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Late-Holocene Environmental History in the Northeastern Caribbean: Multi-proxy Evidence From Two Small Lakes on the Southern Slope of the Cordillera Central, Dominican Republic

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To the Graduate Council:

I am submitting herewith a dissertation written by Chad Steven Lane entitled "Late-Holocene Environmental History in the Northeastern Caribbean: Multi-proxy Evidence From Two Small Lakes on the Southern Slope of the Cordillera Central, Dominican Republic." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Sally P. Horn, Claudia I. Mora, Major Professor

We have read this dissertation and recommend its acceptance:

Henri D. Grissino-Mayer, Kenneth H. Orvis

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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LATE HOLOCENE ENVIRONMENTAL HISTORY IN THE NORTHEASTERN CARIBBEAN: MULTI-PROXY EVIDENCE FROM TWO SMALL LAKES ON THE SOUTHERN SLOPE OF THE CORDILLERA CENTRAL, DOMINICAN REPUBLIC

A Dissertation
Presented for the
Doctor of Philosophy
Degree
University of Tennessee, Knoxville

Chad Steven Lane
May 2007

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I want to thank Dr. Sally Horn for her willingness to always go well above and beyond the call of duty to help her students. Dr. Horn is no stranger to late night editing marathons that are great for meeting deadlines, but also incredibly accurate assuring her students end up with the best documents possible. Dr. Horn is also always on the look out for good student opportunities outside of the university and is responsible for introducing me to the world of grant writing.

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aware of the research needs of her students and is more than willing to help her students obtain any necessary knowledge or materials that might be required. I look forward to continuing collaborations with Dr. Mora, as well as Dr. Horn, well into the future.

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S. Horn and K. Orvis led expeditions to the Dominican Republic in the summer of 2002, summer of 2003, and winter of 2004 to conduct reconnaissance and collect sediment cores from Laguna Castilla, Laguna de Salvador, and other lakes of the Las Lagunas region. Field assistance was provided by my graduate student colleagues Duane Cozadd in 2002 and Jeff Dahoda in 2004.

Laboratory assistance, helpful discussion, and moral support was also provided by my fellow graduate and undergraduate students Zachary Taylor, Kyle Schlachter, Martin Arford, Katie Milam, John Thomasson, Duane Cozadd, Jason Graham, Dana Miller, Whitney Kocis, Dave West, Allison Stork, Brock Remus, and Joe Burgess. I am especially grateful to Martin Arford and Duane Cozadd, who were never hesitant to help me out with pollen identifications, and Katie Milam, John Thomasson, and Jason Graham, who spent endless hours as undergraduate research assistants helping me pick out and analyze ostracods and charophyte oospores. I was assisted in ostracod identifications by Dr. Jonathon Holmes (University College London) and am grateful to him for his time and his willingness to share his expertise. Dr. Lee Newsom (Pennsylvania State University) was kind enough to share her knowledge of Caribbean archaeology, which added greatly to this dissertation. I must also thank the Departments of Geography and Earth and Planetary Sciences for providing outstanding programs and supportive environments that promote academic and scholastic excellence.

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ABSTRACT

This dissertation presents multi-proxy evidence of paleoenvironmental change preserved in sediment records recovered from two lakes on the southern (Caribbean) slope of the Cordillera Central in the Dominican Republic: Laguna Castilla (18°47'51" N, 70°52'33" W, 976 m) and Laguna de Salvador (18°47'45" N, 70°53'13" W, 990 m).

The Castilla and Salvador sediment records contain evidence of prehistoric forest clearance and agriculture, including abundant maize pollen, dating back to around A.D. 1060. These pollen grains constitute the earliest evidence of maize agriculture from the interior of Hispaniola, and represent some of the earliest evidence of maize agriculture from the Caribbean as a whole. This finding is significant geographically because it suggests that prehistoric humans that occupied the interior of the island may have relied more on maize than their coastal counterparts.

The abundance of maize pollen in the sediment records, and the high rates of sediment accumulation in the lakes, provide an ideal situation for testing the sensitivity of stable carbon isotope signatures of total organic carbon ($\delta^{13}C_{TOC}$) in lake sediments to variations in the spatial scale or intensity of agricultural activities. Close correspondence between $\delta^{13}C_{TOC}$ values and maize pollen concentrations in the Castilla sediment record indicates a close relationship between $\delta^{13}C_{TOC}$ signatures and the scale of maize cultivation. Correlations between $\delta^{13}C_{TOC}$ signatures and mineral influx also highlight the sensitivity of the $\delta^{13}C_{TOC}$ record to variations in allochthonous carbon delivery.

More detailed multi-proxy analyses of the Castilla and Salvador sediment records indicate extreme shifts in hydrology, vegetation, and disturbance regimes in response to climate change and human activity in the watersheds over the last ~3000 cal yr B.P. Close correspondence between the hydrological history of Castilla, Salvador, and other circum-Caribbean study sites indicates that much of the hydrologic variability was associated with variations in the mean boreal summer position of the Intertropical Convergence Zone. Human occupation of the Castilla and Salvador watersheds appears to be closely linked to severe drought events and may indicate larger scale cultural responses to severe precipitation variability on the island of Hispaniola.

TABLE OF CONTENTS

LIST OF TABLES

TABLE PAGE

CHAPTER 2: THE EARLIEST EVIDENCE OF MAIZE AGRICULTURE FROM THE INTERIOR OF HISPANIOLA

CHAPTER 3: SENSITIVITY OF SEDIMENTARY STABLE CARBON ISOTOPES IN A SMALL NEOTROPICAL LAKE TO PREHISTORIC FOREST CLEARANCE AND MAIZE AGRICULTURE

CHAPTER 4: MULTI-PROXY ANALYSIS OF LATE-HOLOCENE PALEOENVIRONMENTAL CHANGE IN THE MID-ELEVATIONS OF THE CORDILLERA CENTRAL, DOMINICAN REPUBLIC

LIST OF FIGURES

FIGURE PAGE

CHAPTER 1: INTRODUCTION AND RESEARCH SETTING

CHAPTER 2: THE EARLIEST EVIDENCE OF MAIZE AGRICULTURE FROM THE INTERIOR OF HISPANIOLA

CHAPTER 3: SENSITIVITY OF SEDIMENTARY STABLE CARBON ISOTOPES IN A SMALL NEOTROPICAL LAKE TO PREHISTORIC FOREST CLEARANCE AND MAIZE AGRICULTURE

CHAPTER 4: MULTI-PROXY ANALYSIS OF LATE-HOLOCENE PALEOENVIRONMENTAL CHANGE IN THE MID-ELEVATIONS OF THE CORDILLERA CENTRAL, DOMINICAN REPUBLIC

FIGURE PAGE

CHAPTER 1

Introduction and Research Setting

Hispaniola (17°30'–19°50' N, 68°20'–74°30' W) is the second largest island in the Caribbean, after Cuba, and has the greatest relief and climatic and biological diversity of all Caribbean islands. Elevations range from sea level to the high mountain peaks of the Cordillera Central, which reach over 3000 m elevation (Orvis, 2003). Precipitation totals range from a maximum of ~2500 mm/yr in the northeastern portion of the island to a minimum of ~500 mm/yr in the western portion. The wide range of microclimates and habitats and the geographic isolation of Hispaniola have fostered the development of an incredibly diverse assemblage of organisms and a high level of endemism (Bolay, 1997). In addition, Hispaniola has a compelling human history as it is the geographic epicenter of European contact with the "new world." It was the only Caribbean island visited on all four of Christopher Columbus' voyages. In A.D. 1493, Columbus founded the first European settlement in the Americas at La Isabela, which became a springboard for further exploration and settlement throughout the region.

Despite the compelling physical geography, ecology, and human history of Hispaniola, very little is known about the environmental history of the island. Continuous high-resolution records of Holocene paleoenvironmental change on Hispaniola are geographically limited. One focus of research has been Lake Miragoane, a coastal lake on the southern coast of Haiti. A series of paleoenvironmental analyses have been conducted on a single sediment core recovered from the lake in 1985 (Brenner and Binford, 1988; Hodell et al., 1991; Curtis and Hodell, 1993; Higuera-Gundy, 1991; 1999). A second focus of paleoenvironmental research has been the highlands of the Cordillera Central, where S. Horn, K. Orvis, and collaborators have examined a series of sediment cores from lakes and bogs, as well as soil and geomorphic indicators of paleoenvironmental change and modern pollen-vegetation relationships (Orvis et al., 1997; 2005; Horn et al., 2000; Clark et al., 2002; Kennedy, 2003; Kennedy et al., 2005; 2006). Also in the highlands, J. Speer and H. Grissino-Mayer have joined Orvis, Horn, and Kennedy in investigating the dendrochronological potential of the native pine, *Pinus occidentalis* (Speer et al., 2004). While these records have provided new avenues of research and insights into the impacts of climate variability and shifting disturbance regimes on the island, they could not provide much insight into prehistoric human-environment interactions on the landscape of Hispaniola.

Knowledge of the interrelationships between paleoclimate variability, human populations, and the ecosystems of Hispaniola will only improve with an increase in the number of study sites and areas investigated. Unfortunately, there are only a limited number of natural lakes or other sources of continuous archives of paleoenvironmental change and prehistoric human activity on the island. In this study, I have conducted an in-depth investigation of two mid-elevation lakes in the Cordillera Central in an effort to better understand the interrelationships between climate, ecosystems, and prehistoric human occupants throughout the late Holocene on the island of Hispaniola.

Larger Framework of Dissertation

This dissertation is part of a larger study, funded by a grant to S. Horn, K. Orvis, and C. Mora from the National Science Foundation (BCS-0550382) and an earlier award to K. Orvis and S. Horn from the National Geographic Society. The goal of the National Science Foundation study is to use sediment records from two sites, Las Lagunas and Laguna Saladilla, and the unique topography of Hispaniola to reconstruct Holocene atmospheric dynamics of the region and impacts of prehistoric human populations on the island (Figure 1.1).

The island of Hispaniola is influenced by three primary climate variables: (1) trade wind strength and moisture content, (2) the influence of polar outbreaks, and (3) the migration of mean boreal summer Intertropical Convergence Zone (ITCZ) position. The northeasterly trade winds are the dominant component of the island's climate. Hispaniola's trade-wind-related precipitation is heaviest in the northeastern portions of the island and on the windward slopes of the multiple mountain ranges on the island. However, the WNW-ESE trending mountain ranges of the island are very effective barriers to the trade winds (Figure 1.1).

Laguna Saladilla is located along the leeward slope of one of these mountain ranges, the Cordillera Septentrional (Figure 1.1). The barrier formed by the Cordillera Septentrional creates persistent zones of atmospheric subsidence along the leeward slopes of the range and very strong rain shadow conditions

Figure 1.1. The locations of the Laguna Saladilla and Las Lagunas study sites on the island of Hispaniola and dominant moisture sources for the island. Precipitation delivery to most of the island comes from the northeasterly trade winds. The Laguna Saladilla and Las Lagunas study sites are shielded from trade wind precipitation by the Cordillera Septentrional and Cordillera Central, respectively. Precipitation at Laguna Saladilla is primarily associated with polar air masses, known as "nortes" migrating from North America during the boreal winter. Precipitation at Las Lagunas is primarily associated with intensified sea breezes and increased convective activity during the boreal summer when ITCZ-proximal doldrum conditions dominate. Relief is based on Shuttle Radar Topography Mission 1 elevation data. Lighter shades represent higher elevations. Map provided by K. Orvis.

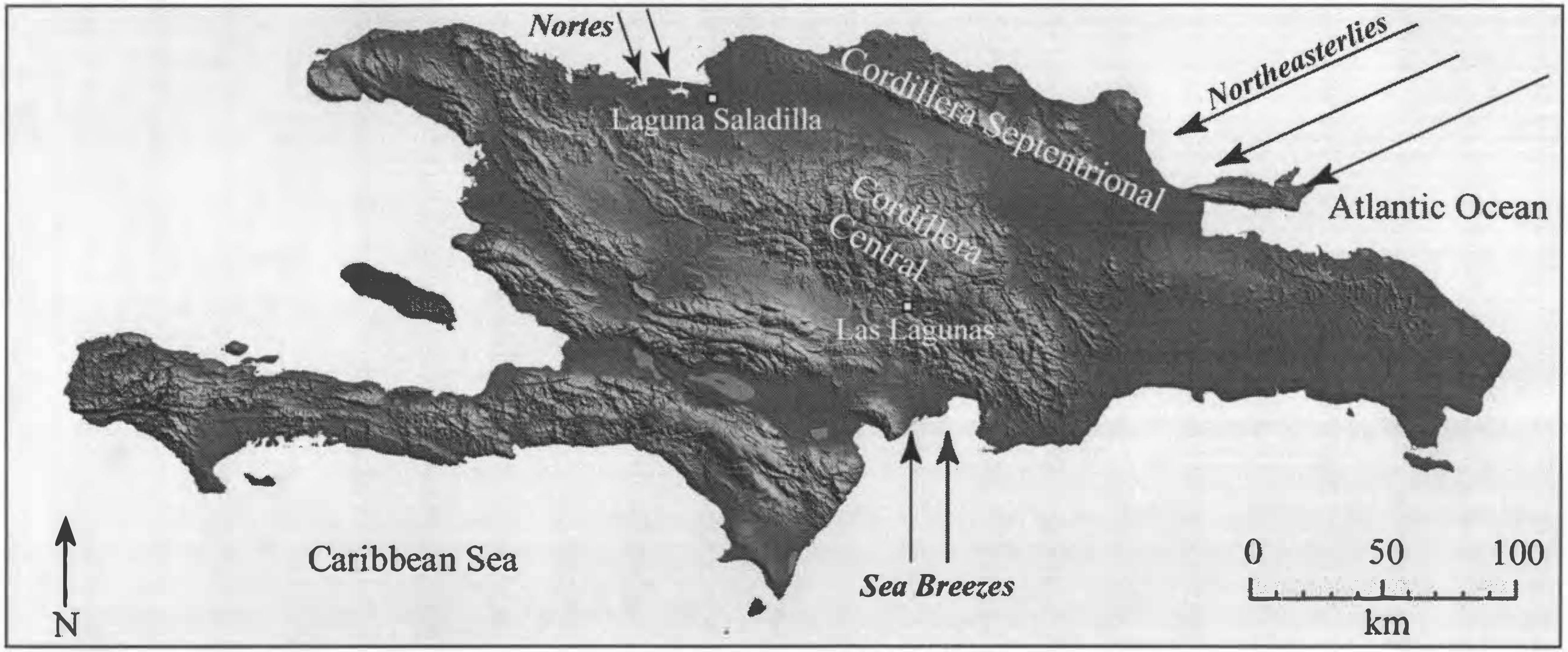

Figure 1.1. Continued

locally, hence the desert conditions around Laguna Saladilla. However, the topography around Laguna Saladilla is open to the WNW, the direction from which polar fronts from North America (nortes) arrive in the boreal winter (Figure 1.1). These polar air outbreaks and fronts are the primary source of precipitation delivery to the Laguna Saladilla area.

The second study area, Las Lagunas, is located on the leeward slope of the largest mountain range on the island of Hispaniola, the Cordillera Central. The Cordillera Central represent an unbroken barrier to the northeast trade winds and the modern precipitation regime in the Las Lagunas area is dominated by convection fed by sea breeze moisture during the boreal summer when ITCZ-proximal doldrums conditions dominate (Figure 1.1; see further discussion in the Environmental Setting section below).

By analyzing and comparing proxy records of paleoprecipitation recovered from Laguna Saladilla and multiple lakes at the Las Lagunas study site it should be possible to reconstruct variations in two distinct classes of weather and the related atmospheric dynamics driving these weather systems. The Laguna Saladilla sediments should hypothetically provide a record of polar outbreak events while the sediments of lakes around Las Lagunas should hypothetically provide a record of ITCZ migration. By comparing reconstructed paleoprecipitation records from both sites it should be possible to reconstruct variations in polar front intensity and ITCZ migration, along with the interrelationships of these atmospheric dynamics, over extended periods of time.

This dissertation is one part of this much larger study. It focuses on the sediment records of two of four lakes under investigation at the Las Lagunas study site and has these specific goals:

1. Search for and examine any palynological evidence of maize agriculture in the sediments of two small lakes in the mid-elevations of the Cordillera Central (Laguna Castilla and Laguna de Salvador) to develop a more in-depth understanding of the introduction, distribution, and importance of maize agriculture in Hispaniola (Chapter 2).
2. Assess the potential of using sedimentary stable carbon isotopes as high-resolution indicators of prehistoric maize agriculture intensity and forest disturbance in a small watershed (Laguna Castilla) in the mid-elevations of the Dominican Republic (Chapter 3).
3. Develop a comprehensive late Holocene record of paleoenvironmental change in the mid-elevations of the Cordillera Central, based on multi-proxy analyses of sediments from Laguna Castilla and Laguna de Salvador, that allows assessments of climate change, vegetation change, prehistoric human impacts, disturbance regimes, and the inter-relationships of all of these variables (Chapter 4).

Dissertation Organization

This dissertation contains five chapters. The first Chapter (1) introduces the dissertation, describes the environmental setting, and reviews prior research on regional paleoclimate and archaeology. Chapters 2, 3, and 4 are presented as stand-alone manuscripts. They are slightly modified versions of manuscripts that have been submitted for publication or are in preparation for submission.

Chapter 2 is an analysis of prehistoric maize (*Zea mays* subsp. *mays*) pollen preserved in the sediment records of Laguna Castilla and Laguna de Salvador. I examine the timing of maize pollen deposition in relation to the archaeological record of maize on Hispaniola and in the circum-Caribbean region, and consider the archaeological relevance of my findings. This manuscript has been submitted to the *Journal of Caribbean Science.*

Chapter 3 presents an analysis of the sensitivity of the sedimentary stable carbon isotope record to variations in the abundance of maize being cultivated in the Laguna Castilla watershed. I compare variations in the bulk sedimentary stable carbon isotope record to sedimentary proxies of the intensity and/or spatial extent of maize cultivation and of allochthonous sediment delivery. This manuscript is in preparation for submission to the *Journal of Paleolimnology.*

In Chapter 4, I present a multi-proxy record of paleoenvironmental change from Laguna Castilla and Laguna de Salvador. I investigate evidence of climate change, vegetation change, prehistoric human activity, and shifting disturbance regimes, and analyze the interrelationships between all of these variables. In addition, I discuss the significance of these paleoenvironmental changes in the context of the region as a whole. This manuscript is in preparation for submission to the journal *Quaternary Science Reviews.*

Finally, Chapter 5 is a summary of the major conclusions of this dissertation.

Environmental Setting

The Cordillera Central extends from northwestern Haiti to the south-central portions of the Dominican Republic (Figure 1.2). The Cordillera Central is the oldest mountain chain on the island of Hispaniola; uplift occurred during the Plio-Pleistocene (Pubellier et al., 1991). The lithology of the Cordillera Central dates back some 60 million years and includes Cretaceous volcanic, metamorphic, and plutonic rocks (Bolay, 1997). In the province of Azua, which includes the study site, much of the plutonic core of the Cordillera Central is covered with soft marine sediments. These ancient marine sediments have been deeply incised by numerous streams and are highly susceptible to slope failure. The small town of Las Lagunas (18° 47'00" N, 70°53'00" W; Figure 1.2) is located at the site of some of the most spectacular of these slope failure events. The large slide(s) that formed the area now occupied by the town of Las Lagunas also formed several lake basins (Figure 1.3). Laguna Castilla (18°47'51" N, 70°52'33" W, 976 m) and Laguna de Salvador (18°47'45" N, 70°53'13" W, 990 m) are the focus of this dissertation.

Climate

The discussion that follows is partially based upon interpretations of Caribbean climate dynamics provided by K. Orvis (pers. comm.). The location of Hispaniola along the northern margin of the tropics means it is susceptible to tropical, subtropical, and extratropical climate dynamics. Tropical influences include the trade winds, atmospheric instability and convergence associated with doldrum conditions, and atmospheric disturbance-related influences such as

Figure 1.2. The island of Hispaniola with sites mentioned in text. Relief is based on Shuttle Radar Topography Mission 1 elevation data. Lighter shades represent higher elevations. Map provided by K. Orvis.

Figure 1.2. Continued

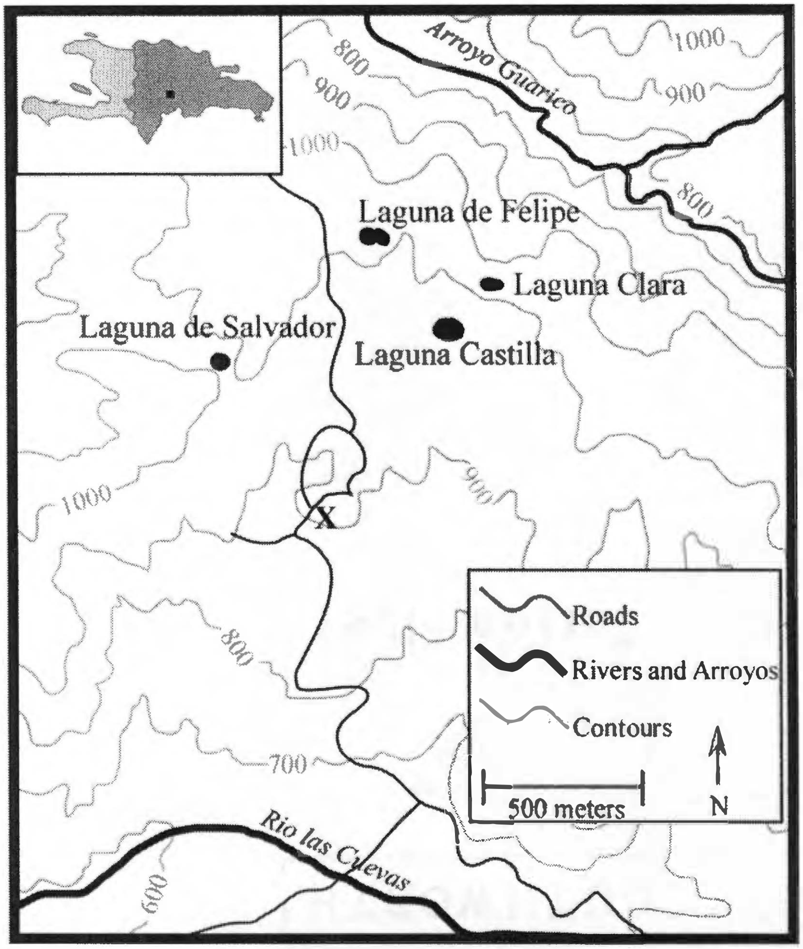

Figure 1.3. Map of the Las Lagunas area. The town center is marked by an "X". Laguna Castilla and Laguna de Salvador are the focus of this dissertation. Map based on the 1:50000 topographic sheet published by the National Geospatial-Intelligence Agency. Lake positions were determined from GPS measurements by K. Orvis.

easterly waves, tropical storms, and other smaller disturbances to the atmospheric system. The northeasterly trade winds are the dominant feature of Hispaniolan climate. The northeasterly trades deliver tropical Atlantic moisture to the eastern shores of the island as well as the windward slopes of the major mountain ranges, but their constancy of direction means that severe leeward rainshadowing occurs. An increase in the intensity of the northeast trades or their moisture content, for example as a result of higher sea surface temperatures in the tropical Atlantic, can yield increased precipitation to those areas of Hispaniola that receive trade wind moisture.

During the boreal summer, when the ITCZ migrates to its northernmost position somewhat south of the island of Hispaniola, air pressures and trade wind intensities decrease regionally. The decreased air pressures promote convective activity over the island and the decrease in northwesterly trade wind intensity also decreases vertical shear, enhances instability, and promotes deeper atmospheric convection. These ITCZ-proximal doldrum conditions are especially important along the leeward slopes of the southern Cordillera on the island of Hispaniola, including the Las Lagunas area, where such activity dominates local background precipitation. Atmospheric disturbances such as easterly waves and tropical storms also play a significant role in the climate of Hispaniola, particularly in the late boreal summer and fall when tropical Atlantic and Caribbean sea surface temperatures are peaking, but this source varies on several time scales.

Subtropical climate influences on the island of Hispaniola primarily consist of the strength and duration of atmospheric subsidence (high pressure) over the Caribbean region, especially during the boreal winter. Sustained high pressure that extends south and west into the region can significantly decrease trade wind intensity and convective activity leading to overall drier conditions on the island of Hispaniola.

Extratropical climate influences on the island of Hispaniola are primarily constrained to the northwestern portions of the island. When polar fronts are intense enough to reach Hispaniola, the uplift associated with frontal convergence can yield limited precipitation to the parts of the island exposed to the front or able to enhance it orographically.

