Simplified Approach to Calibrating C14 Dates

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=26.6 dab. mult=1)

Laboratory number: Beta-223212
Conventional radiocarbon age: 3510±40 BP

2 Sigma calibrated result: Cal BC 1940 to 1730 (Cal BP 3880 to 3680)
(95% probability)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal BC 1870 (Cal BP 3820)

1 Sigma calibrated result: Cal BC 1890 to 1760 (Cal BP 3840 to 3710)
(68% probability)

References:

Data base used:
INTCA1995

Calibration Database

Editorial Comment

INTCA88 Radiocarbon Age Calibration

Mathematics:
A Simplified Approach to Calibrating C14 Dates

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=26.4 lab. mult=1)

Laboratory number: Beta-223213

Conventional radiocarbon age: 3390±40 BP

2 Sigma calibrated result: Cal BC 1760 to 1600 (Cal BP 3710 to 3550)
(95% probability)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal BC 1690 (Cal BP 3640)

1 Sigma calibrated result: Cal BC 1730 to 1630 (Cal BP 3680 to 3580)
(68% probability)

References:

Database used:

INTCAL98

Calibration Database

Editorial Comment


INTCAL98 Radiocarbon Age Calibration


Mathematics

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<table>
<thead>
<tr>
<th>Sample Data</th>
<th>Measured Radiocarbon Age</th>
<th>$^{13}$C/$^{12}$C Ratio</th>
<th>Conventional Radiocarbon Age(*)</th>
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<tr>
<td>Beta - 240844</td>
<td>4300 +/- 40 BP</td>
<td>-19.1 o/oo</td>
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<td>SAMPLE : BSP 13-90</td>
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<td>ANALYSIS : AMS-Standard delivery</td>
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<td>MATERIAL/PRETREATMENT : (organic sediment): acid washes</td>
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<tr>
<td>2 SIGMA CALIBRATION : Cal BC 3270 to 3240 (Cal BP 5220 to 5190) AND Cal BC 3110 to 2910 (Cal BP 5060 to 4860)</td>
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<tr>
<td>Beta - 240845</td>
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<td>-18.9 o/oo</td>
<td>2250 +/- 40 BP</td>
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<td>MATERIAL/PRETREATMENT : (organic sediment): acid washes</td>
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<td>2 SIGMA CALIBRATION : Cal BC 400 to 200 (Cal BP 2340 to 2150)</td>
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<td>Beta - 240846</td>
<td>1880 +/- 40 BP</td>
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<td>MATERIAL/PRETREATMENT : (organic sediment): acid washes</td>
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<tr>
<td>2 SIGMA CALIBRATION : Cal BC 50 to Cal AD 120 (Cal BP 2000 to 1830)</td>
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<td>Beta - 240847</td>
<td>1490 +/- 40 BP</td>
<td>-19.8 o/oo</td>
<td>1380 +/- 40 BP</td>
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<td>SAMPLE : BSP 10-45</td>
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<td>MATERIAL/PRETREATMENT : (organic sediment): acid washes</td>
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<tr>
<td>2 SIGMA CALIBRATION : Cal AD 400 to 570 (Cal BP 1550 to 1380)</td>
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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

Variables: C13/C12=+19.1: lab. multi-1)

Laboratory number: Beta-240844

Conventional radiocarbon age: 4400±40 BP

2 Sigma calibrated results: Cal BC 3270 to 3240 (Cal BP 5220 to 5190) and Cal BC 3110 to 2910 (Cal BP 5060 to 4860)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal BC 3020 (Cal BP 4970)

1 Sigma calibrated result: Cal BC 3090 to 2920 (Cal BP 5040 to 4880)

References:

Database used
INTCAL04

Calibration Database
INTCAL04 Radiocarbon Age Calibration

Mathematics
A Simplified Approach to Calibrating C14 Dates

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

Laboratory number: Beta-240845

Conventional radiocarbon age: 2250 ± 40 BP

2 Sigma calibrated result: Cal BC 400 to 200 (Cal BP 2340 to 2150)
(95% probability)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal BC 370 (Cal BP 2320)

1 Sigma calibrated results: Cal BC 390 to 350 (Cal BP 2340 to 2300) and Cal BC 290 to 220 (Cal BP 2240 to 2170)

References:

Database used
INTCAL04

Calibration Database
INTCAL04. Radiocarbon Age Calibration

Mathematics
A Simplified Approach to Calibrating C14 Dates

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

Laboratory number: Beta-240846

Conventional radiocarbon age: 1970±40 BP

2 Sigma calibrated result: Cal BC 50 to Cal AD 120 (Cal BP 2000 to 1830)
(95% probability)

Intercept data

Intercept of radiocarbon age with calibration curve: Cal AD 30 (Cal BP 1920)

1 Sigma calibrated result: Cal BC 10 to Cal AD 70 (Cal BP 1960 to 1880)
(68% probability)

References:

Database used

INTCAL04

Calibration Database

INTCAL04: Radiocarbon Age Calibration


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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -19.8; lab. mult = 1)

Laboratory number: Beta-240847

Conventional radiocarbon age: 1580 ± 40 BP

2 Sigma calibrated result: Cal AD 400 to 570 (Cal BP 1550 to 1380)
(95% probability)

Intercept data

Intercepts of radiocarbon age with calibration curve:
- Cal AD 440 (Cal BP 1510) and
- Cal AD 490 (Cal BP 1460) and
- Cal AD 520 (Cal BP 1430)

1 Sigma calibrated result: Cal AD 420 to 540 (Cal BP 1530 to 1410)
(68% probability)

References:

Database used
- IntCal04

Calibration Database
- IntCal04: Radiocarbon Age Calibration

Mathematics
- A Simplified Approach to Calibrating C14 Dates

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APPENDIX 6 PERMISSION LETTER FROM CARTOGRAPHIC PERSPECTIVES

----- Original Message -----  
From: "Jason Knowles"  
To: "Scott Freundschuh"  
Subject: Dissertation permission letter  
Date: Fri, 10 Aug 2007 10:54:36

Scott,  

Would it be possible to get a letter of permission from Cartographic Perspectives allowing me to use:


as a chapter in my PhD dissertation? It is a required step from the graduate school. Please let me know your thoughts.

Thank you.

Jason T. Knowles M.Sc.  
PhD Candidate  
Department of Geography & Anthropology  
Louisiana State University  
227 Howe-Russell Geoscience Complex  
Baton Rouge, LA 70803-4105  
Phone: (225) 578-0470  
Fax: (225) 578-4420
February 13, 2008

Jason T. Knowles M.Sc.
PhD Candidate
Department of Geography & Anthropology
Louisiana State University
227 Howe-Russell Geoscience Complex
Baton Rouge, LA 70803-4105

Dear Jason,

As interim editor of Cartographic Perspectives (CP) and representative of the North American Cartographic Information Society (NACIS), I grant you permission to use the paper:


as a chapter in your dissertation. The only stipulation NACIS has is that you give full credit to CP and NACIS.

Best regards,

Scott Freundschuh, Interim Editor
Cartographic Perspectives
VITA

Jason Thomas Knowles was born September, 1975, in New Orleans, Louisiana. He was awarded a Bachelor of Arts degree in geography from California State University, Long Beach, in August of 2000. He was awarded a Master of Science from Louisiana State University in geography in August, 2004. After graduation Jason stayed on at Louisiana State University and began a doctoral program in geography. During his doctoral program, working closely with Dr. Kam-biu Liu and funded by internal and external grants, Jason embarked on an extensive agenda of domestic and international based field research. He expects to receive his Doctor of Philosophy in May of 2008.