Precipitation on the island ranges from as much as 2500 mm in the northeastern part of the country where the tradewinds are unobstructed, to as low as 500 mm annually in the rainshadowed northwestern and southwestern portions of the island (Horst, 1992; Bolay, 1997). The majority of the island experiences at least one relatively dry period during the year, with two relatively dry seasons the norm for many localities.

Temperatures on Hispaniola are typical for a tropical island, with average annual sea level temperatures between 26 °C and 29 °C, and daily temperature variation that exceeds the annual variation in monthly mean temperatures (Schubert and Medina, 1982; Orvis et al., 1997). Mean annual temperatures are considerably lower in the high elevations of the Cordillera Central. Orvis et al. (1997) calculated the mid-elevation lapse rates for the island to be around –8.5 °C km^{-1}. Applying this lapse rate upslope and taking into account the effects of the trade wind inversion, it is plausible that the highest slopes of the Cordillera Central have mean annual temperatures at or below 7 °C (Orvis et al., 1997).

Dependable meteorological records are rare in the less populated areas of the Dominican Republic, including the area around Las Lagunas. Limited meteorological data from the nearby town of Padre Las Casas indicate a mean annual temperature of 24 °C (K. Orvis, pers. comm.). The mean annual temperature for Las Lagunas is likely to be about 3.8 °C lower as it is about 450 m higher in elevation than Padre Las Casas, yielding a mean annual temperature for Las Lagunas somewhere around 20 °C.

Estimates of the mean annual precipitation for the area are more difficult to make as no precipitation data are available from the Padre Las Casas meteorological station. The nearest available precipitation data are from the more distant city of Azua, which is both lower in elevation and subject to a greater rainshadow effect (Figure 1.2). Based on the mean annual precipitation values for Azua of ~700 mm (K. Orvis, pers. comm.), it is reasonable to assume that mean annual precipitation values for the area around Laguna Castilla and Laguna de Salvador are somewhere around 900–1000 mm.

As outlined above, precipitation on the southern slope of the Cordillera Central is primarily the result of convective uplift fed by sea breeze moisture during the boreal summer when the ITCZ is in its northerly position and proximal-doldrum conditions dominate. This results in a rather seasonal precipitation regime, with a distinct dry season in the late winter and early spring (Bolay, 1997). In the Holdridge life zone classification, the Las Lagunas area falls within the lower montane moist forest zone. The Holdridge system is a climatic classification, but zones are named after expected mature vegetation (Holdridge et al., 1971).

In addition to the multiple climate controls outlined above, the inter-annual precipitation regime of Hispaniola is also sensitive to several climate oscillations. Two of the most pervasive climate cycles affecting the Caribbean as a whole are the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), both of which significantly affect Caribbean sea surface temperatures (SSTs) and sea level pressures (SLPs; Enfield, 1996; Enfield and Mayer, 1997; Enfield and Elfaro, 1999; Giannini et al., 2000; 2001a; 2001b; Taylor et al., 2002). The interactions between these two climate cycles are complex and coherent patterns are difficult to isolate, especially with the relatively sparse and limited meteorological records of the Caribbean region (Giannini et al., 2000), but some patterns have emerged.

Giannini et al. (2000; 2001a; 2001b) documented and summarized the impacts of ENSO variations on the climate of the tropical Atlantic and Caribbean. In general, data provided by Giannini and collaborators indicate drier than average conditions in the Caribbean region during the boreal summer of an El Niño event followed by wetter than average conditions during the spring of the following year. The drier than average conditions during the boreal summer of an El Niño year are related to decreased SLPs in the equatorial and tropical Pacific, and higher than average SLPs over the tropical Atlantic (Hastenrath and Heller, 1977; Covey and Hastenrath, 1978; Curtis and Hastenrath, 1995; Poveda and

Mesa, 1997), in a pattern that has been labeled a “zonal seesaw” (Giannini et al., 2001a). This pattern leads to convergence along the margins of the eastern Pacific ITCZ and divergence, hence drier conditions, in the Caribbean basin (Giannini et al,, 2001a). The decreased meridional pressure gradient between the tropical Atlantic and eastern Pacific also leads to a weakening of the northeast trade winds.

The weakening of the meridional pressure gradient, and consequently in the northeast trade winds, diminishes upwelling in the Caribbean basin leading to anomalously high SSTs. It is this delayed increase in Caribbean SSTs (Enfield and Mayer, 1997) that leads to wetter than average conditions during the spring of the year following a warm ENSO event. The mechanism is the resulting increases in atmospheric convection and absolute humidity related to increased SSTs (Giannini et al., 2001a).

It is also worth noting that an increase in vertical shear over the tropical Atlantic during El Niño years has been linked to diminished tropical cyclone activity in the tropical Atlantic (Gray et al., 1994). A decrease in tropical cyclone activity can also lead to a decrease in annual precipitation totals for the Dominican Republic.

The North Atlantic Oscillation (NAO) also significantly affects Caribbean climate (Malmgren et al., 1998). In short, an intensified North Atlantic High (NAH), typical of the positive phase of the NAO (van Loon and Rogers, 1978), leads to the intensification of the northeastern trade winds. This intensification of the trade winds leads to enhanced heat loss from the tropical ocean, hence decreased convection and decreased precipitation (Giannini et al., 2001a). Conversely, a weakened NAH, or more negative phase of the NAO, will lead to weakened northeast trade winds and an increase in SSTs and convective activity, yielding wetter conditions in the tropical Atlantic and Caribbean basin.

Although there is ample evidence to suggest that ENSO and the NAO are not related to each other, and the two oscillations are known to operate on different frequencies (Rogers, 1984; Giannini et al., 2001a), these climate oscillations can amplify or mask each other at different times. For example, when ENSO is in a warm phase and the NAO is in a positive phase, the two climate oscillations can combine to create very dry conditions in the tropical Atlantic and the Caribbean. Conversely, if the NAO is in a more negative phase in the year following a warm ENSO event, conditions can become much wetter than average in the tropical Atlantic and the Caribbean due to the anomalously high SSTs in both locations. Finally, if the two oscillations are having opposite impacts on the tropical Atlantic and Caribbean (i.e. cool phase ENSO and positive NAO, or warm phase ENSO and negative NAO) the climatic impacts of both oscillations can be masked or dampened (Giannini et al., 2001a). With this in mind, Giannini et al. (2001a) pointed out that long term variations in the relationship between ENSO and the NAO through time can lead to significant variations in the precipitation regime of the tropical Atlantic and the Caribbean.

Finally, precipitation totals for the Dominican Republic can also be significantly affected by tropical storms and hurricanes. According to Horst (1992), hurricanes can be expected to make landfall on the Dominican Republic once every 3.6 years. Peak hurricane season occurs between August and mid-October when Atlantic SSTs reach their maximum. Hurricanes can have significant impacts on rainfall totals for the island. For example, in 1998 Hurricane Georges struck the Dominican Republic and, according to satellite estimates, may have dropped ~1000 mm of rain on the country in less than 24 hours (Guiney, 1999).

Vegetation

The island of Hispaniola is home to a wide variety of plant associations and vegetation types, which include mangroves along protected coastlines, evergreen forests in the humid lowlands of the northeast, deserts or dry forests in the rainshadowed portions of the country, montane and submontane rainforests on windward slopes of the cordillera, and pine forests in the highest elevations (Tolentino and Peña, 1998). Much of the natural vegetation of Hispaniola has been heavily affected by human activity, especially in Haiti, and converted into agricultural land. Agriculture, along with tourism and mining, are key components of the economies of both the Dominican Republic and Haiti (Bolay, 1997). According to Bolay (1997), only 10% of the island's pre-Columbian total forest area remains intact.

The vegetation currently surrounding the town of Las Lagunas is classified by Tolentino and Peña (1998) as grassland (pasture) and mixed crops and grasslands. Tolentino and Peña classify intact woody vegetation at the same altitude and slope aspect as lower montane moist forest (i.e. the Holdridge life zone designation; Panamerican Union, 1967). Remnant areas of lower montane moist forest include pines (*Pinus occidentalis* Schwartz) mixed with evergreen and deciduous broadleaved trees (Liogier 1981). Naturally occurring broadleaf assemblages likely included species in the genera *Cecropia, Garrya, Ilex, Juglans, Magnolia, Miconia, Mecranium, Meriania, Myrica, Ocotea, Piper, Trema,* and *Weinmannia,* to name a few, as well as a wide variety of genera and species from the Arecaceae, Poaceae, and Rubiaceae families, along with others in the Urticales order not already mentioned above (Bolay, 1997; Kennedy, 2003; Kennedy et al., 2005).

The vegetation currently surrounding Laguna Castilla and Laguna de Salvador has been heavily modified by crop cultivation and the grazing of livestock. Pastures include remnant stands of *Pinus occidentalis*, and numerous species in the Poaceae (grass) and Cyperaceae (sedge) families. Cultivated fields of corn and beans are also prevalent. The shores of both lakes are currently dominated by arboreal taxa including *Syzygium jambos* (L.) Alst. (Myrtaceae), a few palms, and a limited number of *P. occidentalis* trees. Emergent aquatic plants currently found in both lakes include *Typha domingensis* Pers. (Typhaceae), *Eleocharis interstincta* (Vahl) R&S. (Cyperaceae), and a variety of other species in the Cyperaceae and Poaceae families.

Natural Disturbance

The most common natural disturbances that affect ecosystems on the island of Hispaniola are fires, tropical storms, and slope failures. The natural and anthropogenic fire regimes of the Dominican Republic have only recently begun to receive attention. The frequency and impacts of recent fires on the vegetation of the Cordillera Central have been analyzed by several researchers (Horn et al., 2001; Kennedy, 2003; Martin and Fahey, 2006). Martin and Fahey (2006) developed fire records in the high elevations of the Cordillera Central using dendrochronological analysis of the endemic pine *Pinus occidentalis.* This species poses challenges for dendroclimatic research (Speer et al., 2004) and Martin and Fahey (2006) were not able to determine exact fire return intervals. They suggested conservative fire return intervals of around 42 years for the pine forests of the Cordillera Central, and speculated that many of the fires may be linked with droughts associated with warm ENSO events in the tropical Pacific.

The prehistoric fire regimes and impacts of fires initiated by prehistoric humans of the Dominican Republic are still largely unknown. Horn et al. (2000) recovered charcoal from soil profiles from the high elevations of the Cordillera Central, indicating the natural occurrence of fire over the last 42,000 years. Again using fossil charcoal, Kennedy et al. (2006) documented the occurrence of natural, and potentially anthropogenic, fires over the last 4000 years in a bog sediment record from the Valle de Bao of the Cordillera Central. A conclusion that has emerged from all of this work is that fires, both natural and anthropogenic, have influenced the highland ecosystems of the Dominican Republic for tens of thousands of years.

Modern and historic/prehistoric fire regimes of mid- and low-elevation ecosystems remain largely unstudied, despite the importance of this information to land management and conservation. Land managers in the Dominican Republic have only recently begun to consider the possible ecological role and importance of fire on the landscape (Myers et al., 2004). Land managers have primarily focused on the prevention of fires and not the potentially beneficial aspects of natural fire regimes. To maximize ecosystem health and recovery, land managers will need more information regarding natural disturbance regimes in the many ecosystems of the island.

Some of the most spectacular and devastating natural disturbances in the Dominican Republic are from landfalling hurricanes. Hurricanes can be expected to make landfall on the Dominican Republic once every 3.6 years (Horst, 1992). Clark et al. (2002) and Kennedy et al. (2006) mentioned extensive wind damage, slope failure, and flooding from Hurricane Georges, which struck the Dominican Republic in 1998. In their analysis of sediments collected from Valle de Bao, Kennedy et al. (2005) interpreted re-deposited charcoal fragments and peaks in the abundance of spores produced by the tree fern *Cyathea aroborea* (L.) Sm. as evidence of ecosystem disturbance associated with prehistoric hurricane landfalls.

In many areas of the Dominican Republic with steep topography and high rainfall, including the area around Las Lagunas, slope failures are common. Slope failure events are especially common following extreme precipitation events associated with hurricanes and tropical storms. Some of these slope failure events can be quite large and have significant impacts on ecosystems. No studies have analyzed in detail the short-term or long-term effects of slope failures on ecological communities on the island of Hispaniola. However, research in Puerto Rico indicates significant changes in vegetation as successional species recolonize landslide scars and debris fans (Myster and Fernandez, 1995; Walker et al. 1996; Myster and Walker, 1997).

Late Holocene Paleoclimates of the Circum-Caribbean

In the last few years, the number of paleoclimate studies in the circum-Caribbean region has increased significantly with the realization that the tropics play a fundamental role in climate change and are sensitive to global climate variability (e.g. Bigg, 2003). The climate dynamics invoked by researchers to explain circum-Caribbean climate change can be summarized in three general categories, but it is important to note that these categories may not be mutually exclusive.

The first, and most commonly invoked, explanation for circum-Caribbean climate variability is a shift in the mean boreal summer position of the ITCZ. During the boreal summer, the ITCZ currently migrates as far north as the Yucatan Peninsula in the western Caribbean, and to just off the northern coast of South America in the eastern Caribbean. In the western Caribbean this northern migration of the ITCZ is intimately tied to the Central American Monsoon (CAM). The CAM refers to low pressure fields formed by the heating of the Central American landmass along with southern Mexico during the boreal summer. This regional low pressure can draw the primary thread of convergence (the well defined ITCZ) or a secondary convergent thread northward. In the eastern Caribbean the ITCZ remains farther south because of the thermal low that develops over the northern portions of the South American landmass. In either case, the proximity of the ITCZ brings with it convective activity and proximal doldrum (weakened trade winds) conditions that promote increased precipitation throughout the region (as outlined above). If the ITCZ were to remain farther south, especially during the boreal summer, precipitation throughout the circum-Caribbean would decrease significantly.

Multiple mechanisms could hypothetically change the migrational range of the ITCZ, but the characteristics of these processes over long timescales remain poorly understood. On millennial timescales, shifts in interhemispheric temperature gradients in response to Milankovitch orbital forcings could affect (shrink, expand, or shift north or south) the migratory range of the thermal equator, and hence, the ITCZ. On shorter (centennial to decadal) timescales variations in solar activity (i.e. sunspot cycles) could also impact thermal equator dynamics and ITCZ migration. Alternate explanations could include extra-regional forcings such as a weakening of the CAM in response to North American atmospheric dynamics, which could lead to higher than normal pressures over the western Caribbean and an inability of the CAM to draw the ITCZ or other convergent thread northward.

A second category of commonly invoked explanations for circum-Caribbean climate change relates to climate dynamics in the eastern Pacific ocean and is very similar to the "zonal seesaw" described above. In short, when eastern Pacific SSTs are cool, convective activity is suppressed in the eastern Pacific and enhanced in the Caribbean and tropical Atlantic. In addition, under these conditions the ITCZ tends to establish farther northward of the eastern Pacific cold tongue, enhancing the CAM and convective activity in the Caribbean. If eastern Pacific SSTs increase, convective activity is enhanced in the eastern Pacific and suppressed in the Caribbean. In this situation vertical shear also increases in the Caribbean and tropical Atlantic, inhibiting deep convection and the formation of tropical storms. We are currently familiar with these atmospheric dynamics as they are common features of the El Niño Southern Oscillation (ENSO). Similar longer-term variations, or variations in the intensity or frequency of ENSO-type events in the Pacific over time, could significantly impact circum-Caribbean climate dynamics.

The third category of commonly invoked explanations for circum-Caribbean climate change relates to variations in Caribbean SSTs. In general, an increase in Caribbean SSTs will lead to increased atmospheric humidity, latent heat, and convection. Some researchers have postulated that Caribbean, or more specifically Gulf of Mexico, SSTs are intimately related to southeast trade wind intensity with more powerful trade winds "pushing" more warm tropical Atlantic water across the equator and into the region. Under this assumption, a more northerly position of the ITCZ, and hence of the reach of the southeast trade winds, would enhance advection of warm tropical Atlantic waters into the Caribbean and increase Caribbean SSTs. Other researchers have speculated that the intensity of meridional overturning circulation (MOC) in the north Atlantic is a primary driver of Caribbean SST variation in the past. The strength of the MOC determines how much water is being advected northward from the tropical Atlantic, into the Caribbean, and eventually up through the Gulf Stream into the north Atlantic. A weakening of the MOC would hypothetically decrease warm tropical Atlantic water advection into the Caribbean and decrease SSTs.

In this section, I summarize selected paleoclimate studies from the circum-Caribbean region, focusing primarily on high-resolution records spanning the middle to late Holocene in which climate signals are not overpowered by signals of human disturbance or in which climate and human signals can be confidently distinguished. In some of the studies I summarize in this section the researchers have chosen to invoke one or more of the explanations I have summarized above. My intention is to provide an overview of climate variability and potential climate forcing mechanisms affecting the circum-Caribbean region during the Holocene (Figure 1.4) as a theoretical framework to better understand any evidence for climate variations I might see in the Las Lagunas records. I have grouped the studies according to geographic locality.

Hispaniola

Paleoenvironmental research has only just begun in most areas of Hispaniola. Lake sediments recovered from lowland Lake Miragoane, located on the southern coast of Haiti, have provided climate and vegetation records extending back some 10,500 years (Hodell et al., 1991; Curtis and Hodell, 1993; Higuera-Gundy et al., 1999). Hodell et al. (1991) and Curtis and Hodell (1993) presented an oxygen isotope record for Lake Miragoane based on analysis of monospecific ostracod (*Candona* sp.) valves extracted from the sediments. This oxygen isotope record provides an evaporation-precipitation (E/P) ratio record for Lake Miragoane that extends throughout the Holocene. Higuera-Gundy et al.

Figure 1.4. Qualitative summary diagram of centennial-scale climate variability in the circum-Caribbean during the Holocene. Elevations of the study sites and references are in parentheses. Dark gray highlights indicate periods of wet climate and the light gray highlights indicate periods of dry climate. The terms "wet" and "dry" refer only to relative shifts in climate for each individual study site. The highlighted (black) sections of the Mayewski et al. 2004 record refer to discrete "rapid climate change" events identified by the authors.

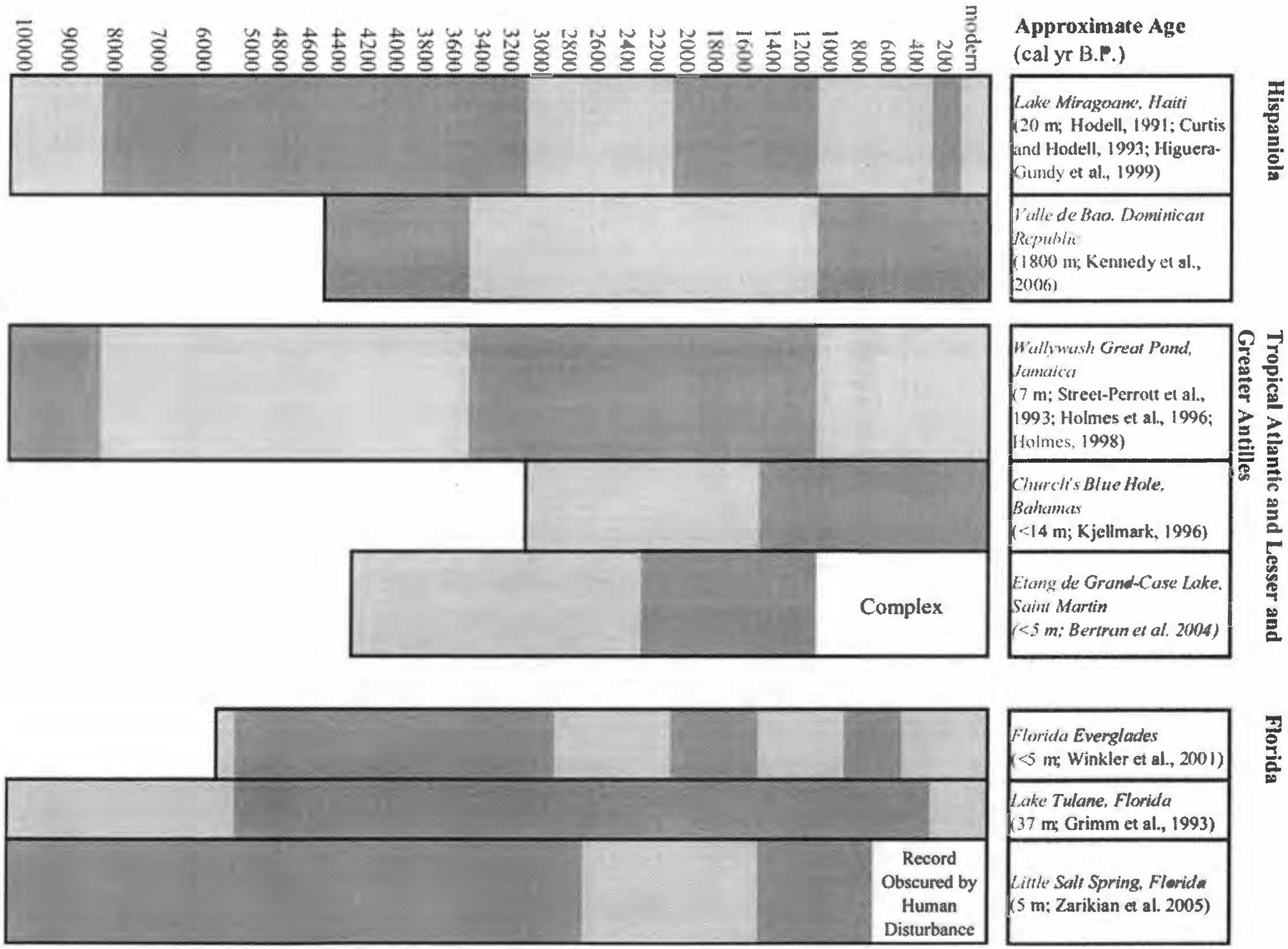

Figure 1.4. Continued.

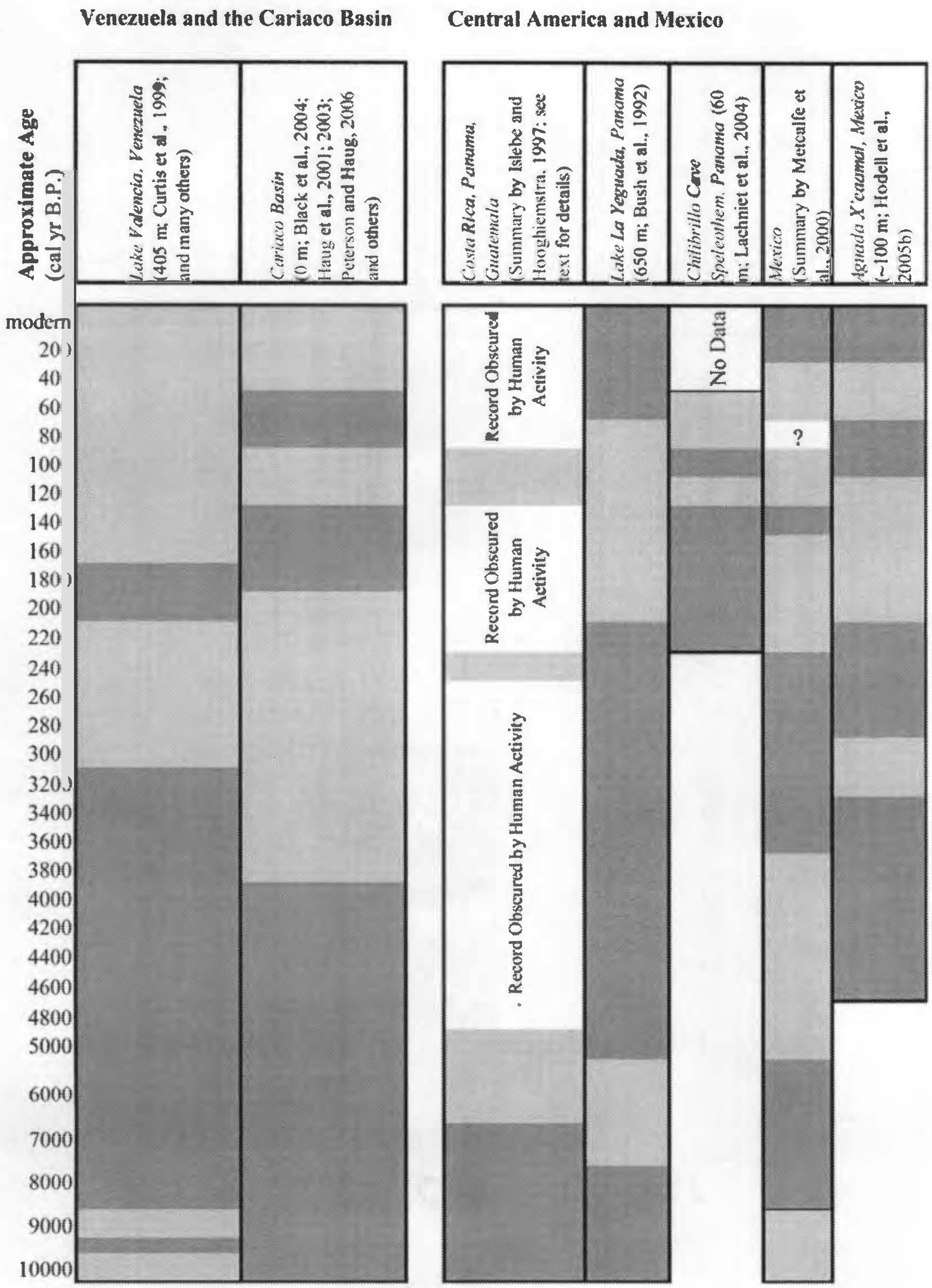

Figure 1.4. Continued.

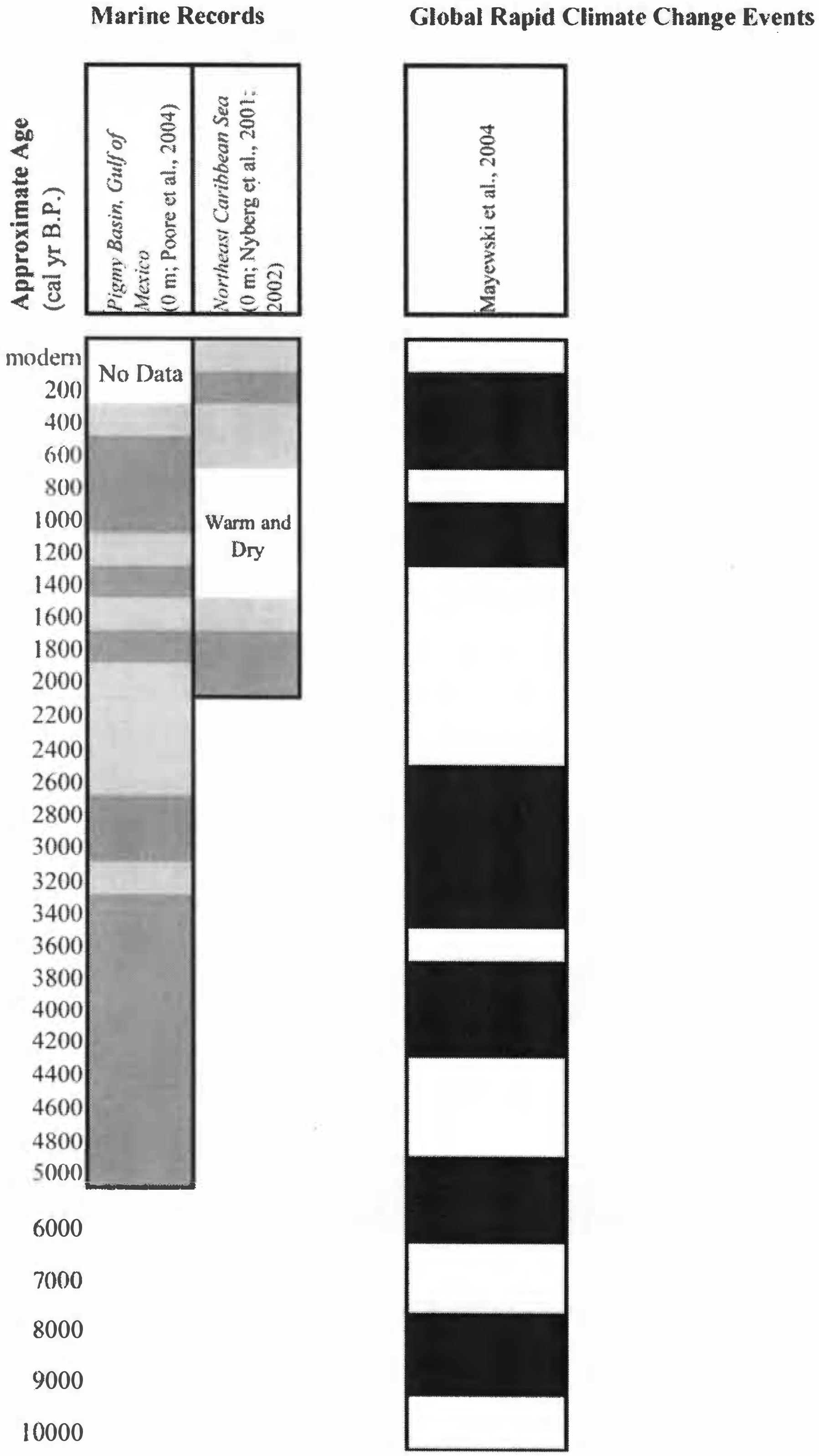

Figure 1.4. Continued.

(1999) presented a pollen record that provides a complimentary vegetation history for the Miragoane region.

The oxygen isotope record for Lake Miragoane indicates an arid early Holocene (~10,000 to 8,000 cal yr B.P.) climate for southwestern Hispaniola. The pollen record also indicates dry conditions, with xeric palms and shrubs dominating. Gradually decreasing oxygen isotope ratios of ostracod valves deposited during the middle Holocene (~8,000 to 3000 cal yr B.P.) suggest moist conditions around Lake Miragoane. The pollen record also indicates moist conditions during this time with increases in mesic arboreal taxa such as taxa in the Moraceae family and the genera *Cecropia* and *Trema*. Following the more mesic middle Holocene, the Lake Miragoane record indicates a general increase in E/P ratios and an increasing dominance of more dry-adapted plant taxa during the late Holocene (3000 cal yr B.P. to present). The most recent sediments recovered from Lake Miragoane contain pollen and sedimentary evidence of human activity in the watershed, including deforestation and maize agriculture (Brenner and Binford, 1988; Higuera-Gundy et al., 1999).

Hodell et al. (1991) and Curtis and Hodell (1993) attributed the variations in effective precipitation recorded in the Lake Miragoane oxygen isotope and pollen records to variations in the intensity of the annual cycle (ITCZ migration) in response to Milankovitch orbital forcing mechanisms, in this case the precession cycle. During periods of increased solar radiation receipt in the Northern Hemisphere, the mean boreal summer position of the ITCZ migrates further northward, enhancing precipitation in southern Hispaniola. During periods of decreased solar radiation receipt in the Northern Hemisphere, the mean boreal summer position of the ITCZ does not penetrate as far northward and more arid conditions dominate in southern Hispaniola.

Hodell et al. (1991) and Curtis and Hodell (1993) pointed out that variations in orbital geometry cannot explain all of the variations in E/P ratios and vegetation change observed in the Miragoane record. Numerous sub-millennial scale variations in E/P ratios are present in the Lake Miragoane oxygen isotope record. The mechanisms responsible for these rapid, centennial-scale variations in climate are not discussed by Hodell et al. (1991) or Curtis and Hodell (1993) in any detail.

The only other continuous record of middle to late Holocene paleoenvironmental change published for the island of Hispaniola is a ~4000 cal yr B.P. sediment, charcoal, and fossil pollen record from a bog in the Valle de Bao located in the high elevations (~1800 m) of the Cordillera Central in the Dominican Republic (Kennedy et al., 2006). The initial formation of the Valle de Bao bog around 4500 cal yr B.P. seems to coincide with high-elevation lake and bog formation in the Dominican Republic and may be indicative of a larger scale shift in atmospheric dynamics (Orvis et al., 2005). Poor pollen preservation between ~3700 and ~1200 cal yr B.P. suggests variable water table depth during this period, perhaps in response to highly variable precipitation totals for the region. After ~1200 cal yr B.P., pollen preservation improves markedly, suggesting more mesic conditions.

Other Records from the Tropical North Atlantic and Lesser and Greater Antilles

Several middle to late Holocene paleoenvironmental records have been reconstructed using sediment records recovered from sites in the tropical north Atlantic and the Lesser and Greater Antilles outside of Hispaniola. Sediments collected from Wallywash Great Pond, Jamaica have been studied extensively to reconstruct the limnological and climate history of the lake (Holmes, 1998; Street-Perrott et al., 1993; Holmes et al., 1995). The Wallywash Great Pond sediment record is old, stretching back some 125,000 years, but is plagued by radiocarbon dating problems and relatively slow sedimentation rates, which hamper high-resolution paleoenvironmental reconstructions.

Based on analyses of geochemistry and ostracod assemblages, Street-Perrott et al. (1993) and Holmes (1998) suggested that Wallywash Great Pond dried out completely during the late Pleistocene. During the early Holocene (~10,000 to 8300 cal yr B.P.) the sediment and ostracod data indicate a significant increase in precipitation and subsequent increase in lake depth. Following this mesic period in the lake's history, paleolimnological data indicate that water depths began to fall, and remained low, from ~8300 to 3500 cal yr B.P. Between ~3500 and 1000 cal yr B.P. the oxygen isotope values of inorganic marls decrease and shifting ostracod assemblages indicate an increase in lake levels. Paleolimnological evidence in the form of decreased stable carbon isotope ratios in the marl and shifts in fossil ostracod and mollusk assemblages suggests a rather large flood event may have occurred around 1200 cal yr B.P. and drastically affected the geochemistry of the lake water. Over the last 1000 cal yr B.P., the Wallywash Great Pond sediment record indicates increasing aridity for the region.

The pollen, charcoal, and sediment records of Church's Blue Hole on Andros Island in the Bahamas extend to ~3000 cal yr B.P. and indicate significant climatic variability over this period. Kjellmark (1996) suggested that water levels in Church's Blue Hole were much lower between ~3000 and 1500 cal yr B.P., but based much of this interpretation on evidence from other circum-Caribbean records. Following this period of apparent aridity, the Church's Blue Hole record indicates increasing precipitation and water levels. However, more detailed interpretations of the timing and intensity of this late Holocene climate change are hindered by poor chronological control and anthropogenic impacts in the watershed.

Paleoenvironmental records from sediment profiles are rare for the Lesser Antilles, but Beets et al. (2006) analyzed the oxygen and carbon isotope composition of land snail (*Bulimulus guadaloupensis*) shells recovered from the archeological site Anse à la Gourde on the island of Guadeloupe to reconstruct precipitation variability and vegetation change over the last ~2000 years. Their oxygen isotope record indicates periods of severe drought centering on ~350, 900, and 1950 cal yr B.P. Thick sand lenses are associated with these periods indicating an increase in the aeolian transport of sand to the site as a result of increased aridity and increased trade wind strength. One of the most compelling aspects of the Anse à la Gourde record is that the archaeology of the site indicates human abandonment of the area coincident with the drought interval centered around ~900 cal yr B.P. Beets et al. pointed out that this drought is also roughly coincident with the collapse of Mayan society, which has also been attributed to drought conditions on the Yucatan Peninsula. Following this period of drought, the isotopic record indicates an increase in precipitation from ~850 to 650 cal yr B.P. and the archaeological record indicates re-occupation of the site by a new group of inhabitants. The Anse à la Gourde record is valuable not only because it is one of the few existing paleoprecipitation records in the eastern Caribbean, but also because it provides some of the first evidence of the impacts of climate change on prehistoric occupants of Caribbean islands.

The only other detailed paleoenvironmental record in the eastern Caribbean comes from St. Martin. Bertran et al. (2004) recovered a sediment core from Étang de Grand-Case that extends back ca. 4000 cal yr B.P. Bertran et al. reconstructed the climate history of Étang de Grand-Case using a wide variety of sedimentary analyses. Their results suggest relatively low lake levels from ~4200 to 2300 cal yr B.P. and a high occurrence of hurricane landfalls as indicated by numerous sand lenses. An increase in organic mud deposition at the expense of carbonate precipitation between ~2300 and 1150 cal yr B.P. indicates an increase in lake level. The most recent ~1150 years of the Étang de Grand-Case sediment record are confounded by anthropogenic activity in the watershed and by a more complex sediment stratigraphy, preventing high-resolution paleoclimate reconstructions.

Florida

The close proximity and similar climate dynamics of the Florida Peninsula and the Greater Antilles makes the paleoenvironmental history of Florida pertinent to this study. Several Floridian sediment cores have been recovered and analyzed to reconstruct the paleoenvironmental history of the region (Watts, 1969; 1971; 1975; 1980; Watts and Stuiver, 1980; Watts et al., 1992; Grimm et al., 1993; Watts and Hansen, 1994; Zarikian et al., 2005; Huang et al., 2006). Analyses have been primarily focused on the vegetation history of the region during the Pleistocene-Holocene transition. Very few of these records have the temporal resolution necessary to make detailed analyses of late Holocene climatic variability.

Watts (1980) summarized many of the coarse-resolution records of Holocene climatic change for the southeastern U.S. He described a Holocene precipitation record for the southeastern U.S. that is, at a temporally broad scale, very similar to that described by Hodell et al. (1991) for Lake Miragoane, Haiti. Pollen records from Florida suggest that the early Holocene vegetation was predominantly dry oak forest, indicating warmer and more arid conditions than exist there today. This arid period was later identified at Camel Lake located on the Florida panhandle (Watts et al., 1992). Sometime around ~7,000 cal yr B.P., oaks declined in importance and gave way to more mesic tree taxa. These mesic tree taxa dominate Floridian pollen records for the duration of the middle Holocene, suggesting an increase in precipitation for the region as a whole. Unlike the Lake Miragoane record, the sediment records from Florida show no indication of increasing aridity in response to decreasing Northern Hemisphere radiation receipt during the latest portions of the Holocene.

In a higher resolution study, Winkler et al. (2001) presented an in-depth analysis of Holocene sediments collected from locations throughout the Florida Everglades. Winkler et al. presented fossil pollen, charcoal, diatom, sclereid, sponge spicule, sediment chemistry, and stable carbon isotope data from a total of 18 sediment cores that they analyzed to reconstruct the late Holocene paleoenvironmental history of the Everglades. The various proxies suggest a relatively moist middle Holocene, as indicated in a variety of other circum-Caribbean climate reconstructions, followed by an arid period between ~3000 and 2200 cal yr B.P. Mesic conditions returned between ~2200 and 1600 cal yr B.P., but the ~1600–1100 cal yr B.P. period was apparently again arid. This period of aridity coincides with drought intervals inferred from sediments of the Cariaco Basin, Yucatan Peninsula, and other study sites in the circum-Caribbean. Following this arid period, climate conditions in the Everglades appear to become more variable up until the present. Winkler et al. noted that drastic changes in Everglades hydrology due to anthropogenic activities are likely masking many of the climate signals in the most recent portions of the sediment records.

Winkler et al. (2001) suggested that the increased precipitation totals for the Everglades region during the middle Holocene were most likely the result of increased SSTs in the Caribbean as a result of increased solar radiation in the Northern Hemisphere during this time period, as discussed above. Ruddiman and Mix (1993) presented marine oxygen isotope data from sediments collected off the southern coast of Florida that do suggest increased SSTs during the middle Holocene. Winkler et al. attributed the moist middle to late Holocene conditions to increasing El Niño activity and tropical cyclone activity in the area as a result of increased SSTs. Winkler et al. provided no hypotheses regarding the forcing mechanisms responsible for the sub-millennial variations in precipitation apparent in their sediment records.

Zarikian et al. (2005) presented a high-resolution paleoenvironmental record from Little Salt Spring located in western Florida. The researchers analyzed the sediments, ostracod assemblages, and isotopic composition of monospecific ostracod valves preserved in the sediments of Little Salt Spring. The hydrology of the site is rather complex and intimately tied to sea level variations, making dependable interpretations of climate variability based on variations in water chemistry and isotope composition difficult. Zarikian et al. recognized these complexities and tried to constrain their heuristic model of hydrology based on these complexities. Zarikian et al. primarily interpreted their oxygen isotope record as a record of water table depth and salt water intrusion.

Using this interpretation, Zarikian et al. suggested that conditions around Little Salt Spring were drier during the early Holocene (~12,000 to ~10,000 cal yr B.P.), which is in agreement with other paleoenvironmental records from Florida and the circum-Caribbean region. Zarikian et al. characterized the subsequent middle Holocene as relatively moist and stable in terms of hydrology (~10,000 to ~5900 cal yr B.P.). From ~5900 cal yr B.P. up until the present, the Little Salt Spring oxygen isotope record indicates considerable hydrologic variability.

Zarikian et al. interpreted the oxygen isotope record to indicate relatively mesic conditions from ~5900 to ~2800, and from ~1200 to ~700 cal yr B.P., and extremely arid conditions from ~2600 to ~1900 cal yr B.P. This is in contrast to many other circum-Caribbean records of late Holocene precipitation, especially those from the Cariaco Basin and the Yucatan Peninsula (see discussion below), which indicate that some of the most arid conditions in those regions were occurring simultaneously around 1200–1100 cal yr B.P. and again well after 700 cal yr B.P.

Venezuela and the Cariaco Basin

Very few paleoenvironmental records are available from sites along the northern coast of South America. However, since the early 1980s, several researchers have analyzed sediments recovered from Lake Valencia, which is located near the northern coast of Venezuela. Studies of the Lake Valencia sediments have included pollen (Salgado-Labouriau, 1980; 1987; Leyden, 1985), diatoms (Bradbury et al., 1981), sediment chemistry (Lewis and Weibezahn, 1981; Binford, 1982; Curtis et al., 1999), animal remains (Binford, 1982), and the isotope geochemistry of biogenic carbonates (Curtis et al., 1999).

Curtis et al. (1999) summarized the climate history of Lake Valencia using the multiple proxy records listed above as well as their own sediment and isotope geochemistry records. In short, Lake Valencia was very shallow during the late Pleistocene and early Holocene. From ~10,000 cal yr B.P. to ~8500 cal yr B.P., the climate became more mesic and the lake deepened. Between ~8500 and 3500 cal yr B.P., Lake Valencia became a permanent lake and deepened enough to become an open basin. This shift in lake depth and hydrology indicates a significant increase in precipitation delivery to the region. Pollen deposited during this period also indicates relatively moist conditions with significant increases in tree taxa at the expense of more drought tolerant herbaceous taxa (Leyden, 1985). From ~3500 cal yr B.P. up until the present, the sediment records of Lake Valencia indicate decreasing water levels as a result of decreasing precipitation delivery to the region.

Another site that has been studied extensively in this area is the Cariaco Basin (10°N, 65°W), which is an anoxic ocean basin located off the northern coast of Venezuela (Haug et al., 2001; 2003; Peterson et al., 1991; 2000; Hughen et al., 1996; 2000; 2004a; 2004b; Tedesco and Thunell, 2003a; 2003b). The combination of anoxic conditions and large annual fluctuations in biogenic carbonate sedimentation due to annual variations in upwelling intensity with the migration of the ITCZ has produced annual varves that allow highly detailed paleoclimate reconstructions. In addition to sediments of marine origin, the Cariaco Basin also accumulates terrigenous sediments delivered by the Orinoco, Tuy, Unare, Neveri, and Manzanares rivers (Milliman and Syvitski, 1992; Peterson and Haug, 2006). Haug et al. (2001; 2003) conducted high resolution (~4–5 yr) analyses of iron and titanium concentrations in the Cariaco Basin sediments under the assumption that these minerals originate from terrestrial sources within these different watersheds. The concentration of titanium and iron are thought to indicate the level of sediment transport and erosion in these various watersheds, and therefore should provide a record of precipitation for this portion of northern South America.

Both the Ti and Fe records indicate a wet early to middle Holocene (~10,500 to 5,400 cal yr B.P.) and more variable precipitation during the middle to late Holocene with a long-term average decline in precipitation totals over the entirety of this time span for northern South America. More specifically, the Cariaco Ti and Fe records indicate very large fluctuations in precipitation delivery to the region between 3,800 and 2,800 cal yr B.P. (Haug et al., 2001). Following this period of seemingly large fluctuations in terrigenous element delivery is a period of relative stability in the record (~2,800 to 600 cal yr B.P). Despite the apparent relative climate stability around this time, there is evidence for three multi-year droughts in the Ti and Fe record during this period (~810, 860, and 910 A.D.) that have been implicated in the fall of the Mayan civilization on the Yucatan Peninsula (Haug et al., 2003). Finally, the Cariaco Basin record indicates some of the largest decreases in precipitation in the 14,000 cal yr B.P. sediment record during the Little Ice Age (~600 to 100 cal yr B.P.; Haug et al., 2001).

Using data from the Cariaco Basin sediment record, Peterson and Haug (2006) argued that the variations in precipitation for northern South America have resulted from shifts in the mean boreal summer position of the ITCZ during the Holocene. The wet season in northern South America occurs when the ITCZ is located towards the northern end of its range (boreal summer and fall). During the boreal winter and early spring, when the ITCZ reaches its most southerly position, the northern coast of South America experiences a dry season. Peterson and Haug attributed the long-term precipitation pattern of increasingly wet conditions from the early to middle Holocene, and subsequent increasingly arid conditions from the middle to late Holocene, to long-term variations in the mean latitudinal position of the ITCZ. Peterson and Haug further suggested that these millennial scale variations in the mean position of the ITCZ are linked to the 21,000 year Milankovitch precession cycle and are also possibly due to variable El Niño frequency and strength throughout the Holocene. Clement et al. (2000) suggested that El Niño frequency and strength may have been lower during the early to middle Holocene as compared to the late Holocene and provided evidence that these variations in El Niño activity may also be linked to Milankovitch forcing mechanisms.

In short, a shift in the 21,000 year Milankovitch precession cycle leads to decreased seasonality in the Northern Hemisphere as compared to the Southern Hemisphere. This decrease in warm season solar energy receipt leads to an inability of the Northern Hemisphere to "pull" the ITCZ into the Northern Hemisphere and a more southerly mean boreal sumer position for the ITCZ (Berger and Loutre, 1991). Increased El Niño frequency and strength could also result in a more southerly mean annual position of the ITCZ because El Niño events lead to an increase in southern pacific SSTs, which can then lead to decreased sea surface pressures. Conversely, decreased El Niño frequency and strength could lead to a more northerly mean annual position of the ITCZ (Fedorov and Philander, 2000).

Black et al. (2004) analyzed the oxygen isotope composition of foraminiferal tests from Cariaco Basin sediments to reconstruct variations in the hydrographic conditions of the basin. They proposed that the oxygen isotope compositions of the foraminiferal tests are sensitive to variations in sea surface temperature and/or salinities in the Cariaco Basin. Their 2,000 cal yr B.P. record indicates a consistent long-term increase in oxygen isotope values over the entirety of the late Holocene. Black et al. primarily interpreted this increase in oxygen isotope values as an indication of decreasing SSTs as a result of increased upwelling or an increase in salinity.

Both a decrease in Cariaco Basin sea surface temperatures and an increase in salinity would be expected with a more southerly mean boreal summer position of the ITCZ. When the ITCZ is located in a more southerly position, the increased trade winds over the Cariaco Basin (Black et al., 1999) promote more upwelling of cold subsurface waters and thereby decrease SSTs (Haug et al., 2001). In addition, a more southerly mean boreal summer position of the ITCZ would result in increased evaporation and decreased freshwater delivery to the Cariaco Basin, thereby increasing regional ocean salinities.

While the millennial scale migration of the ITCZ to a more southerly mean boreal summer position appears to primarily be the result of earth-sun geometry and possible variations in the El Niño Southern Oscillation, some of the shorter-scale variability in the Cariaco Basin sediment records has been attributed to sunspot cycles (Black et al., 2004). Using cross-spectral analyses of the oxygen isotope data from the Cariaco sediment record, Black et al. (2004)

reported a cyclicity in the record of 158, 24, 10.9, and 8.2 years, which is within the bandwidth estimate of the 121, 22, and 11 year sunspot cycles. Although the exact mechanism that could be responsible for such a relationship between sunspots and tropical climate remains elusive, several other researchers working in tropical locales have reported similar cyclicities in their datasets (Peterson et al., 1991; Linsley et al., 1994; Black et al., 1999; deMenocal et al., 2000; Hodell et al., 2001).

The Yucatan Peninsula

One of the most intensively studied areas in the circum-Caribbean region in terms of Holocene climate change is the Yucatan Peninsula (Leyden et al., 1994; 1998; Hodell et al., 1995; 2001; 2005a; 2005b; Curtis et al., 1996; 1998; Islebe et al., 1996a; Whitmore et al., 1996; Rosenmeier et al., 2002; Hillesheim et al., 2005; Wahl et al., 2006). Much of the interest in past climate derives from the proposed connection between rapid late Holocene climate change in the region and the collapse of the once dominant Mayan civilization (Hodell et al., 1995; Gill, 2000; Haug et al., 2003).

One well studied site on the Yucatan Peninsula is Lake Chichancanab, Mexico. The Lake Chichancanab sediment record extends back some ~9500 cal yr B.P. (Hodell et al., 1995), but the majority of analyses of Chichancanab sediment profiles have focused on the last ~3000 cal yr B.P. (Hodell et al., 2001; 2005a). The absence of lacustrine microfossils (ostracods and gastropods), along with other sedimentary and isotopic data from Lake Chichancanab, indicate dry conditions in the Yucatan region during the early Holocene (~9500 to 7500 cal yr

B.P.). Like most other climate records around the circum-Caribbean region, the Lake Chichancanab record indicates, on average, a peak in effective precipitation from ~7500 to 3500 cal yr B.P. Following this moist period in the Lake Chichancanab sediment record, isotopic and sediment geochemistry data suggest greater precipitation variability over the last ~3500 cal yr B.P. with relatively arid periods between ~3200 to 3000, ~2200 to 2000, and ~1400 to 900 cal yr B.P. The most recent drought interval (~1400 to 900 cal yr B.P.) has been associated with the collapse of the Mayan civilization.

The drought interval associated with the collapse of the Mayan civilization has also been detected in lake sediments recovered from Lake Punta Laguna, Mexico (Curtis et al., 1996). Sedimentary and isotopic data from Lake Punta Laguna generally indicate moist conditions from ~3500 to 2000 cal yr B.P., followed by relatively arid conditions between ~2000 and 950 cal yr B.P. The oxygen isotope composition of ostracods preserved in the Lake Punta Laguna sediments indicates a rapid shift from relatively arid conditions to moist conditions around the lake around 950 cal yr B.P. that then persist for ~200 years. Between ~750 and 450 cal yr B.P. the oxygen isotope record of Lake Punta Laguna indicates a return to relatively arid conditions with significant precipitation variability. From 450 cal yr B.P. to the present, the Lake Punta Laguna sediment record indicates a relative increase in effective moisture with the exception of two short-lived arid periods around 350 and 100 cal yr B.P.

The exact mechanisms responsible for these sub-millennial variations in precipitation delivery to the Yucatan Peninsula are still poorly understood, but

Hodell et al. (2001) proposed that much of this variability may be the result of the variations of solar activity with a periodicity of 208 years. This sub-millennial scale variation is superimposed upon the millennial scale patterns of decreasing precipitation totals in the northern tropics hypothetically linked to Milankovitch forcings (Hodell et al., 1991; Haug et al., 2001).

To further understanding of climate change on the Yucatan Peninsula and the interconnections with global climate events, Hodell et al. (2005b) analyzed a very high-resolution sediment record from Aguada X'caamal, Mexico, using a variety of techniques. Hodell et al. focused on a short period of time (~A.D. 1400 to 1500) encompassed by the Little Ice Age (LIA) and the associated climate changes that occurred in the region during this period. They reported significant decreases in precipitation and a subsequent decrease in Aguada X'caamal lake levels during the LIA. Hodell et al. attributed this decrease in effective precipitation for the region to decreased Caribbean SSTs that have also been reported at this time in several other studies (Winter et al., 2000; Nyberg et al., 2001; 2002; Watanabe et al., 2001). Hodell et al. proposed that decreased SSTs in the Caribbean may have decreased evaporation, and hence precipitation over the Yucatan Peninsula. In addition, Hodell et al. proposed the possibility that decreased precipitation totals over the Yucatan Peninsula were the result of large-scale change in oceanic and atmospheric fields during the LIA that may have led to a more southerly mean boreal summer position of the ITCZ. This shift in the mean latitudinal position of the ITCZ would decrease precipitation totals for northern tropical locales, such as the Yucatan Peninsula.

Central America and Mexico

While a large number of Holocene paleoenvironmental records for Central America and Mexico exist, most of these records are strongly dominated by signals of prehistoric human activity and lack the proxies necessary to isolate climate change from those human impacts (Horn, in press). Islebe and Hooghiemstra (1997) combined pollen data from a bog and soil profile in Costa Rica with other regional records of climate change to produce a synoptic picture of Holocene climate change for Central America. In their review, Islebe and Hooghiemstra suggested a moist early Holocene based on pollen assemblages preserved in lake and bog sediments in Costa Rica (Horn, 1993; Islebe et al., 1996b). Paleolimnological evidence from Panama indicated decreased precipitation totals from ~7000 to 5000 cal yr B.P. (Piperno et al., 1991). However, decreased macroscopic charcoal influx into Lago de las Morrenas 1, located in the highlands of Costa Rica, at this time may indicate wetter conditions (League and Horn, 2000). Central American paleoclimate records since ~5000 cal yr B.P. become increasingly difficult to interpret due to prehistoric human impacts, but several researchers have suggested drought intervals that possibly occurred throughout Central America around 2500 cal yr B.P. and between 1300 and 1100 cal yr B.P. (e.g. Horn and Sanford, 1992; Horn, 1993; Hodell et al., 1995; Islebe and Hooghiemstra, 1997; Haberyan and Horn, 1999; League and Horn, 2000; Anchukaitis and Horn, 2005).

One of the few continuous records of climate variability in Central America was assembled by Bush et al. (1992), who conducted multi-proxy analyses of a ~14,000 cal yr B.P. sediment record from Lake La Yeguada, Panama. Paleoshorelines and exposed lake deposits suggest that Lake Yeguada was much deeper during the early Holocene than it is today. Conditions around La Yeguada remained moist until ~8000 cal yr B.P., after which time phytolith assemblages and geomorphic evidence suggest significantly decreased precipitation until ~6000 cal yr B.P., when diatom assemblages and geomorphic evidence indicate an increased lake level. The increased lake level persisted until ~2000 cal yr B.P. when paleolimnological evidence indicates decreasing lake level. However, the most recent 4000 cal yr B.P of the sediment record indicate prehistoric human impacts in the Lake Yeguada watershed that may be masking signals of climate change for the region.

Lachniet et al. (2004) developed an oxygen isotope record from a speleothem collected from Chilibrillo Cave, Panama, that spans much of the late Holocene. Results indicate relatively moist conditions from ~2150 to 1400 cal yr B.P., followed by a severe drop in precipitation around 1300 cal yr B.P. that Lachniet et al. associated with the Maya Hiatus, a period of decreased monument construction, abandonment in some areas, and social unrest in the Mayan lowlands. From this point on, the Chilibrillo Cave speleothem record indicates a general decrease in precipitation with discrete, severe periods of drought around 1150, 950, 800, 700, and 600 cal yr B.P. Lachniet et al. attributed this precipitation variability to variations in the strength of the "Central American Monsoon" (CAM), which is sensitive to ENSO oscillations. In short, warm ENSO events are associated with a decrease in the intensity of the CAM and a decrease in precipitation for the region. Based on spectral analysis of the oxygen isotope data, Lachniet et al. concluded that ENSO variability, and not solar output variability, is the primary driver of precipitation variability for southern Central America.

The paleoenvironmental history of Mexico has received considerable attention from researchers. In an in-depth review, Metcalfe et al. (2000) summarized over 30 Mexican paleoclimate records. These records were developed using a variety of materials (lake sediments and packrat middens) and proxies (pollen, diatoms, other microfossils, sediment chemistry, isotopic signatures) from locations throughout the country including the Mexican portion of the Yucatan Peninsula (discussed above). These records indicate that Mexico was much more arid than today during the late Pleistocene and early Holocene (until ~9000 cal yr B.P.). Most records suggest an increase in effective precipitation between ~9000 and 6000 cal yr B.P., followed by a period of variable precipitation from ~6000–5000 cal yr B.P. On average, conditions appear to have become more arid throughout Mexico between ~5000 and 3500 cal yr B.P. Over the last ~3000 cal yr B.P., climate conditions become increasingly variable with several notable periods of drought, including one of the most arid periods in the Holocene around 1000 cal yr B.P. Metcalfe et al. focused their discussion of climate forcing mechanisms on the Pleistocene to Holocene transition and did not engage in any in-depth discussion of climate forcing mechanisms that might be responsible for the variations in Holocene precipitation patterns for Mexico. They did suggest that the position and intensity of the

Bermuda High, which is intimately related to ITCZ position, may play a significant role in Holocene climate variability for Mexico.

Gulf of Mexico and Caribbean Marine Sediment Records

Several sediment records have been collected from the Gulf of Mexico and the Caribbean Sea over the last few decades, but many of these studies have focused on the Pleistocene-Holocene transition, with very little attention devoted to Holocene climate variability (e.g. Ericson and Wollin, 1968; Malmgren and Kennett, 1976; Schmidt et al., 2004). Poore et al. (2003) reanalyzed sediments collected from the Gulf of Mexico in 1968 in an effort to reconstruct Holocene variations in Gulf of Mexico ocean currents. They interpreted foraminiferal assemblages and the oxygen isotope composition of foraminferal tests as indicators of Loop Current intensity during the Holocene. When the mean latitudinal position of the ITCZ is displaced northward, southeasterly surface winds across the Caribbean Sea and Gulf of Mexico intensify. This intensification of southeasterly winds can increase ocean current strength through the Yucatan Strait causing the Loop Current to penetrate further northward into the Gulf of Mexico. Hence, more intense incursions of the Loop Current into the Gulf of Mexico, as indicated by fossil foraminfera assemblages and the isotopic compositions of foraminifera tests, are interpreted by Poore et al. as indications of a more northerly mean boreal summer position of the ITCZ. Poore et al. suggested that a more northerly mean boreal summer position of the ITCZ and related intensification of the Loop Current would lead to increased precipitation totals for much of the Caribbean region. An increase in Loop Current intensity has also been associated with increased SSTs in the Gulf of Mexico and enhanced evaporation, which might also lead to increased precipitation totals for North America and the Caribbean (Brown et al., 1999; Poore et al., 2003).

Based on the foraminiferal data from the Gulf of Mexico, Poore et al. (2003) suggested a more intense Loop Current (and an inferred increase in regional precipitation) during the middle Holocene as compared to today. Analyzing the forminiferal abundance data at shorter time intervals, Poore et al. (2003) reported cycles in the data with periods of ~500, 300, and 200 years. Poore et al. noted the similarity of these cycle periods to those of solar output, as reconstructed using records of ^{14}C (Stuiver and Braziunas, 1989; Stuiver et al. 1991; Stuiver et al., 1998) and ^{10}Be production (Finkel and Nishiizumi, 1997), and cycles reported by Hodell et al. (2001) for oxygen isotope records from the Yucatan Peninsula.

In a more detailed analysis, Poore et al. (2004) conducted a similar study using sediments from the Pigmy Basin in the Gulf of Mexico. Using the abundance of the foraminifer *Globigerinoides sacculifer* as a proxy of Loop Current intrusion into the gulf, Poore et al. attempted to reconstruct the position of the ITCZ over the last 5000 cal yr B.P. According to Poore et al., the mean boreal summer position of the ITCZ was located further northward between ~5000 and ~2900 cal yr B.P. than at any other time in the last 5000 cal yr B.P. Over the last 2900 cal yr B.P., incursions of the Loop Current into the Gulf of Mexico have, on average, decreased, except for brief increases in Loop Current incursions around ~1900, 1400, and 1200 cal yr B.P. Concentrations of *G. sacculifer* reach minimum values around ~2800, 2600, 2300, 2100, 1000, 900, 600, and 400 cal yr B.P., a pattern interpreted to indicate a more southerly mean summer position of the ITCZ during these times. Again, Poore et al. associated this variability in the position of the ITCZ with variations in solar output as outlined above.

High-resolution, late Holocene analyses of Caribbean Sea surface temperature variability are few in number, but Nyberg et al. (2001; 2002) analyzed sediments collected from the Caribbean Sea, just south of Puerto Rico, and present sedimentary evidence for variations in Caribbean sea surface temperatures and sea surface salinities (SSSs), as well as upwelling intensity, spanning the last 2000 cal yr B.P. Nyberg et al. invoked numerous feedback mechanisms and teleconnections, including ENSO variability and thermohaline circulation intensity, to explain their Caribbean SST and SSS records. In general, Nyberg et al. associated increased SSSs and decreased SSTs with decreases in precipitation for the Caribbean region, brought about by a more southerly mean boreal summer position of the ITCZ.

Nyberg et al. (2001; 2002) focused the majority of their discussion on two climate events during the late Holocene. The first event, which occurred between ~1250 and 1000 cal yr B.P., is typified by increased SSTs and decreased SSSs, which is opposite of the expected pattern. Nyberg et al. attributed this unexpected relationship to very strong ENSO warm events, which have been detected at this time in a variety of other climate records (Quinn, 1992; Ely et al., 1993). The second climate event emphasized by Nyberg et al. (2001; 2002) occurred between ~400 and 550 cal yr. B.P., concurrent with the LIA. Nyberg et al. suggested a cooling of Caribbean SSTs of ~2 °C and increased SSSs, which they associated with increased penetration of troughs of cold air from the north, or possibly increased upwelling associated with stronger trade winds. In either case, it seems that the ITCZ was displaced southward during this time, which would decrease precipitation for the region. In a spectral analysis of their entire dataset, Nyberg et al. (2001) suggested a close link between variations in Caribbean climate and solar output variability. However, they emphasized the importance of internal mechanisms in amplifying the impacts of variations in solar output, which were relatively weak and could not be the sole mechanism responsible for global climate variability.

Correlations with Late Holocene Global Climate Changes

To fully understand the origin of climatic change in the circum-Caribbean region, records must be analyzed in a broader context. In their comprehensive review of Holocene climate change, Mayewski et al. (2004) identified what they call periods of rapid climatic change (RCC) globally. Using more than 50 high-resolution records of climate change from locations around the world, Mayewski et al. identified 9000–8000, 6000–5000, 4200–3800, 3500–2500, 1200–1000, and 600–150 cal yr B.P. as periods of RCC.

In general, Mayewski et al. characterized these periods of RCC as intervals of decreased temperatures in polar regions and increased aridity in tropical regions as a result of reorganizations in atmospheric circulation. However, the RCC period between ~600–150 cal yr B.P. may have been an instance of decreased polar temperatures coinciding with increases in tropical moisture availability. The periods of RCC identified by Mayewski et al. seem to generally correlate with periods of climatic change in the circum-Caribbean region. This is especially true for the periods between 1200–1000 and 600–150 cal yr B.P. However, unlike many of the tropical records summarized by Mayewski et al., the circum-Caribbean records summarized here seem to indicate increased aridity during the 600–150 cal yr B.P. RCC event. The RCC period proposed by Mayweski et al. between ~3500 and 2500 cal yr B.P. does seem to express itself in paleoclimate records from the Yucatan Peninsula, Lake Miragoane, the Cariaco Basin, Lake Valencia, the Gulf of Mexico, and select study sites in Central America, but is not apparent in most other records from the circum-Caribbean. Mayewski et al. attributed most of these Holocene RCCs to variations in solar output, but also noted the importance of other climatic forcing mechanisms such as shifting orbital geometries, volcanic activity, changes in ocean circulation dynamics, and greenhouse gas concentrations.

Summary of Holocene Circum-Caribbean Paleoclimate

Developing a synoptic picture of Holocene climate change for the circum-Caribbean is not straightforward, but the recent increases in study site density throughout the region make possible the delineation of general qualitative patterns (Figure 1.4). Generally speaking, it appears as though much of the circum-Caribbean region was arid during the late Pleistocene and very early Holocene. Following this period, long-term increases in northern Hemisphere solar insolation from the early to middle Holocene may have increased precipitation totals for most of the circum-Caribbean. This was likely the result of a more northerly mean boreal summer position of the ITCZ and increased SSTs for the region. Despite the general increase in precipitation delivery to the region throughout the middle Holocene, some rather drastic climate variability is apparent in some of the high- resolution paleoclimate records.

Since ~3000 cal yr B.P., circum-Caribbean climate conditions seem to have become less coherent with increased inter- and intra-site variability, perhaps as a result of the greater numbers of high-resolution paleoclimate studies spanning this time. There does appear to be a general consensus that precipitation decreased for most areas of the Caribbean between ~3000 and 2000 cal yr B.P. and that a major drought event affected much of the region between ~1200 and 900 cal yr B.P. The drought between ~1200 and 900 cal yr B.P. is the same drought, or series of droughts, that has been associated with the collapse of the Mayan civilization.

Interpreting climate variability in the circum-Caribbean over the last millenium becomes increasingly difficult. For example, inferred precipitation records from the Cariaco Basin suggest that the most arid conditions in the entirety of the Holocene occurred between ~500 cal yr B.P. and 100 cal yr B.P., but this apparent extreme decrease in precipitation is not seen in most other circum-Caribbean records (Haug et al., 2003; Peterson and Haug, 2006). In addition, the majority of circum-Caribbean records summarized here seem to suggest a gradual decrease in precipitation spanning the last ~200 cal yrs B.P., but records from Central America and Mexico seem to indicate relative increases in precipitation over this period. Developing any sort of coherent picture of climate change over this time period will require more high-resolution records from a variety of locales throughout the circum-Caribbean.

Most researchers who analyze Holocene climate change in the circum-Caribbean have attributed the observed climate variations to variations in solar insolation and solar intensity. One interpretation of long-term climate change in the Caribbean that has been widely accepted is the hypothesis that variations in earth-sun geometry, primarily due to the precession cycle, have been driving the general pattern of precipitation in the tropics. The general idea is that the gradual increase in solar energy receipt in the northern hemisphere during the early- to middle Holocene, as a result of the precession cycle, gradually led to a more northerly mean boreal summer position of the ITCZ and increased SSTs in the Caribbean Sea, which increased regional precipitation. Gradually decreasing solar energy receipt for the northern hemisphere during the middle to late Holocene gradually led to a more southerly mean boreal summer position of the ITCZ, decreased SSTs in the Caribbean Sea, and decreased regional precipitation over this time. This interpretation has been supported by Holocene climate records from Africa, where ITCZ dynamics operate in much the same manner (deMenocal et al., 2000), and Holocene climate records from South America, where, as expected, an inverse pattern of precipitation delivery has been noted (Abbott et al., 2000; Cross et al., 2000; Mayle et al., 2000).

On sub-millennial time scales, it appears that variations in solar output may be the driving force behind circum-Caribbean climate variability. Several researchers have reported periodicities in proxy datasets for precipitation and temperature that correlate well with established periodicities of solar intensity (e.g. deMenocal, 2001; Hodell et al., 2001; Nyberg et al., 2001; Poore et al., 2003; Black et al., 2004), particularly at cyclicities of ~200 years. Yet, the link between solar output variability and sub-millennial Caribbean climate variability remains somewhat of a mystery. Several researchers have suggested that the relationship cannot be a direct one, but must also involve some other internal forcing mechanism or mechanisms (e.g. Turney et al., 2005). Resolving the link between solar output variability and Caribbean climate change will require more high-resolution records of Caribbean climate variability and a more in-depth understanding of the complex internal feedback mechanisms and global teleconnections affecting Caribbean climate during the Holocene.

Nyberg et al. (2001; 2002) invoked rather complex feedback mechanisms and teleconnections as potential drivers of Holocene climate variability in the Caribbean, including variations in ENSO cyclicity and intensity and the strength of deep water formation in the North Atlantic. They proposed that during extended periods of cold ENSO phases, consequent increases in atmospheric water transport into the tropical Atlantic could lead to a decrease in SSSs, which would then lead to a decrease in deep water formation in the North Atlantic as the fresh water influx is propagated northward by the North Atlantic Current system. A decrease in deep water formation in the North Atlantic would hypothetically result in a decrease in SSTs in the northeastern Caribbean as the northward flow of warm tropical Atlantic waters into the region would slow considerably. This decrease in SSTs could then lead to increased surface pressure over the

Caribbean, and in turn, a more southerly mean boreal summer position of the ITCZ and more arid conditions for the northern tropics.

Conversely, Nyberg et al. suggested that enhanced export of freshwater out of the North Atlantic region during periods of exceptionally intense or more frequent warm ENSO phases may act to increase Caribbean SSSs. As these salty Caribbean waters are advected northward by the North Atlantic Current system, they might then stabilize or intensify deep water formation in the North Atlantic and thereby maintain, or intensify, the northward advection of warm waters from the tropical Atlantic into the Caribbean Sea. This stabilization could explain the reconstructed increase in SSTs south of Puerto Rico between ~1200 and 1000 cal yr. B.P. presented by Nyberg et al. (2002). In other words, Nyberg et al. hypothesized that, through a series of teleconnections, variations in the Pacific climate system could be the source of much of the climate variation observed around the Caribbean region throughout the Holocene.

The development of more high-resolution paleoclimate records and a more in-depth understanding of oceanic and atmospheric dynamics and inter-relationships will help to elucidate these interconnections and the resulting impacts on regional climate regimes. The development of more high-resolution paleoclimate records from around the world will also help us to develop a better understanding of alternate forcing mechanisms possibly responsible for sub-millennial scale variations in Caribbean climate such as volcanic activity, atmospheric aerosol concentrations, or possibly even anthropogenic activities.

Prehistoric Human Occupation and Agriculture on the Island of Hispaniola

No archaeological data are available for the Las Lagunas area, but the general human history of the island of Hispaniola is fairly well understood. The first humans on the island of Hispaniola are thought to have migrated from the Yucatán region of Mexico and to have arrived on the island during the Lithic Age, roughly 7,000 yr BP as dated by the Casimiroid complexes on Hispaniola (Rouse, 1992). This initial settlement was apparently followed by several migrations from the mainland areas of both Central and South America and migrations between the individual islands of the Antilles.

The Casimiroid peoples of the Dominican Republic have been further distinguished as the Barrera-Mordán people. It is thought that the Barrera-Mordán were primarily hunter-gatherers with a heavy reliance on marine resources such as shellfish. Archaeological evidence suggests that the Barrera-Mordán never settled the interior portions of the island of Hispaniola (Rouse, 1992; Petersen, 1997). Most archaeological sites on the island of Hispaniola are located along the coast. Far less archaeological data are available from the interior of the island and temporal and spatial patterns of settlement are poorly known.

Newsom and collaborators (Newsom and Wing, 2004; Newsom, 2006) have suggested that some of the early inhabitants of the island of Hispaniola may have been low-level plant cultivators, who may have managed native vegetation in home gardens or other settings. However, it was not until much later (~2000 yr BP) that people began to move into the lowland interior of the island and rely more on agricultural subsistence systems (Rouse, 1992). This change in subsistence patterns seems to be coincident with the arrival of the Saladoid peoples from the northern coast of South America. Interactions between the Saladoid peoples and the native populations already inhabiting the Antilles led to the development of the Taino culture.

Archaeological data suggest that the Saladoid people had developed an agricultural system based on a mixture of slash and burn agriculture and the cultivation of crops in floodplains during the dry season in South America (Rouse, 1992). It seems reasonable to assume that the Saladoid peoples implemented these same agricultural techniques in the Antilles, where possible. Early European settlers of the Antilles reported the use of slash and burn techniques by the native inhabitants (Newsom, 2006).

Unlike many ancient horticultural populations in the mainland neotropics, the prehistoric occupants of the Antilles apparently did not rely heavily upon maize agriculture, but were more dependent upon root crops such as cassava and sweet potatoes (Petersen, 1997; Newsom, 2006). Archaeological evidence suggests that maize was used more as a vegetable in the diet of Saladoid people than as a staple crop (Rouse, 1992; Newsom and Deagan, 1994; Petersen, 1997; Newsom, 2006). Only scant botanical evidence presently exists for the timing of arrival and spread of maize agriculture in Hispaniola.

Some of the best evidence of maize agriculture on Hispaniola comes from the En Bas Saline archaeological site, on the northeastern coast of Haiti. Maize macroremains, including a cob fragment, cupules, and kernel fragments, recovered from En Bas Saline have been dated to A.D. 1250. In addition to these macroremains, maize pollen dating to between A.D. 1000 and A.D. 1500 has been recovered from the sediments of Lake Miragoane (Higuera-Gundy et al., 1999) and maize pollen possibly dating back to A.D. 1020 has been reported from soil profiles near El Jobito in the Dominican Republic (Newsom, 2006). Finally, Ortega and Guerrero (1981) have speculated that maize pollen from the El Curro and Puerto Alejandro archaeological sites may have been deposited as early as 1450 B.C. In any case, it appears that maize agriculture arrived somewhat late to Hispaniola compared to many other Mesoamerican and circum-Caribbean sites.

The scant evidence of maize agriculture and consumption has led some researchers to believe that maize played a secondary role in the diet of prehistoric horticulturists on the island of Hispaniola and may suggest a relatively restricted usage pattern on the island. The exact reason, or reasons, why this protein-rich grain may have played only a secondary role in the diet of prehistoric human populations of Hispaniola remains a mystery, especially considering the few native terrestrial mammals available to prehistoric hunters. It has been proposed that maize may have been primarily consumed by the upper class and during religious ceremonies. It has also been proposed that the predominantly root crop and marine-based diet of native inhabitants provided a stable source of protein that did not require maize agriculture as a supplement (Newsom and Deagan, 1994; Newsom, 2006). This would be especially true along the coastal margins of the island.

CHAPTER 2

The Earliest Evidence of Maize Agriculture from the Interior of Hispaniola

This chapter is a slightly modified version of a manuscript that has been submitted for publication in the *Journal of Caribbean Science* by me, Sally P. Horn, Kenneth H. Orvis, and Claudia I. Mora. The manuscript, which is currently under review, includes additional information on the study area that is presented in Chapter 1 of this dissertation. My use of "we" in this chapter refers to my co-authors and myself.

Introduction

The prehistoric domestication of maize (*Zea mays* subsp. *mays*) and subsequent spread of maize agriculture throughout the Central, South, and North American mainlands have been topics of considerable research in recent years (e.g. Johannessen and Hastorf, 1994; Staller et al., 2006). In contrast, the introduction and subsequent spread of maize agriculture throughout the Caribbean region has received much less attention until quite recently (Newsom, 2006). This lack of attention has not been due to a lack of interest, but rather to a lack of evidence.

Despite the relative abundance of excavated archaeological sites distributed throughout the Caribbean (Newsom and Pearsall, 2003; Newsom and Wing, 2004), evidence of prehistoric maize agriculture has proven to be a rare find. In fact, only two Caribbean archaeological sites have produced prehistoric macroremains of maize. The first, the Tutu site on St. Thomas, yielded maize kernels that were dated to around A.D. 1140 (Pearsall, 2002). At the second site, En Bas Saline in Haiti, maize cobs, cupules, and kernels were recovered and dated to around A.D. 1250 (Newsom and Deagan, 1994). Not only are Caribbean sites that contain macrobotanical evidence of prehistoric maize agriculture rare, but even when this evidence is present there is very little of it. For example, at En Bas Saline, only 34% of the plant macroremains recovered from the site were maize macroremains, with half of those remains coming from a single prehistoric pit (Newsom and Deagan, 1994; Newsom, 2006).

Microremains of maize, typically pollen grains, are more commonly found in Caribbean archaeological sites than are macroremains, but these finds are still very limited in geographic extent. Maize pollen has been reported from three coastal or near-coastal sites on Hispaniola (Figure 2.1). García Arévalo and Tavares (1978) found maize pollen in a soil pit at the El Jobito archaeological site in the southeastern Dominican Republic. Based on the presence of Ostionoid artifacts at the site, the pollen grains in the excavation were assumed to have been deposited sometime around A.D. 1020. Higuera-Gundy (1991) reported maize pollen possibly dating back to around A.D. 850 from a sediment core from Lake Miragoane, Haiti. This age was assigned using down-core extrapolation of Pb-210 dates acquired some 40 cm above the stratigraphic position of the maize pollen in the sediment core (Brenner and Binford, 1988). Later radiocarbon analyses indicated that the maize pollen was probably deposited closer to A.D. 1500 (Higuera-Gundy et al., 1999). Finally, Ortega and Guerrero (1981) reported fossil maize pollen at the El Curro archaeological site in Puerto Alejandro, Dominican Republic. Dated to 1450 B.C., the El Curro site is a preceramic,

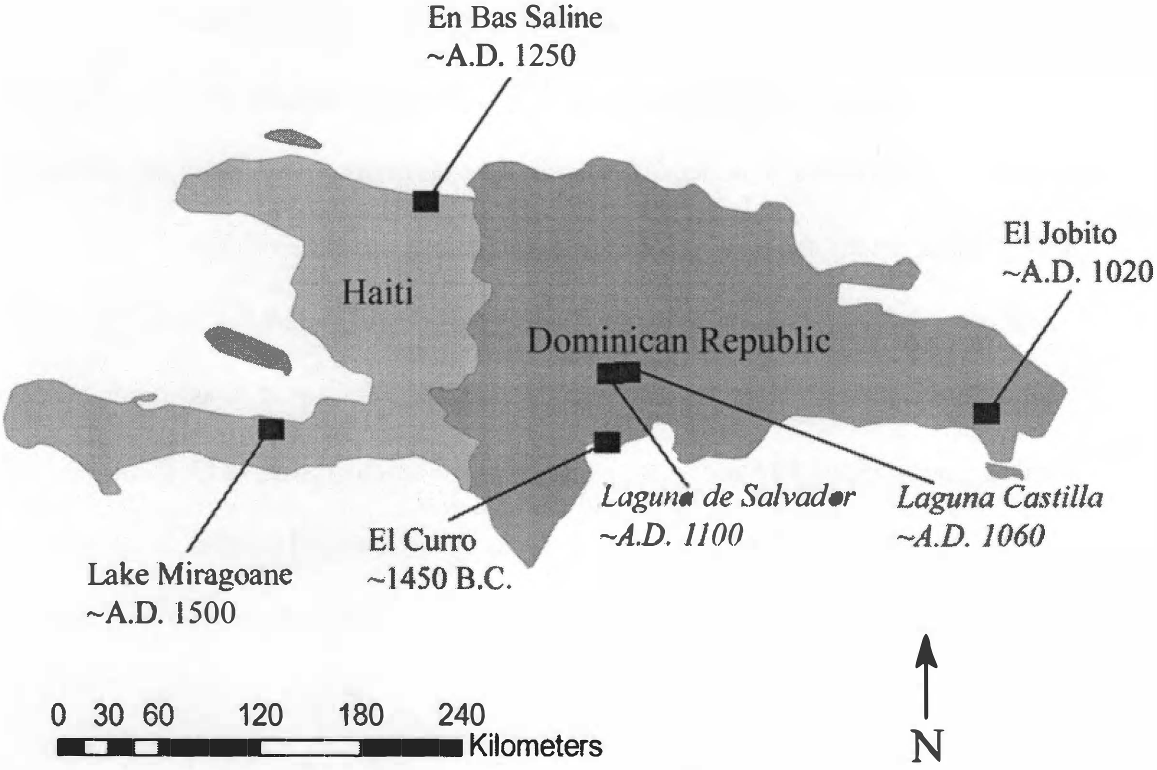

Figure 2.1. The locations of Hispaniolan study sites containing macrofossil or microfossil evidence of maize agriculture prior to A.D. 1500. Laguna Castilla and Laguna de Salvador (italics) are the sites addressed in this study.

preagricultural site developed on a former mangrove swamp. Sediment samples from three shallow excavations were analyzed for pollen by Luis Fortuna, whose results are reported as an appendix to Ortega and Guerrero's monograph. Fortuna found maize grains at 10–20 cm depth that he interpreted as evidence of maize consumption, though not necessarily farming, at the site as early as 1450 B.C. Ortega and Guerrero, however, regarded the maize pollen (as well as some surficial ceramics and a shell amulet found at 0–7 cm) as intrusive elements introduced during later occupation of the area by agricultural peoples.

Phytolith and starch residue analyses provide additional evidence of maize agriculture in the Caribbean, but this evidence is also limited geographically. D. M. Pearsall (Newsom and Pearsall, 2003) reported maize phytoliths in the sediments of a pond near the Maisabel archaeological site in northern Puerto Rico dating back to ca. 2000 B.C. J.R. Pagán-Jiménez et al. (2005) reported starch residues indicative of maize processing from two Archaic Age sites in southern Puerto Rico (Maruca and Puerto Ferro) and a late Ceramic Age site (UTU-27) in the central mountains of Puerto Rico (Newsom, 2006).

Several hypotheses have been put forth to explain the low signals of prehistoric maize agriculture found in the Caribbean. Lee Newsom and her collaborators have been at the forefront of this issue (Newsom and Deagan, 1994; Newsom and Pearsall, 2003; Newsom and Wing, 2004; Newsom, 2006). They have suggested that one possible explanation for the low signals of prehistoric maize agriculture in the Caribbean was heavy reliance by prehistoric inhabitants of the region on root crops (Petersen, 1997), marine resources (Stokes, 1998), and possibly small home gardens, primarily comprising species other than maize (Newsom and Wing, 2004). Excavated artifacts, animal and plant remains, and isotopic analyses of human remains support this hypothesis (e.g. Keegan, 1985; Wilson, 1990; 1997; van Klinken, 1991; Rouse, 1992; Keegan and Deniro, 1998; Stokes, 1998; Wing, 2001). Based on the spatial context of maize macroremains found around the En Bas Saline archaeological site in Haiti, Newsom and her colleagues (Newsom and Deagan, 1994; Newsom and Wing, 2004; Newsom, 2006) also suggested that maize may have been reserved for high status individuals or communal feasts, with limited daily maize consumption by the vast majority of the population. Furthermore, early accounts by Spanish colonists describe the consumption of maize as a "vegetable" by prehistoric inhabitants of the Caribbean (Newsom, 2006, page 333), suggesting that it was a dietary supplement, but never a staple in the prehistoric diet.

With the exception of the UTU-27 site in Puerto Rico, all of the aforementioned archaeological sites are located along the coastal margins of their respective islands. Much of the microfossil evidence has come from excavated soil horizons in which vertical mixing and rapid downwash can complicate pollen stratigraphies (Horn et al., 1998) and possibly also phytolith results. The small amounts of material available as either macrofossils or microfossils has made direct dating impossible; most dating has been based on archaeological context.

To further refine understanding of the introduction and spread of maize agriculture in the Caribbean, we present evidence of prehistoric maize agriculture preserved in the sediment records of two mid-elevation lakes on the Caribbean slope of the Cordillera Central in the Dominican Republic. The sediment records from Laguna Castilla and Laguna de Salvador (Figure 2.1) contain abundant maize pollen dating back to as early as ~A.D. 1060. This find represents the earliest evidence of maize agriculture from the interior of Hispaniola, and some of the oldest and most securely dated evidence of maize agriculture from the island of Hispaniola and the Caribbean as a whole.

Methods

Study Area

Laguna Castilla (18°47'51" N, 70°52'33" W, 976 m) and Laguna de Salvador (18°47'45" N, 70°53'13" W, 990 m) are mid-elevation lakes located on the southern slope of the Cordillera Central in the Dominican Republic (Figure 2.1), about 45 km inland from the Caribbean coast, near the small community of Las Lagunas in the province of Azua. The lakes are located in an area of large hills composed of ancient marine sediments deeply incised by streams. To our knowledge, no archaeological surveys have been undertaken in the area.

Sediment Core Retrieval and Analysis

We collected sediment cores from near the centers of Laguna Castilla and Laguna de Salvador during field expeditions in 2002 and 2004, respectively. Sediments were retrieved in aluminum core tubes in 1 m sections using a Colinvaux-Vohnaut (C-V) locking piston corer (Colinvaux et al., 1999). The uppermost sediments from both lakes were collected with a PVC tube fitted with a rubber piston, and then extruded and sliced in 2-cm increments and the intervals bagged individually in the field. After opening the C-V core sections in our lab, we described color (Munsell) and textural changes.

We constructed chronologies for both sediment cores by obtaining accelerator mass spectrometry (AMS) radiocarbon dates on charcoal, other organic macrofossils, and bulk sediment. We calibrated the AMS radiocarbon dates using the CALIB 5.0 computer program (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004). We determined the weighted mean of the probability distribution of the calibrated age (Telford et al., 2004a; 2004b) for each AMS date and used this single calendar age to calculate sedimentation rates. Calendar ages for lake sediment horizons with maize pollen were calculated based on linear interpolation between dated intervals.

Pollen Analysis

We sub-sampled the sediment cores from Laguna Castilla and Laguna de Salvador for pollen analysis at varying depth intervals (4 to 16 cm), chemically processed the samples using standard techniques (Berglund, 1986; Faegri and Iverson, 1989), added *Lycopodium* tablets as controls (Stockmarr, 1971), and mounted the pollen residues on microscope slides in silicone oil (Appendix A). We scanned at least two slides from each sample level in their entirety at low (100x) magnification (Horn, 2006) searching for maize pollen.

We identified as maize pollen all Poaceae pollen grains with a diameter greater than 62 μm. This identification criterion is based on the work of Whitehead and Langham (1965) who measured and compared the grain and pore diameters of pollen from 12 races of cultivated maize, 10 races of teosinte, and two races of grass from the genus *Tripsacum*, all mounted in silicone oil. Several researchers have documented the potential influence of mounting media, especially glycerine jelly, on the sizes of maize pollen grains (Ludlow-Wiechers, et al. 1983; Sluyter, 1997), but our use of silicone oil for the Castilla and Salvador samples makes possible direct comparison with the work of Whitehead and Langham (1965). Their measurements indicated that pollen grains produced by modern cultivars of *Zea mays* subsp. *mays* and mounted in silicone oil ranged in diameter from 58 µm to 98.6 µm (Whitehead and Langham, 1965); Ludlow-Wiechers et al. (1983) later reported some Mexican races of maize to have pollen grains as large as 120 µm in diameter. It is important to acknowledge that there is overlap in the sizes of pollen grains produced by cultivated maize and those produced by wild maize or teosinte (*Zea mays* subsp. *parviglumis* H. H. Iltis & Doebley, *Zea perennis* (Hitchc.) Reeves & Mangelsd., and other *Zea* L. spp.; taxonomy follows Sluyter, 1997). Measurements of teosinte pollen grains mounted in silicone oil range in diameter from 46.4 to 87 µm (Whitehead and Langham, 1965). However, islands of the Caribbean are outside the natural range of *Zea* and there is no evidence that teosinte was present in prehistoric times on Hispaniola.

Results

A total of 20 down-core pollen samples from the Laguna Castilla sediment core contained prehistoric maize pollen grains (Table 2.1). Most samples from this pre-modern maize interval were extracted from clay-rich sediments with fine laminations suggesting minimal vertical mixing of sediments and associated

Table 2.1. Stratigraphic position, abundance, and dimensions of maize pollen grains from the Laguna Castilla pre-modern maize interval.

Depth[a] (cm)	Approximate Age[b] (cal yr A.D.)	Maize Pollen Grains (n)	Grain Size Range (μm)	Annulus Size Range (μm)	Average Grain Size (μm)	Average Annulus Size (μm)
350	1271	4	74.4–79.4	13.6–16.1	75.0	14.6
366	1253	9	69.4–79.4	12.4–14.9	74.4	13.8
382	1236	12	62.0–86.8	12.4–16.1	72.3	13.8
398	1219	17	66.9–81.8	12.4–14.9	73.1	13.6
414	1201	8	64.5–74.0	12.4–17.4	69.7	14.3
430	1184	2	71.9 (2)	13.6–14.9	71.9	14.3
446	1166	3	66.9–74.4	13.6–16.1	69.4	14.9
462	1149	3	69.4–76.9	13.6–14.9	71.9	14.5
470	1132	5	74.4–76.9	13.6–14.9	75.9	14.6
474	1123	2	76.9–84.3	13.6–14.9	80.6	14.2
478	1119	5	66.9–74.4	12.4–16.1	71.4	14.1
482	1114	4	71.9–76.9	12.4–14.9	74.1	14.3
486	1110	6	66.9–76.9	13.6–14.9	70.3	14.3
490	1105	1	70.7	13.6	70.7	13.6
502	1092	1	70.7	13.6	70.7	13.6
506	1088	2	74.4–76.9	13.6–14.9	75.6	14.3
510	1084	2	69.4 (2)	13.6–14.9	69.4	14.3
514	1079	2	70.7–71.9	13.6 (2)	71.3	13.6
522	1071	3	74.4–76.9	13.6–14.9	76.1	14.1
530	1062	1	71.9	13.6	71.9	13.6

[a] Depth refers to the depth below the sediment-water interface.

[b] Ages were estimated using linear interpolation between the calibrated radiocarbon dates bracketing this stratigraphic section.

pollen grains (Figure 2.2). Linear interpolation between the calibrated ages bracketing this interval of maize pollen deposition indicates that the grains range in age from cal yr A.D. 1062 to cal yr A.D. 1271 (Tables 2.1 and 2.2). Our relatively coarse pollen sampling of the Laguna de Salvador sediment core has resulted in the discovery of fewer maize pollen grains at this site; however, the timing of maize pollen deposition was similar. Three pollen samples from Laguna de Salvador contained prehistoric maize pollen with interpolated ages ranging from cal yr A.D. 1108 to cal yr A.D. 1187 (Tables 2.3 and 2.4). The grain and annulus diameters of the maize grains (Tables 2.1 and 2.3) from both sediment profiles are well within the expected size ranges of pollen grains of modern cultivars of *Zea mays* subsp. *mays* (Whitehead and Langham, 1965) and of prehistoric maize pollen from the Central American mainland (Horn, 2006).

Discussion and Conclusions

The palynological evidence of prehistoric maize agriculture presented here represents some of the earliest documented evidence of maize agriculture from the island of Hispaniola (Figure 2.1), and the only evidence from the interior of the island. The maize pollen grains preserved in Laguna Castilla also represent some of the most securely dated evidence of early maize agriculture in Hispaniola and the entire Caribbean region. Three aspects of our findings give us great confidence in our dating. First, we have obtained AMS radiocarbon dates on organic sediments positioned only 6 cm deeper than the lowest stratigraphic position of prehistoric maize pollen, and only 20 cm higher than the upper stratigraphic boundary of the pre-modern maize pollen interval in the Laguna

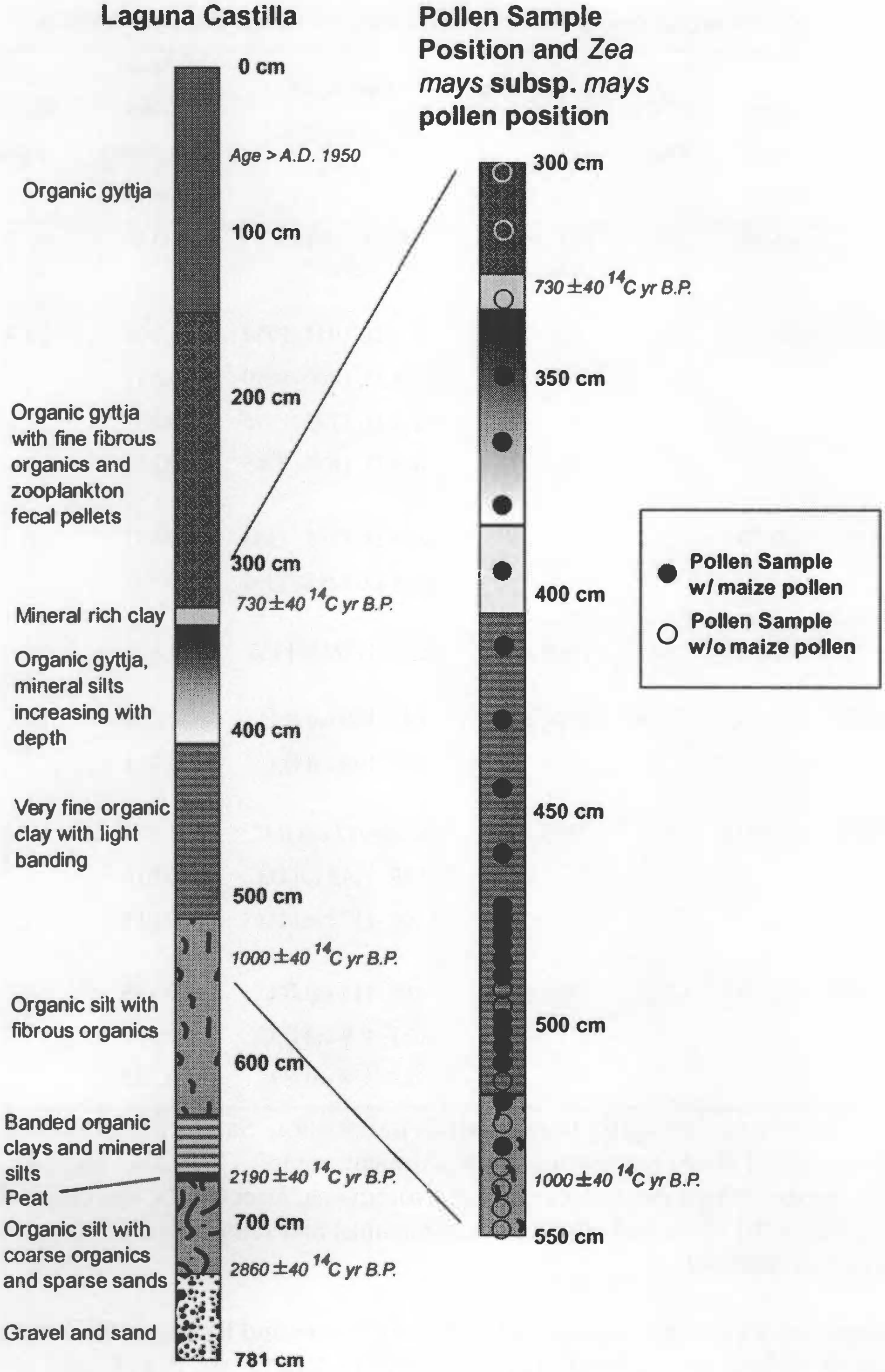

Figure 2.2. Stratigraphy of the Laguna Castilla sediment core and the stratigraphic position of pollen samples within the pre-modern maize interval. Filled circles represent pollen samples containing cultivated maize pollen.

Table 2.2. Radiocarbon determinations and calibrations for Laguna Castilla.

Lab Number[a]	Depth (cm)	$\delta^{13}C$ (‰)	Uncalibrated ^{14}C Age (^{14}C yr BP)	Calibrated Age Range[b] ± 2 σ	Area Under Probability Curve	Weighted Mean[c]
β-196817	66–68	–25.6	103.9% of Modern	cal A.D. 1951.5 – 1954.5*	1.000*	cal A.D. 1953*
β-204702	204–207	–24.5	110 ± 40	cal A.D. 1951–1954	0.008	cal A.D. 1817
				cal A.D. 1800–1940	0.651	
				cal A.D. 1772–1776	0.007	
				cal A.D. 1677–1765	0.333	
β-196818	329–331	–25.9	730 ± 40	cal A.D. 1365–1383	0.063	cal A.D. 1276
				cal A.D. 1218–1303	0.937	
β-171499	536–537	–24.2	1000 ± 40	cal A.D. 975–1155	1.000	cal A.D. 1051
β-192641	651–653	–23.8	2190 ± 40	127–120 cal B.C.	0.009	267 cal B.C.
				382–163 cal B.C.	0.991	
β-171500	724–725	–23.2	2860 ± 40	1130–912 cal B.C.	0.970	1033 cal B.C.
				1159–1143 cal B.C.	0.016	
				1190–1177 cal B.C.	0.014	
β-171501	758–761	–25.3	2470 ± 40	469–413 cal B.C.	0.118	602 cal B.C.
				673–478 cal B.C.	0.600	
				763–678 cal B.C.	0.282	

[a] Analyses were performed by Beta Analytic Laboratory. Samples β-196817, β-196818, and β-171499 consisted of bulk sediment; samples β-192641 and β-204702 consisted of a mixture of plant macroremains, insect parts, and charcoal; sample β-171501 consisted of plant macroremains; and sample β-171500 consisted of charcoal.

[b] Calibrations were calculated using Calib 5.0 (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004).

[c] Weighted mean of the calibrated age probability distribution curve.

*Dates were calibrated using the CALIBomb program (Reimer et al., 2004).

Table 2.3. Stratigraphic position, abundance, and dimensions of maize pollen grains from Laguna de Salvador.

Depth[a] (cm)	Approximate Age[b] (cal yr A.D.)	Maize Pollen Grains (n)	Grain Size Range (μm)	Annulus Size Range (μm)	Average Grain Size (μm)	Average Annulus Size (μm)
268	1187	1	69.4	14.9	69.4	14.9
276	1147	1	76.9	14.9	76.9	14.9
284	1108	5	71.9–79.4	13.6–14.9	75.9	14.6

[a] Depth refers to the depth below the sediment-water interface.

[b] Ages were estimated using linear interpolation between the calibrated radiocarbon dates bracketing this stratigraphic section.

Table 2.4. Radiocarbon determinations and calibrations for Laguna de Salvador.

Lab Number[a]	Depth (cm)	$\delta^{13}C$ (‰)	Uncalibrated ^{14}C Age (^{14}C yr BP)	Calibrated Age Range[b] ± 2 σ	Area Under Probability Curve	Weighted Mean[c]
β-219035	76.5	–25.7	100 ± 40	cal A.D. 1951–1954	0.013	cal A.D. 1825
				cal A.D. 1801–1939	0.673	
				cal A.D. 1680–1763	0.315	
β-204696	204	–27.5	410 ± 40	cal A.D. 1558–1631	0.243	cal A.D. 1504
				cal A.D. 1427–1524	0.757	
β-196821	359	–29.8	1280 ± 40	cal A.D. 841–861	0.028	cal A.D. 736
				cal A.D. 787–824	0.065	
				cal A.D. 658–783	0.907	
β-192645	504	–25.1	2060 ± 40	183 cal B.C.–cal A.D. 24	1.000	79 cal B.C.

[a] Analyses were performed by Beta Analytic Laboratory. Samples β-219035, β-204696, β-196821 consisted of wood fragments and sample β-192645 consisted of charcoal.

[b] Calibrations were calculated using Calib 5.0 (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004).

[c] Weighted mean of the probability distribution of the calibrated age (Telford et al., 2004b).

Castilla sediment record (Figure 2.2), such that our interpolated ages are very close to directly dated horizons. Second, the sedimentation rate in Laguna Castilla during this period was quite high (0.92 cm/yr), which allows for relatively precise interpolation of dates. Third, most of the maize pollen grains are preserved within finely laminated sediments, and the oldest maize pollen grains are preserved in organic silts a few cm below the laminated sediments (Figure 2.2). This stratigraphic context makes it highly unlikely that any vertical mixing of the sediments and their associated microfossils took place. With the exception of Lake Miragoâne, the secure stratigraphy of the Castilla pollen grains contrasts with the stratigraphy of all prehistoric maize sites on Hispaniola. That evidence has come from excavations in soil that may have been prone to vertical mixing or downwashing of younger microfossils and for which dating has primarily relied on ceramic styles and on limited radiocarbon analyses not closely tied to the pollen spectra.

The lack of archaeological research around Laguna Castilla and Laguna de Salvador limits our ability to interpret the archaeological context of our pollen results. However, the radiocarbon dates place the interval of pre-modern maize pollen deposition in both lakes within the Ostionoid archaeological period (~A.D. 500 to A.D. 1500; Wilson, 1997). This is a period that has been associated with an intensification of horticultural production throughout Hispaniola as indicated by increased use of agricultural terraces (Ortiz Aguilu et al., 1991) and by the construction of small earthen mounds (conucos) associated with more intensive agricultural production (Rouse, 1992).

Although the inland location of Laguna Castilla and Laguna de Salvador does not preclude the possibility that aquatic and marine resources were an important part of the prehistoric diet in this area (Wilson, 1993), it is conceivable that the approximately 45-km distance from the Caribbean coast may have led to a greater local dependence on terrestrial food sources, including cultivated maize, than is apparent at contemporaneous coastal sites on Hispaniola (Newsom 2006). The hypothesis that interior populations in the Caribbean were more dependent on terrestrial food sources, including maize, than coastal populations was advanced by Stokes (1998) and is supported by her isotopic analyses of human remains collected from the Paso del Indio site located in the interior of Puerto Rico.

Our discovery of prehistoric maize pollen grains in the sediments of Laguna Castilla and Laguna de Salvador, together with starch residue and phytolith evidence of prehistoric maize cultivation (Newsom, 2006) and isotopic evidence of maize consumption from the interior of Puerto Rico (Stokes, 1998), emphasize the need for further archaeological research into the importance of maize agriculture in the interior of Hispaniola and other Caribbean islands. More archaeological investigations of inland sites on the Greater Antilles would improve our understanding of the geography and history of maize cultivation in the prehistoric Caribbean and its role in the evolving ethnobotany of the region.

CHAPTER 3

Sensitivity of Sedimentary Stable Carbon Isotopes in a Small Neotropical Lake to Prehistoric Forest Clearance and Maize Agriculture

This chapter is in preparation for submission to the *Journal of Paleolimnology* by me, Claudia I. Mora, Sally P. Horn, and Kenneth H. Orvis. The submitted manuscript will include additional information on the study area that is presented in Chapter 1 of this dissertation. My use of "we" in this chapter refers to my co-authors and myself.

Introduction

Much of what we currently know about the environmental impacts of prehistoric human populations has come from lake sediment records of paleoenvironmental change. Lake sediment records from around the world have been used to document a variety of prehistoric human activities including deforestation (Burney et al., 1994; Islebe et al., 1996; Northrop and Horn, 1996; Goman and Byrne, 1998; Clement and Horn, 2001; Rosenmeier et al., 2002a; Rosenmeier et al., 2002b; Fisher et al., 2003; Wahl et al., 2006), soil degradation (Ohara et al., 1994; Jacob and Hallmark, 1996; Beach, 1998; Conserva and Byrne, 2002; Lucke et al., 2003), water pollution (Oldfield et al., 2003; Davies et al., 2004; Ekdahl et al., 2004), and agriculture (Sluyter, 1997b; Leyden et al., 1998; Dull, 2006; Horn, 2006). The majority of these studies have taken a qualitative approach, documenting the occurrence and timing, but not the spatial scale, of these activities.

In a recent study, Lane et al. (2004) documented prehistoric forest clearance and crop cultivation in the neotropics using the stable carbon isotope composition of total organic carbon ($\delta^{13}C_{TOC}$) in lake sediments. Subsequently, Lane et al. (in press) proposed that relative shifts in the $\delta^{13}C_{TOC}$ values of lake sediments could be used to compare the relative spatial scale of prehistoric forest clearance and agriculture at a particular site through time. These studies raised the possibility of quantitatively reconstructing the spatial scale of these activities at high temporal resolutions using the stable carbon isotope proxy.

Lane et al. (2004) and Lane et al. (in press) provided a full overview of the theoretical basis behind the $\delta^{13}C_{TOC}$ proxy record of prehistoric forest clearance and agriculture. This proxy is effective because maize (*Zea mays* subsp. *mays*) and a few other tropical cultigens, as well as many associated agricultural weeds, use the C_4 photosynthetic pathway, whereas mesic neotropical forest ecosystems are dominated by trees and shrubs that use the C_3 photosynthetic pathway. Plants that use the C_3 photosynthetic pathway produce tissues with $\delta^{13}C$ values ranging between –35‰ and –20‰ V-PDB, but plants that use the C_4 photosynthetic pathway produce tissues with $\delta^{13}C$ values ranging between –14‰ and –10‰ V-PDB (Bender, 1971; O'Leary, 1981). After the deforestation of a C_3-dominated ecosystem, such as a neotropical forest, and replacement by C_4 cultigens and weeds, a shift in the isotopic composition of organic carbon is produced by the ecosystem as a whole. The shift in the carbon isotope compositions can be recorded in lake sediments as long as carbon from the ecosystem is input to those lake sediments (Aucour et al., 1999; Huang et al., 2001; Street-Perrott et al., 1997; 2004).

The detection of prehistoric forest clearance and agriculture using stable carbon isotopes only allows assessment of the relative importance of these activities through time. To develop a more quantitative assessment of the environmental impacts of prehistoric human populations on the environment, based on the isotope proxy, it is necessary to develop a more in-depth understanding of how the sedimentary $\delta^{13}C_{TOC}$ record responds to numerous and complex watershed variables. Two critical variables are variations in the abundance of C_4 plants, most notably maize, in the watershed and variations in the contribution of allochthonous carbon to the lake sediments. In this study, we attempt to assess the influence of these variables on $\delta^{13}C$ values of lake sediments from Laguna Castilla, a small lake in the Dominican Republic, over a period of ~300 years using a multi-proxy approach at high temporal resolution.

The most well-established technique for reconstructing the abundance of C_4 plants within a watershed is a mass balance approach in which the relative contributions of C_3 and C_4 plants to the bulk carbon isotope compositions of lake sediments and soils are estimated based on their end-member isotopic compositions. However, this is the very proxy we are seeking to study. An alternative approach to establishing the relative C_4 plant abundance through time in the mesic neotropics is to use the maize pollen concentration of sediments. Forest ecosystems are dominated by C_3 plants, and because any increase in C_4 plants within the ecosystem is most likely linked to agricultural activities and will be proportional in scale to agriculture within the watershed. Although the exclusive use of maize pollen may underestimate the total abundance of C_4 plants in the watershed, it is not possible to distinguish the pollen of other C_4 species from C_3 species in the same families.

Maize pollen grains preserved in lake sediments have been previously used as an indicator of prehistoric agriculture (*c.f.,* Staller et al., 2006). Pollen produced by *Zea mays* subsp *mays*, as well as several other species in the genus *Zea*, is relatively large, and has a very high settling velocity and short dispersal distance (Raynor et al., 1972; Luna et al., 2001; Aylor et al., 2005). Based on the short dispersal distance of maize pollen, some researchers have conjectured that the presence of maize pollen in lake sediments may require that the plants be grown on the very shore of the lake (Islebe et al., 1996). This short dispersal distance is somewhat problematic in the context of reconstructing the abundance of maize at the landscape scale because the cultigen is typically poorly represented in pollen assemblages. However, the small size of the Laguna Castilla watershed (see Study Site description below) suggests that any maize cultivation in the watershed occurred fairly close to the lake itself. In addition, the relatively high abundance of maize grains in the Laguna Castilla sediment record (Chapter 2) should make it possible to reliably estimate maize pollen concentrations. Variations in the abundance of maize pollen are thus hypothesized to track, at least semi-quantitatively, changes in the relative abundance of maize and closely associated agricultural weeds in the watershed through time.

The contribution of sediments that originate from allochthonous sources can be assessed using a variety of techniques. In this study, we use mineral influx as a proxy of allochthonous sediment delivery. While some of the mineral components of lake sediments can originate from autochthonous sources (*e.g.*, diatoms, ostracods, gastropods, charophytes, marl, sponge spicules), the mineral component of sediments with low calcite or aragonite concentrations, such as those analyzed here, primarily originates from the physical and chemical breakdown of surrounding rocks and soils and subsequent delivery of that material to the lake through erosion and sediment transport. Therefore, we hypothesize that the mineral influx into Laguna Castilla can be used as a proxy of the relative importance of allochthonous sediment delivery through time.

By comparing variations in sedimentary $\delta^{13}C_{TOC}$ values, maize pollen concentrations, and mineral influx in the Laguna Castilla sediment record, it should be possible to assess the sensitivity of lake sediment $\delta^{13}C_{TOC}$ values to variations in the abundance of C_4 cultigens and associated weeds on the surrounding landscape, as well as variations in allochthonous sediment delivery. In addition, by conducting these analyses at a high resolution (approximately 5–20 years) it should also be possible to assess the temporal sensitivity of sedimentary $\delta^{13}C_{TOC}$ values to variations in these variables. Because agricultural activities are typically based on an annual cycle of field clearance and crop cultivation, it is essential that the $\delta^{13}C_{TOC}$ record be responsive at a high temporal resolution if we hope to use this proxy to quantitatively reconstruct these past activities.

Study Site

Laguna Castilla (18°47'51" N, 70°52'33" W, 976 m) is located on the Caribbean slope of the Cordillera Central in the Dominican Republic (Figure 3.1),

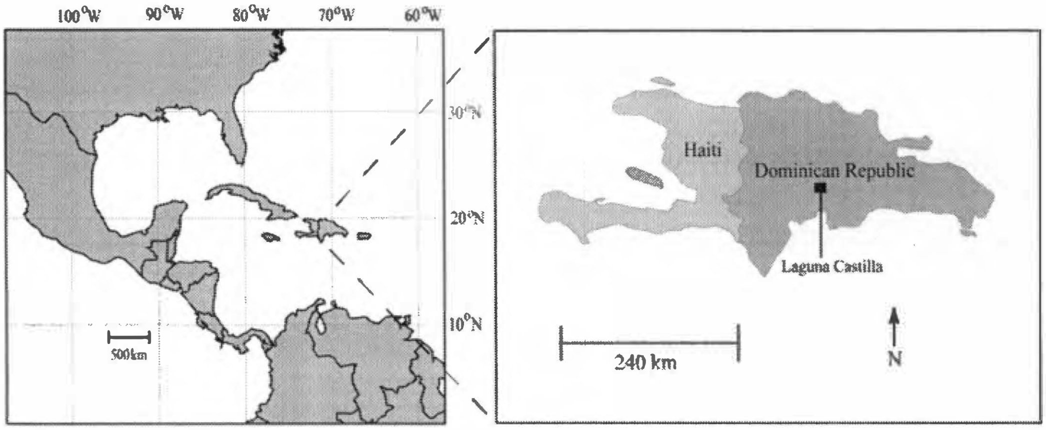

Figure 3.1. Location of the Dominican Republic and Laguna Castilla.

near the small community of Las Lagunas in the province of Azua. Based on aerial photographs and topographic maps of the area, the Laguna Castilla watershed appears to be less than 25 ha in total area (Figure 3.2). Laguna Castilla itself is a fairly small lake with a surface area of approximately 1.5 ha.

The landscape around Laguna Castilla is currently being used for a wide range of activities including cattle and goat ranching and agriculture (Figure 3.2). Humans living in the area today cultivate a variety of crops including beans, corn, and coffee. Vegetation of nearby areas with similar climate conditions, but with less human impact, has been classified as lower montane moist forest (i.e. the Holdridge life zone designation; Tolentino and Peña, 1998). Lower montane moist forest in the Dominican Republic is a C_3-dominated ecosystem consisting of pines (*Pinus occidentalis* Schwartz) mixed with a wide variety of evergreen and deciduous broadleaved trees and shrubs (Liogier, 1981).

Methods

Sediment Core Recovery and Chronology

We collected a 7.8 m sediment core from near the center of Laguna Castilla in 2002. Sediments 40 cm below the sediment/water interface were retrieved in aluminum core tubes in 1 m sections using a Colinvaux-Vohnaut (C-V) locking piston corer (Colinvaux et al., 1999). After opening the C-V core sections in our lab, we photographed and described the stratigraphy of the core. In this study, we focus on sediments from 3 m to 6 m below the sediment-water interface, which span the period of prehistoric human occupation of the watershed (Chapter 3).

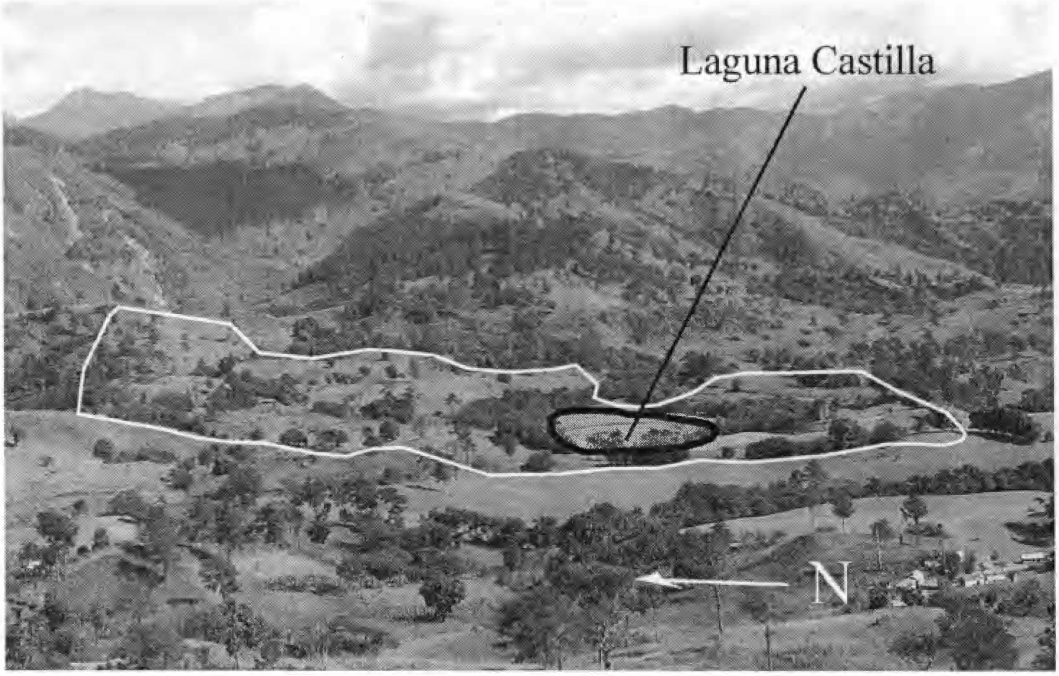

Figure 3.2. Photograph of Laguna Castilla and the surrounding landscape. Note the small size of the Laguna Castilla watershed (highlighted in white). The shore of Laguna Castilla has been highlighted in black. For scale, the width of Laguna Castilla is approximately 100 m.

We constructed a chronology for the Laguna Castilla sediment core by obtaining accelerator mass spectrometry (AMS) radiocarbon dates from Beta Analytic Laboratory, Inc., in Miami, Florida. Radiocarbon determinations were made on a variety of organic materials including charcoal, non-carbonized organic macrofossils, and bulk sediment. We calibrated the AMS radiocarbon dates using the CALIB 5.0 computer program (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004). To calculate sedimentation rates, we calculated a single calibrated age by determining the weighted mean of the calibrated age probability distribution (Telford et al., 2004a; b). We calculated the calendar ages for lake sediment horizons located between the positions of radiocarbon dated materials using linear interpolation.

Laboratory Analyses

Stable carbon isotope analysis

We measured the stable carbon isotope ratios of bulk sedimentary organic carbon ($\delta^{13}C_{TOC}$) from Laguna Castilla at intervals of 4 to 16 cm. We removed carbonates from the sediment samples by reacting the sediment with 10% HCl. Following neutralization with distilled water, we dried the sediment overnight at 50 °C, removed any large organic macrofossils, and ground the dried samples to a fine powder with a mortar and pestle to ensure the samples were homogenized and representative of the organic carbon fraction of the bulk sediment. We then combusted the sediment samples at 800 °C under vacuum in quartz tubes in the presence of 500 mg of copper, 500 mg of copper oxide, and a small platinum wire. Next, we cryogenically purified the rendered CO_2 and analyzed its carbon isotope composition using a dual-inlet Finnigan MAT Delta-plus mass spectrometer at the University of Tennessee. We report all carbon isotopic compositions in standard δ-per mil notation relative to the Vienna-Pee Dee belemnite (V-PDB) marine-carbonate standard, where:

$$\delta^{13}C \text{ (per mil)} = 1000\ [(R_{sample}/R_{standard}) - 1],$$

$$\text{where } R = {}^{13}C/{}^{12}C.$$

Repeated analyses of the USGS 24 graphite standard indicate that the precision of these offline carbon isotopic determinations are better than ± .05‰ V-PDB.

Maize pollen concentration

A detailed explanation of our pollen sampling and processing procedures, along with the criteria used to identify maize (*Zea mays* subsp. *mays*) pollen, was presented earlier (Chapter 2). In short, we sub-sampled 0.5 cc of sediment from the Laguna Castilla core for pollen analysis at the same depth intervals sub-sampled for isotope analysis. We prepared and scanned at least two slides from each sample level for maize pollen.

We calculated the concentration of maize pollen grains (grains/cm^3) in each 0.5 cc sample using the following equation:

$$\text{Maize grain concentration (grains/cm}^3\text{)} =$$

$$(\text{Controls}_{sample} * \text{Maize}_{slides}) / \text{Controls}_{slides}) * 2$$

where Controls_{sample} represents the total number of controls (*Lycopodium* spores) added to the 0.5 cc sample (approximately 13,911 *Lycopodium* spores), Maize_{slides} represents the total number of *Zea mays* subsp. *mays* pollen grains counted on two slides, and Controls_{slides} represents the number of controls on two slides. The number of controls on two slides was estimated based on the extrapolation of the number of controls counted during full pollen counts that covered a known area of the slides.

Mineral influx analysis

We took duplicate 0.5 cc sediment sub-samples from the Laguna Castilla sediment core at the same intervals as those taken for isotope and pollen analysis. We combusted the pre-weighed sub-samples at 550 °C for one hour to estimate the organic carbon content of the sediment and 1000 °C for one hour to estimate the carbonate content of the sediment (Dean, 1974). We assumed that any material remaining after the 550 °C burn was mineral. We then calculated the mineral influx for each sample using the following equation:

$$\text{Mineral Influx (mg/cm}^2\text{/yr)} = \text{Mineral Bulk Density (mg/cm}^3\text{)} / \text{Sedimentation Rate (cm/yr)}$$

We calculated the sedimentation rate using linear interpolation of the weighted means of the probability distribution of the calibrated radiocarbon ages bracketing the positions of the two adjacent sub-samples.

Results

Sediment Stratigraphy and Chronology

Between 5.2 and 6.0 m, the Laguna Castilla sediments consist of organic silts and clays with fine fibrous organics (Figure 3.3). Subsequently, a rather abrupt transition to faintly banded organic and mineral clays occurs around 5.2 m. The fact that these sediments are laminated indicates minimal vertical mixing of

Figure 3.3. Stratigraphy and radiocarbon chronology of the entire Laguna Castilla sediment core. This study focuses on the sediments located between 300 and 600 cm (dashed line). The asterisks designate the section of the sediment record that contains pollen grains of prehistoric maize (*Zea mays* subsp. *mays*).

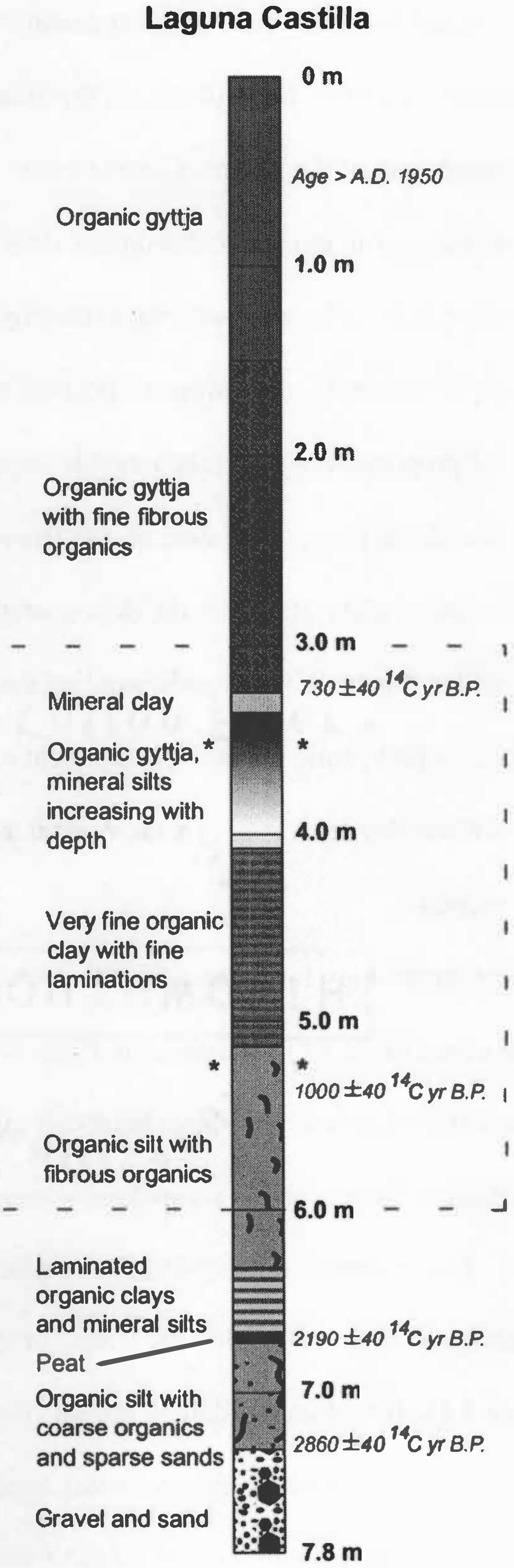

Figure 3.3. Continued.

the sediments and associated fossils. Based on the appearance of maize pollen in the sediment record around this time, we hypothesize that this transition represents the initial occupation of the Laguna Castilla watershed by prehistoric humans and a resulting increase in erosion and sediment delivery to the lake. These sediments have very low carbonate contents, averaging around 2% by mass. At approximately 4.1 m depth, the sediments become mineral rich. Within the overlying 50 cm, the proportion of mineral content to organic gyttja gradually decreases. At 325 cm depth, an abrupt transition occurs from gyttja to a relatively small lens (5.5 cm) of mineral clay. Based on the disappearance of maize pollen from the sediment record at this time, we hypothesize that these sediments coincide with the period of prehistoric human abandonment of the watershed. Following deposition of this clay lens, total organic content and the abundance of fine fibrous organics increase.

The radiocarbon chronology for Laguna Castilla includes one date reversal near the bottom of the core (Table 3.1). We chose to reject this date because it appears that the organic material dated may have been root material that grew down through the Castilla sediments and is anomalously young compared to the surrounding sediment. Radiocarbon sample β-171500 consisted of charcoal and is likely to be a more reliable date for estimating the timing of the formation of Laguna Castilla (Table 3.1). Based on this date, it appears that Laguna Castilla formed around 2980 cal yr B.P. Sedimentation rates in Laguna Castilla vary between 0.09 cm/yr and 1.32 cm/yr, with the highest sedimentation rates

Table 3.1. Radiocarbon determinations and calibrations for Laguna Castilla.

Lab Number[a]	Depth (cm)	δ^{13}C (‰)	Uncalibrated ^{14}C Age (^{14}C yr BP)	Calibrated Age Range[b] ± 2 σ (cal yr B.P.)	Area Under Probability Curve	Weighted Mean[c] (cal yr B.P.)
β-196817	66–68	–25.6	103.9% of Modern	–1.5 – –4.5*	1.000*	–3*
β-204702	204–207	–24.5	110 ± 40	–1 – –4	0.008	133
				150–10	0.651	
				178–174	0.007	
				273–185	0.333	
β-196818	329–331	–25.9	730 ± 40	585–567	0.063	674
				732–647	0.937	
β-171499	536–537	–24.2	1000 ± 40	975–795	1.000	899
β-192641	651–653	–23.8	2190 ± 40	2077–2070	0.009	2217
				2332–2113	0.991	
β-171500	724–725	–23.2	2860 ± 40	3080–2862	0.970	2983
				3109–3093	0.016	
				3140–3127	0.014	
β-171501	758–761	–25.3	2470 ± 40	2419–2363	0.118	2552
				2623–2428	0.600	
				2713–2628	0.282	

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[a] Analyses were performed by Beta Analytic Laboratory. Samples β-196817, β-196818, and β-171499 consisted of bulk sediment; samples β-192641 and β-204702 consisted of a mixture of plant macroremains, insect parts, and charcoal; sample β-171501 consisted of plant macroremains; and sample β-171500 consisted of charcoal.

[b] Calibrations were calculated using Calib 5.0 (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004).

[c] Weighted mean of the calibrated age probability distribution curve.

*Dates were calibrated using the CALIBomb program (Reimer et al., 2004).

occurring during periods of prehistoric and modern human occupation (Chapter 4; Figure 3.4).

Stable Carbon Isotopes, Maize Pollen Concentrations, and Mineral Influx

We have delineated six zones (A–F) in the Castilla sediment section based on the interrelationships of $\delta^{13}C_{TOC}$, maize pollen concentrations, and mineral influx (Figure 3.5).

Zone F (600–535 cm)

Zone F represents a period when conditions in and around Laguna Castilla favored low mineral influx (2–8 mg/cm^2/yr). No maize pollen is present and stable carbon isotope values increase gradually from –27 to –24‰, with the exception of a large negative $\delta^{13}C_{TOC}$ excursion around 570 cm.

Zone E (535–460 cm)

Zone E contains the first appearance of maize in the Laguna Castilla watershed. Concentrations of maize pollen range from 0 to 59 grains per cm^3. Maximum $\delta^{13}C_{TOC}$ values (–21‰) occur early in Zone E, decrease around 500 cm, and then increase again around 480 cm. There appears to be a good correspondence between $\delta^{13}C_{TOC}$ values and maize pollen concentrations in Zone E, but with a slight lag in the response of the $\delta^{13}C_{TOC}$ values to changes in maize pollen concentrations. The $\delta^{13}C_{TOC}$ and mineral influx records display similar patterns through Zone E, with mineral influx values slightly leading shifts in the $\delta^{13}C_{TOC}$ record. Mineral influx values reach some of the highest values in the entire sediment record in Zone E ranging from a minimum of 32 mg/cm^2/yr to a maximum of 356 mg/cm^2/yr.

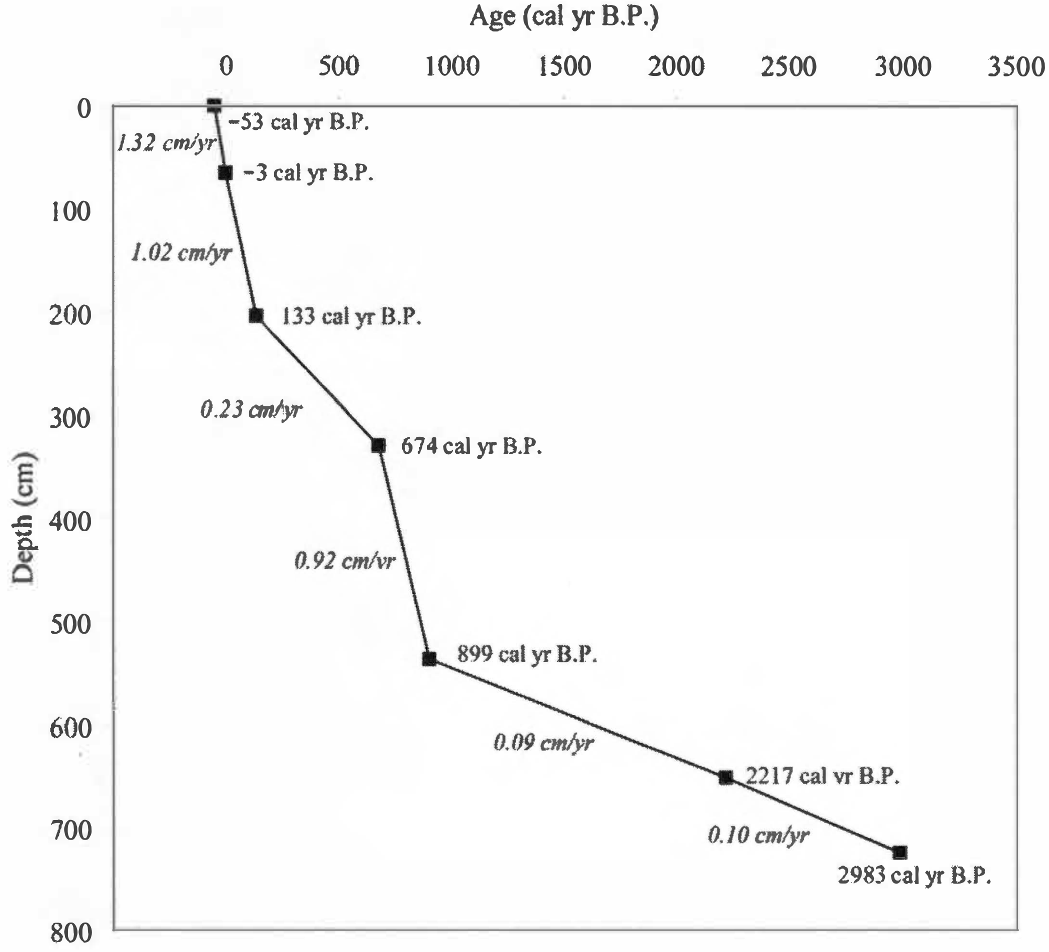


Figure 3.4. Age-depth graph for the Laguna Castilla sediment core based on weighted means of the probability distributions for radiocarbon dates (Table 1). Sediment accumulation rates (italics) are reported in cm/calendar year.

Figure 3.5. Summary diagram of Laguna Castilla sedimentary $\delta^{13}C_{TOC}$ values, maize pollen concentrations, and mineral influx variation. Radiocarbon dates (^{14}C yr B.P.) at left are uncalibrated.

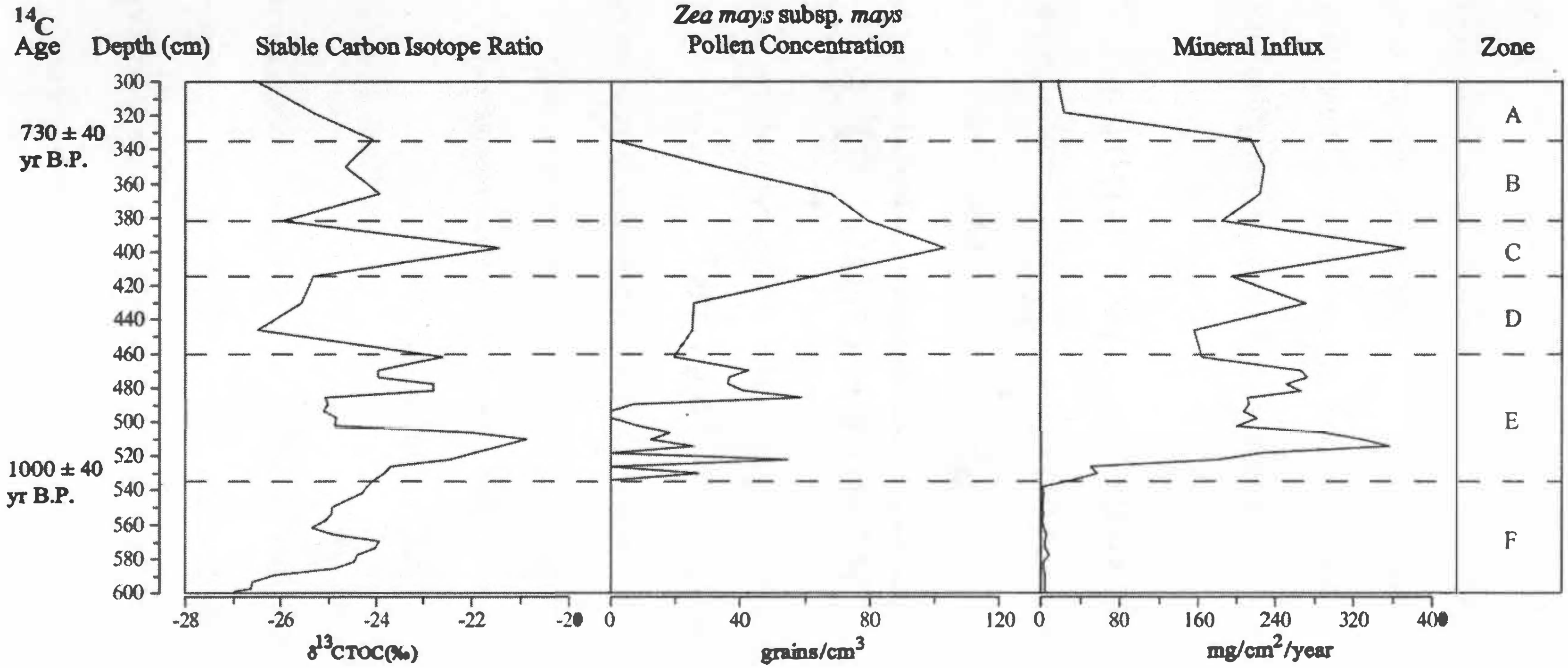


Figure 3.5 Continued

Zone D (460–414 cm)

Average mineral influx values and maize pollen concentrations decrease significantly in Zone D , but still remain high compared to Zone F. The $\delta^{13}C_{TOC}$ values remain relatively low and stable, but there is a slight increase in the $\delta^{13}C_{TOC}$ values coincident with a sharp increase in mineral influx from 446 to 430 cm.

Zone C (414–382 cm)

Zone C contains the highest maize pollen concentrations in the entire sediment record (103 grains/cm^3). Along with this increase in maize pollen concentration is an increase in $\delta^{13}C_{TOC}$ values to around –21‰, and the highest mineral influx in the entire sediment record (370 mg/cm^2/yr). Following these increases, all three proxy indicators decline toward the top of Zone C.

Zone B (382–335 cm)

Zone B is characterized by a steady decline in maize pollen and its eventual disappearance from the sediment record. Mineral influx and $\delta^{13}C_{TOC}$ values remain steady. The mineral influx values average around 200 mg/cm^2/yr and the $\delta^{13}C_{TOC}$ values average around –24‰.

Zone A (335–300 cm)

Mineral influx values in Zone A approach pre-occupational levels (20 mg/cm^2/yr). Stable carbon isotope ratios progressively decrease from approximately –24‰ to around –27‰. There is no maize pollen present.

Discussion

Zone F (600–535 cm): Pre-Settlement Conditions

Prior to the settlement of the Laguna Castilla watershed by prehistoric humans, mineral influx was low, indicating a small contribution of allochthonous materials to the sediments, and $\delta^{13}C_{TOC}$ values were low, indicating that organic carbon that originated from terrestrial vegetation in the watershed was most likely being produced by C_3 plants (average $\delta^{13}C_{TOC}$ value = –25‰). Modest increases in $\delta^{13}C_{TOC}$ values through Zone F may indicate increasing regional aridity, with a resulting slight increase in the local dominance of C_4 plants or drought stress in C_3 plants (e.g. Stewart et al., 1995). It seems unlikely that the increase in $\delta^{13}C_{TOC}$ values was the result of prehistoric deforestation because we observed no concurrent increase in mineral influx that would be expected with deforestation and increased soil erosion.

Zone E 535–460 cm): Initial Settlement

The most striking aspects of Zone E are the sudden appearance of maize pollen and the steep increases in mineral influx and carbon isotope ratios. Mineral influx increases by two orders of magnitude compared to pre-settlement conditions and is most likely associated with significant forest clearance during initial human settlement of the watershed. The $\delta^{13}C_{TOC}$ data in Zone E correspond well with both the maize concentrations and mineral influx data and indicate that the bulk organic carbon in the watershed includes a significant component of cultivated maize or C_4 agricultural weeds.

A slight lag in the response of the $\delta^{13}C_{TOC}$ record to maize abundance is indicated in the pollen concentrations. For example, peaks in maize concentration around 520, 485, and 470 cm match well with peaks in $\delta^{13}C_{TOC}$ values around 510, 480, and 462 cm, respectively. In addition, a conspicuous drop in maize pollen concentration around 495 cm is accompanied by a decrease in $\delta^{13}C_{TOC}$ values around 490 cm. This temporal relationship between the $\delta^{13}C_{TOC}$ record and the maize pollen concentration record appears to exist throughout the 300–600 cm subsection of the Laguna Castilla sediment record.

The close relationship between the $\delta^{13}C_{TOC}$ and maize pollen concentration curves are clearly evident when the depths of carbon isotope data are shifted downward by 4 cm (Figure 3.6). This shift is arbitrary and merely intended to clarify the relationships between these two datasets. Realistically, the temporal response of $\delta^{13}C_{TOC}$ values is unlikely to be linear through time, as it will depend upon numerous, and quite complex, environmental variables. Despite the simplistic nature of this linear correction, the close correspondence between $\delta^{13}C_{TOC}$ values and maize pollen concentrations is quite clear.

If we assume that the maize pollen concentrations in the Laguna Castilla sediment record are representative of the abundance of maize on the landscape, then a slight lag in the response of the $\delta^{13}C_{TOC}$ record should be expected. This section of the Castilla sediment record has very high sedimentation rates (Figure 3.4; 1 cm/yr) and we have analyzed proxies at high temporal resolution (approximately 5–15 years between samples). We may actually be seeing in these datasets the time lag between pollen production by living maize plants and the

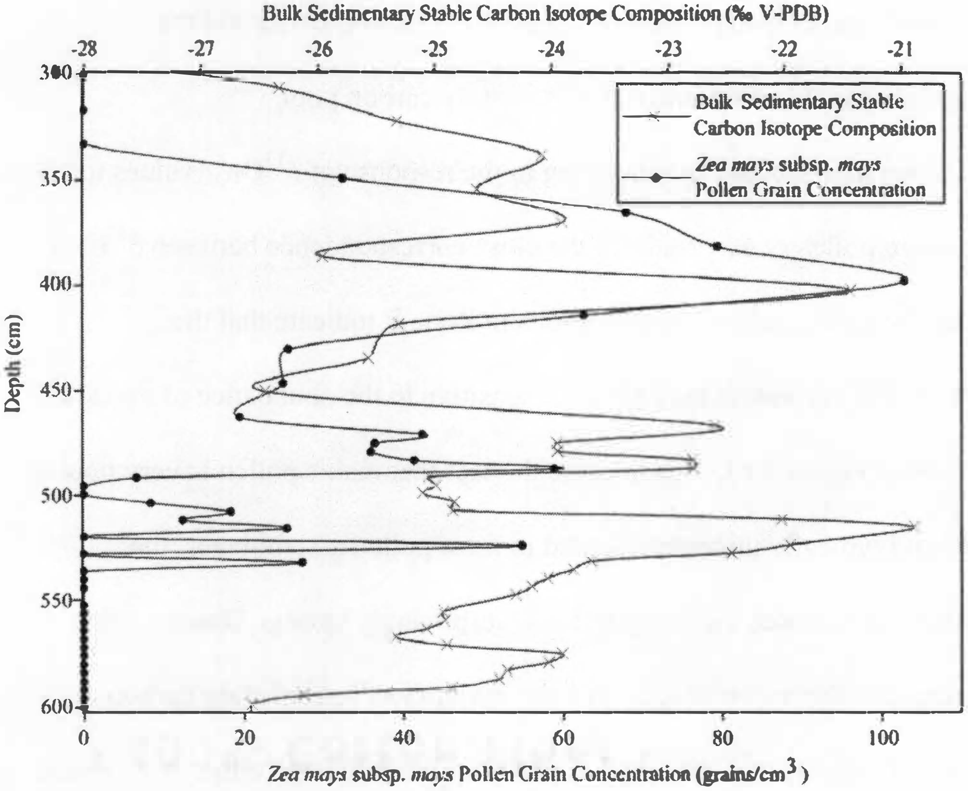


Figure 3.6. Comparison of Laguna Castilla sedimentary $\delta^{13}C_{TOC}$ values and maize pollen concentrations, with $\delta^{13}C_{TOC}$ data graphed 4 cm higher in the profile than actual depths to capture the inherent time lag between the two proxies.

decomposition and delivery of maize tissues to Laguna Castilla and the incorporation of that carbon into the sedimentary carbon pool.

Taking into account the slight lag in the response of $\delta^{13}C_{TOC}$ values to shifting maize pollen concentrations, the close correspondence between $\delta^{13}C_{TOC}$ values and the maize pollen concentrations in Zone E indicate that the sedimentary $\delta^{13}C_{TOC}$ values may be quite sensitive to the abundance of maize in the watershed (Figure 3.6). Considering the fact that maize pollen is very poorly dispersed and typically underrepresented in most pollen assemblages, the correspondence between the two proxies is surprisingly strong. Based on this strong correspondence, we suggest that the majority of sedimentary carbon produced by C_4 plants and entering Laguna Castilla originated either from maize itself, or from C_4 weeds closely associated with maize agriculture.

The strong correspondence between the $\delta^{13}C_{TOC}$ record and mineral influx data indicates that the $\delta^{13}C_{TOC}$ record is also sensitive to variations in allochthonous sediment delivery. Unlike the relationship between the $\delta^{13}C_{TOC}$ record and maize pollen concentrations, there is virtually no lag in the relationship between the $\delta^{13}C_{TOC}$ and mineral influx records. Conceptually, this relationship makes sense because it is ultimately the delivery of allochthonous C_4 carbon that drives the $\delta^{13}C_{TOC}$ record. In other words, the co-variation of the $\delta^{13}C_{TOC}$ and maize pollen concentration records indicate that the $\delta^{13}C_{TOC}$ record is sensitive to variations in the abundance of maize being cultivated within the watershed, but it appears that the efficiency of transport of the organic carbon produced by these terrestrial sources ultimately controls the response of the $\delta^{13}C_{TOC}$ record.

Zone D (460–414 cm): Decreased Prehistoric Human Impact

We hypothesize that Zone D represents a period of decreased human impact in the Laguna Castilla watershed because a decrease in $\delta^{13}C_{TOC}$ values, maize pollen concentrations, and mineral influx values occurred when compared to the previous time interval of Zone E. The $\delta^{13}C_{TOC}$ values and maize pollen concentrations are relatively low throughout Zone D, but mineral influx varies significantly, spiking from a minimum of 156 mg/cm^2/yr to a maximum of 270 mg/cm^2/yr around a depth of 430 cm. The correspondence between the $\delta^{13}C_{TOC}$ and maize pollen concentration data, and the lack of a response in the $\delta^{13}C_{TOC}$ data to the spike in mineral influx around 430 cm, seem to indicate that the $\delta^{13}C_{TOC}$ record is more responsive to variations in the abundance of maize on the landscape than it is to variations in the delivery of allochthonous sedimentary material throughout Zone D.

The exact mechanisms responsible for this departure between the $\delta^{13}C_{TOC}$ record and mineral influx data in Zone D cannot be resolved with the limited analyses conducted here. It is hypothetically possible that the increase in allochthonous sediment delivery around 430 cm was accompanied by a slight increase in the dominance of C_3 plants in the watershed due to the apparent decrease in cultivation during this period. An increased contribution of C_3 organic matter could explain the lack of a response in the $\delta^{13}C_{TOC}$ record.

Zone C (414−382 cm): Maximum Human Impact

Zone C includes very high concentrations of maize pollen and some of the highest $\delta^{13}C_{TOC}$ and mineral influx values in the entire sediment record. All three proxies indicate that the period encompassed in Zone C may have been the period of most severe prehistoric human impacts in the Laguna Castilla watershed.

Much like Zone E, we found a close correspondence between the $\delta^{13}C_{TOC}$ record and the mineral influx data. Perhaps more importantly, a comparison of the isotopic shift ($\Delta^{13}C_{TOC}$) in Zone E to that of Zone C reveals the impact of allochthonous sediment delivery on the $\delta^{13}C_{TOC}$ record. In Zone E, a shift was found in $\delta^{13}C_{TOC}$ values from –24‰ to –21‰ ($\Delta^{13}C_{TOC} = 3$‰) between 515 and 535 cm. Taking into account the slight lag in the response of the $\delta^{13}C_{TOC}$ record (Figure 3.6), this shift is associated with a peak in maize pollen concentrations of approximately 60 grains/cm^3. In Zone D there is a shift in $\delta^{13}C_{TOC}$ values from –25.5‰ to –22.5‰ ($\Delta^{13}C_{TOC} = 3$‰) between 390 and 420 cm. Again taking into account the slight lag in the response of the $\delta^{13}C_{TOC}$ record (Figure 3.6), this shift is associated with a peak in maize pollen concentrations of approximately 100 grains/cm^3. This shift in maize pollen concentrations corresponds to a three-fold increase in the raw number of maize grains observed on two pollen slides. If the concentration of maize pollen in the sediments is a good proxy for maize abundance in the watershed, and if the $\delta^{13}C_{TOC}$ record was primarily responding to the abundance of maize being cultivated within the watershed, then there should hypothetically be a larger isotopic shift in Zone D than that observed in Zone B, but the isotopic shifts are quite similar. However, the peak mineral influx values for Zone B and Zone D are also quite similar. The similarity between the response of the $\delta^{13}C_{TOC}$ record in Zones B and D to the mineral influxes during those periods indicates that allochthonous sediment delivery is potentially the primary control on the amplitude of change observed in the $\delta^{13}C_{TOC}$ record. Again, this is not surprising considering the fact that the amount of C_4 organic matter that enters the lake is ultimately controlled by the size of the carbon source area and efficiency of allochthonous organic matter delivery.

This finding is important because it indicates that the $\delta^{13}C_{TOC}$ value of the sediment alone cannot be used as an accurate representation of the exact amount of maize being cultivated within the watershed without taking into account variations in allochthonous sediment delivery. This does not mean that the $\delta^{13}C_{TOC}$ record is not providing a reliable estimate of the *relative* extent of maize cultivation in the watershed through time (Lane et al., in press), only that developing an accurate estimate of the extent of these activities is not as simple as only analyzing variations in the $\delta^{13}C_{TOC}$ record.

Zone B (382–335 cm): Decreased Human Impact

Compared to Zone C, Zone B marks the beginning of a different relationship between $\delta^{13}C_{TOC}$ values, maize pollen concentrations, and mineral influx in the Laguna Castilla sediment record. Maize pollen concentrations decrease steadily throughout Zone B, but the $\delta^{13}C_{TOC}$ and mineral influx data display little variation. The similarity in the $\delta^{13}C_{TOC}$ record and the mineral influx data seems to indicate that the $\delta^{13}C_{TOC}$ record in Zone B is more sensitive to variations in allochthonous sediment delivery than it is to variations in the abundance of maize on the landscape.

Based on our limited analyses, it is difficult to explain why the $\delta^{13}C_{TOC}$ record appears to be more sensitive to variations in allochthonous sediment delivery than to maize abundance at this time. It is possible that prehistoric human impacts in the Laguna Castilla watershed were so severe through the period encompassed by Zone C that they had an effect on the available terrestrial carbon pool that lasted through the period encompassed by Zone B. If the majority of the Laguna Castilla watershed was deforested and under cultivation during the period encompassed by Zone C, an abundance of C_4 organic matter would have been available for transport into the lake. Thus, even with a decrease in Zone B in the abundance of maize being cultivated, there may still have been a significant component of C_4 organic material in the terrestrial carbon pool available for transport to the lake.

Zone A (335–300 cm): Land Abandonment

Maize pollen deposition in Laguna Castilla terminates at the Zone B/Zone A boundary indicating the cessation of maize agriculture around the lake and apparent abandonment of the watershed around 730 cal yr B.P. (Table 1). Mineral influx and $\delta^{13}C_{TOC}$ values nearly drop to pre-settlement levels indicating decreased watershed erosion and the recovery of C_3-dominated lower montane moist forest. Based on the evidence currently available, it is unclear why the watershed was abandoned at this time.

Conclusions

The stable carbon isotope composition of lake sediments is an effective proxy of prehistoric forest clearance and agriculture in the neotropics, but the development of quantitatively robust reconstructions of these activities will require a more in-depth understanding of the sensitivity of sedimentary $\delta^{13}C_{TOC}$

values to factors such as shifts in the relative dominance of C_3 and C_4 plants and variations in allochthonous carbon delivery. The Laguna Castilla data we present here indicate that sedimentary $\delta^{13}C_{TOC}$ values are temporally sensitive to rapid variations in C_3 and C_4 plant dominance, but may lag the vegetation shifts by a few years. In addition, the close correspondence between sedimentary $\delta^{13}C_{TOC}$ and mineral influx values in Zones E, C, and B of the Laguna Castilla record highlights the sensitivity of sedimentary $\delta^{13}C_{TOC}$ values to variations in allochthonous carbon delivery. More importantly, comparisons between the $\delta^{13}C_{TOC}$ record and the mineral influx data indicate that the amplitudes of shifts in the $\delta^{13}C_{TOC}$ record are intimately linked with variations in allochthonous sediment delivery.

The sensitivity of the sedimentary $\delta^{13}C_{TOC}$ record to the limited number of watershed variables analyzed here further reinforces the need for an increased understanding of carbon dynamics and cycling in lake watersheds. Despite the complexity of the exact response of the sedimentary $\delta^{13}C_{TOC}$ record to numerous watershed variables, the close correspondence between the $\delta^{13}C_{TOC}$ record and maize pollen concentrations indicates that the $\delta^{13}C_{TOC}$ record can be used to reliably assess the *relative* extent of these activities through time. We also believe that this proxy still has enormous potential as a technique that could eventually be used to quantitatively reconstruct the areal extent of anthropogenic forest clearance and crop cultivation in tropical watersheds.

Future analyses that utilize compound-specific isotopic analyses could further refine this technique by providing a purely allochthonous stable carbon isotope record, thereby eliminating any complications brought on by autochthonous carbon isotope variability. In addition, the development of modern analogs, where the areal extent of maize cultivation, erosion rates, sedimentation patterns, and sedimentation rates can all be monitored precisely over relatively short time intervals, could further our understanding of how to best apply this proxy to prehistoric settings.

CHAPTER 4

Multi-Proxy Analysis of Late Holocene Paleoenvironmental Change in the Mid-Elevations of the Cordillera Central, Dominican Republic

This chapter is in preparation for submission to the journal *Quaternary Science Reviews* by me, Sally P. Horn, Claudia I. Mora, and Kenneth H. Orvis. The submitted manuscript will include additional information on the study area that is presented in Chapter 1 of this dissertation. My use of "we" in this chapter refers to my co-authors and myself.

Introduction

Several high-resolution paleoclimate records from sites in the circum-Caribbean region indicate significant climate variation during the middle to late Holocene (e.g. Hodell et al., 1991; 2005a; 2005b; Curtis et al., 1996; 1998; Black et al., 1999; 2004; Haug et al., 2001; Rosenmeier et al., 2002a; Tedesco and Thunell, 2003; Peterson and Haug, 2006). These climate variations have received considerable attention because of the importance of tropical climate dynamics in the global climate system (e.g. Diaz and Markgraf, 2000; Rittenour et al., 2000; Schmidt et al., 2004; Ivanochko et al., 2005) and their potential impact on prehistoric human populations including, most famously, the Mayan civilization (Hodell et al., 1995; 2005a; Gill, 2000; deMenocal, 2001; Haug et al., 2003).

Despite this burgeoning interest and our rapidly expanding knowledge of circum-Caribbean climate change, little is known about the paleoenvironmental and societal impacts of climate variability on the many islands of the Caribbean region. To date, published records of late Holocene paleoenvironmental change are available for just nine island study sites in the eastern Caribbean and tropical north Atlantic: Anse à la Gourde, Guadeloupe (Beets et al., 2006); Church's Blue Hole, Bahamas (Kjellmark, 1996); Grande-Case Lake, St. Martin (Bertran et al., 2004); Laguna de la Leche, Cuba (Peros et al., 2007); Laguna Tortuguero, Puerto Rico (Burney et al., 1994); Lake Antoine, Grenada (McAndrews and Ramcharan, 2003); Lake Miragoane, Haiti (Brenner and Binford, 1988; Hodell et al., 1991; Curtis and Hodell, 1993; Higuera-Gundy et al., 1999); Valle de Bao, Dominican Republic (Kennedy et al., 2006); and Wallywash Great Pond, Jamaica (Street-Perrott et al., 1993; Holmes et al., 1995; Holmes, 1998). With the exception of Valle de Bao, these are all low-elevation, coastal sites, and their distribution leaves a void in our knowledge of the paleoenvironmental history of Caribbean island interiors. Apart from Anse à la Gourde and Lake Miragoane, the majority of these records are also fairly low-resolution records with little or no evidence of prehistoric human activity.

In this study, we present a ~3000 cal yr B.P. record of paleoenvironmental change from a mid-elevation site in the Dominican Republic. We conducted high-resolution analyses of pollen, charcoal, biogenic carbonate macrofossil assemblages and stable isotope geochemistry, and bulk sedimentary stable carbon isotope ratios from sediment cores recovered from two small lakes, Laguna Castilla and Laguna de Salvador, to better understand the climate, vegetation, and human history of the area.

Study Area

Laguna Castilla (18°47'51" N, 70°52'33" W, 976 m) and Laguna de Salvador (18°47'45" N, 70°53'13" W, 990 m) are located on the Caribbean slope of the Cordillera Central in the Dominican Republic (Figure 4.1). Laguna Castilla and Laguna de Salvador are located near the small community of Las Lagunas in the province of Azua. Four lakes exist in the Las Lagunas area, all of which occupy small basins created by slope failures (Figure 4.1). Laguna Castilla (Castilla) and Laguna de Salvador (Salvador) are relatively small lakes with surface areas of approximately 1.2 and 0.5 ha, respectively, but both do have open water. Laguna de Felipe (Felipe; ~0.8) and Laguna Clara (Clara; ~0.4 ha) are similar in size, but choked with aquatic macrophytes and have no open water. Paleoshorelines around Castilla and Salvador evident in aerial photographs indicate lake levels in the past perhaps 1–2 m above current levels.

Climate

The precipitation regime of the Caribbean slope of the Cordillera Central, including the Las Lagunas area, is primarily controlled by the seasonal proximity of the Intertropical Convergence Zone (ITCZ). During the boreal summer, when the ITCZ reaches its northernmost position, convection fed by sea breezes on the southern slope of the Cordillera Central increases as a result of the dominant ITCZ-proximal doldrum conditions. As the ITCZ migrates southward during the boreal winter, the descending arm of the Hadley cell moves over the region, limiting convective activity and decreasing precipitation.

No site-specific meteorological data are available for Las Lagunas. Based on environmental lapse rates calculated for the Cordillera Central by Orvis et al. (1997) and limited meteorological data from the nearby town of Padre Las Casas

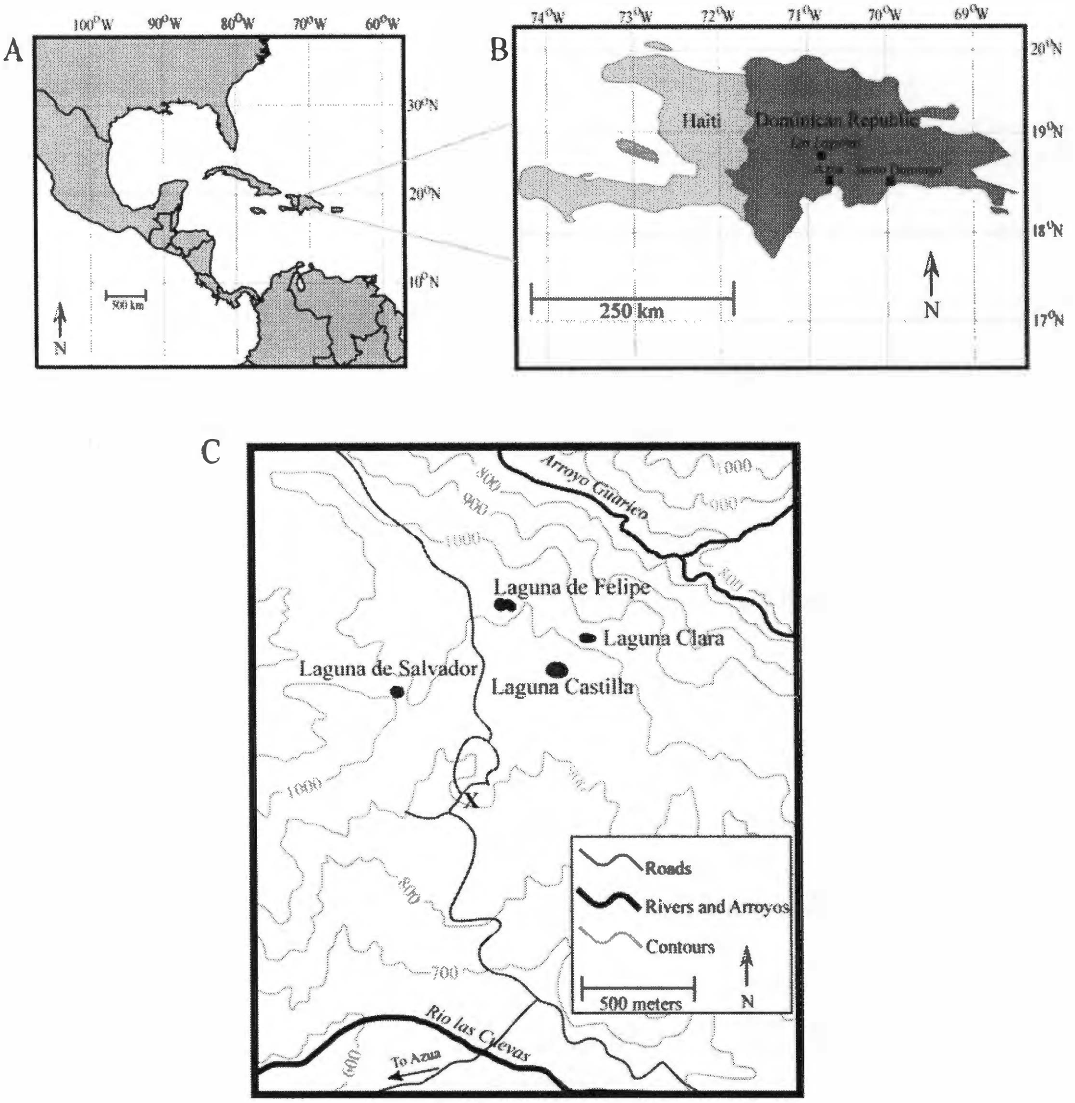


Figure 4.1. The location of the island of Hispaniola (A); Las Lagunas study site within the Dominican Republic, nearby city of Azua, and capital city of Santo Domingo (B); and topographic map of the Las Lagunas area (C). Laguna Castilla and Laguna de Salvador are the focus of this study. The "X" marks the town center of Las Lagunas. Map C is based on the 1:50000 topographic sheet published by the National Geospatial-Intelligence Agency. Lake positions were determined from GPS measurements by K. Orvis.

(~520 m; MAT = 24 °C), the mean annual temperature of the Las Lagunas area is likely to be around 20 °C. The nearest available precipitation data are from the city of Azua 40 km to the south (Figure 4.1), which is more arid because it is lower in elevation (100 m) and subject to a greater rainshadow effect. Based on the mean annual precipitation value for Azua of ~700 mm, we assume that mean annual precipitation values for the Las Lagunas area are somewhere around 900–1000 mm.

Vegetation

The vegetation now surrounding Castilla and Salvador has been heavily modified by modern human activity. People living in the area today cultivate a variety of crops including beans, corn, and coffee, and raise cattle, goats, horses, and chickens. The vegetation currently surrounding the town of Las Lagunas is classified by Tolentino and Peña (1998) as grassland (pasture) and mixed crops and grasslands. Tolentino and Peña classify intact woody vegetation at the same altitude and slope aspect as lower montane moist forest (i.e. the Holdridge life zone designation; Panamerican Union, 1967). Remnant areas of lower montane moist forest include pines (*Pinus occidentalis* Schwartz) mixed with evergreen and deciduous broadleaved trees (Liogier 1981). Naturally occurring broadleaf assemblages likely included species in the genera *Cecropia, Garrya, Ilex, Juglans, Magnolia, Miconia, Mecranium, Meriania, Myrica, Ocotea, Piper, Trema,* and *Weinmannia,* just to name a few, as well as a wide variety of species from the Arecaceae, Poaceae, and Rubiaceae families, and the Urticales order (Bolay, 1997; Kennedy, 2003; Kennedy et al., 2005). Associated herbaceous plants include species in the Amaranthaceae, Asteraceae, Cyperaceae, and Poaceae families (Liogier, 1981; Bolay, 1997; Horn et al., 2001; Kennedy et al., 2005). Emergent aquatic plants currently found in both lakes include *Typha domingensis* Pers. and a variety of species in the Cyperaceae and Poaceae families.

Methods

Sediment Core Retrieval, Sediment Stratigraphy, and Radiocarbon Dating

We recovered a 7.8 m sediment core near the center of Castilla and a 5.2 m sediment core near the center of Salvador during field expeditions in 2002 and 2004. We collected the watery, uppermost sediments at both sites with a PVC tube fitted with a rubber piston, and then extruded, sliced, and bagged this uppermost core section in 2 cm intervals in the field. We recovered deeper sediments in ~1 m sections using a Colinvaux-Vohnaut locking piston corer (Colinvaux et al., 1999). We returned core sections to the University of Tennessee in their original aluminum coring tubes and stored them at 6 °C. We cut the aluminum core tubes lengthwise using a specialized router and sliced the sediments using a thin wire.

We photographed core sections upon opening and described color (Munsell) and textural changes. We determined water content by drying sub-samples overnight at 100 °C, and estimated organic and carbonate content using loss-on-ignition at 550 °C and 1000 °C, respectively (Dean, 1974). Chronologies are based on AMS radiocarbon dates on charcoal, other organic macrofossils, and bulk sediment. Dates were calibrated using the CALIB 5.0 computer program

(Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004). Sedimentation rates were calculated using the weighted means of the calibrated age probability distributions (Telford et al., 2004a; 2004b), and ages for lake sediment horizons located between the positions of radiocarbon-dated materials were calculated using linear interpolation.

Pollen and Microscopic Charcoal Analyses

Sediment cores from Castilla and Salvador were sub-sampled for pollen analysis at regular intervals of approximately 16 cm (some sections were also sampled at finer intervals) and chemically processed using standard techniques (Appendix A; Berglund, 1986; Faegri and Iverson, 1989). Tablets containing *Lycopodium* spores were added as controls (Stockmarr, 1971) and the pollen residues were mounted on microscope slides in silicone oil. Pollen and spores were identified and counted to a minimum of 300 pollen grains, excluding *Typha domingensis* pollen, indeterminate pollen grains, and all spores.

Pollen was identified at 400x magnification based on comparison with pollen reference slides prepared from vouchered plant specimens, and with published pollen descriptions, illustrations, photographs, and keys (Heusser, 1971; Bartlett and Barghoorn, 1973; McAndrews et al., 1973; Markgraf and D'Antoni, 1978; Moore and Webb, 1978; Hooghiemstra, 1984; Horn, 1986; Moore et al., 1991; Roubik and Moreno, 1991). Pollen grains of the order Urticales were classified by pore number, except for *Cecropia* and *Trema*, which were identified to genus. Unknown pollen and spore types were sketched and recorded as morphological types. Algal remains and other microfossils that may indicate paleoenvironmental conditions were also identified. In addition to the full pollen counts, two slides from each level were scanned completely at low-power (100x) magnification for the presence of maize pollen (*Zea mays* subsp. *mays*; Chapter 2).

Microscopic charcoal was tallied during the regular pollen counts. Charcoal was identified as dark (black), opaque, angular fragments. All fragments over 50 μm in length were tallied in one of two size classes (50–125 μm and >125 μm).

Bulk Sedimentary Carbon Isotope Analysis

The Castilla and Salvador sediment cores were sub-sampled for bulk sedimentary stable carbon isotope analysis at the same intervals sampled for pollen. A detailed explanation of our methods can be found in Chapter 3. In short, dried and decalcified sediment samples were combusted under vacuum in quartz tubes in the presence of copper, copper oxide, and a small platinum wire at 800 °C. The rendered CO_2 was purified cryogenically offline and analyzed using a dual-inlet Finnigan MAT Delta-plus mass spectrometer at the University of Tennessee. All carbon isotopic compositions are reported in standard δ-per mil notation relative to the Vienna-Pee Dee belemnite (VPDB) marine-carbonate standard, where:

$$\delta^{13}C \text{ (per mil)} = 1000\ [(R_{sample}/R_{standard}) - 1],$$

$$\text{where } R = {}^{13}C/{}^{12}C.$$

Repeated analyses of the USGS 24 graphite standard indicate that the precision of these analyses are better than ±0.05‰ V-PDB.

Aquatic Macrofossil Extraction

Ostracod valves, charophyte oospores, and gastropod shells were present in some sections of each core. Core sections rich in aquatic macrofossils were identified using a binocular scope, and macrofossils were isolated using nested 500, 250, and 125 µm sieves at 1 cm sampling intervals. Fossil ostracod valves were identified with the assistance of Dr. Jonathan Holmes (University College London). Charophyte oospores were identified based on the descriptions of Wood and Imahori (1964) and Wood (1967). Rare gastropod shells were not identified.

Carbon and Oxygen Isotope Analysis of Biogenic Carbonates

Adult monospecific ostracod valves and calcified charophyte oospores were isolated for carbon and oxygen isotope analysis and cleaned using a soft brush and distilled water. Due to the fragility of these biogenic carbonates, especially the ostracod valves, we avoided ultrasonic cleaning and instead removed any remaining organic matter using a modified version of the methods of Lister (1988) and Diefendorf et al. (2006), which involved roasting the carbonate fossils under vacuum at 375 °C for 3 hours.

The oxygen and carbon isotope compositions of the biogenic carbonates were determined using an automated Finnigan CarboFlo system interfaced with a Finnigan MAT Delta-plus mass spectrometer at the University of Tennessee. Biogenic carbonates were reacted with orthophosphoric acid at 120 °C and the evolved CO_2 was cryogenically purified on-line. Sample masses analyzed on the CarboFlo system were typically about 0.3 mg (approximately 15 *Cythridella* *boldii* ostracod valves, 5 *Candona* sp. ostracod valves, or 20 *Chara haitensis* oospores). All carbon and oxygen isotopic compositions have been temperature corrected to 25 °C and are reported in standard δ-per mil notation relative to the Vienna-Pee Dee belemnite (VPDB) marine-carbonate standard. Precision of the CarboFlo system was determined to be ±0.05‰ for δ^{13}C V-PDB and ±0.10‰ for δ^{18}O V-PDB using several internal laboratory standards.

Results

Sediment Recovery, Stratigraphy, and Chronology

Coring operations at Castilla and Salvador penetrated a complex sequence of sediments of varying texture and organic content (Figures 4.2 and 4.3). The basal sediments of Castilla (781−730 cm) consist of a mixture of coarse gravels, sands, and gleyed silts and clays (5G 4/2 to 10GY 5/1). From 730 to 670 cm, the Castilla sediments consist of organic silts (10YR 2/1) with abundant fibrous organics and sparse sands. A relatively thin layer of coarse fibrous organics and peat (2.5Y 4/2 to 10YR 3/1) extends from 670 to 650 cm. The thin peat layer is overlain by finely laminated organic clays and mineral silts (2.5Y 7/1 to 2.5Y 2/1) from 650 to 610 cm. From 610 cm to 520 cm, the sediments consist of very fine organic clays (10YR 2/1) with abundant fibrous organics. From 610 to 339 cm, the Castilla sediments consist of finely laminated mineral silts and clays (2.5Y 3/1 to 5Y 3/1) capped by a section of mineral clay that slowly grades into organic gyttja. A thin layer of mineral rich silts and clays (10Y 5/2) extends from 339 to 334 cm. The uppermost sediments of the Castilla core (334 to 0 cm sub-bottom)

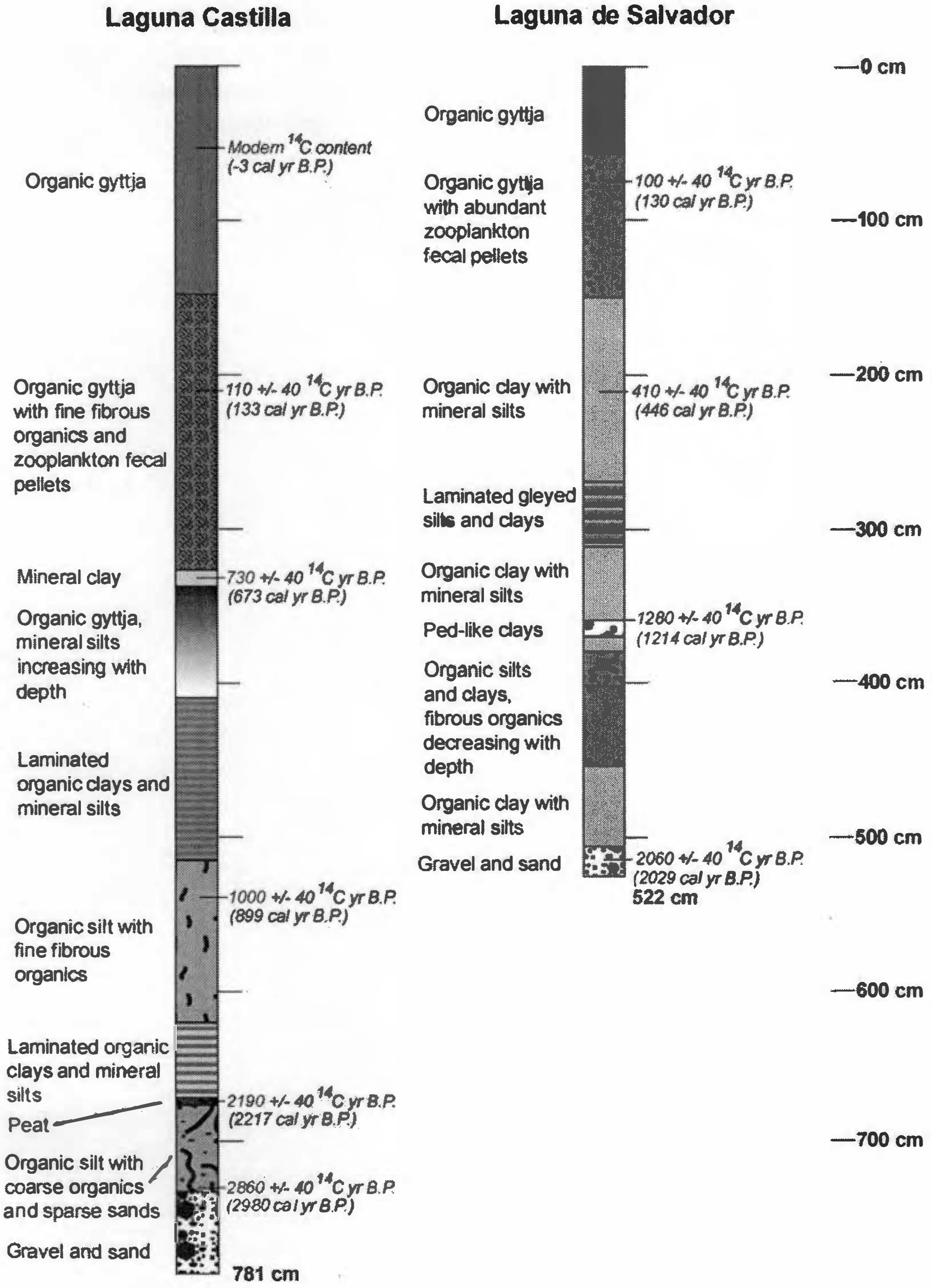
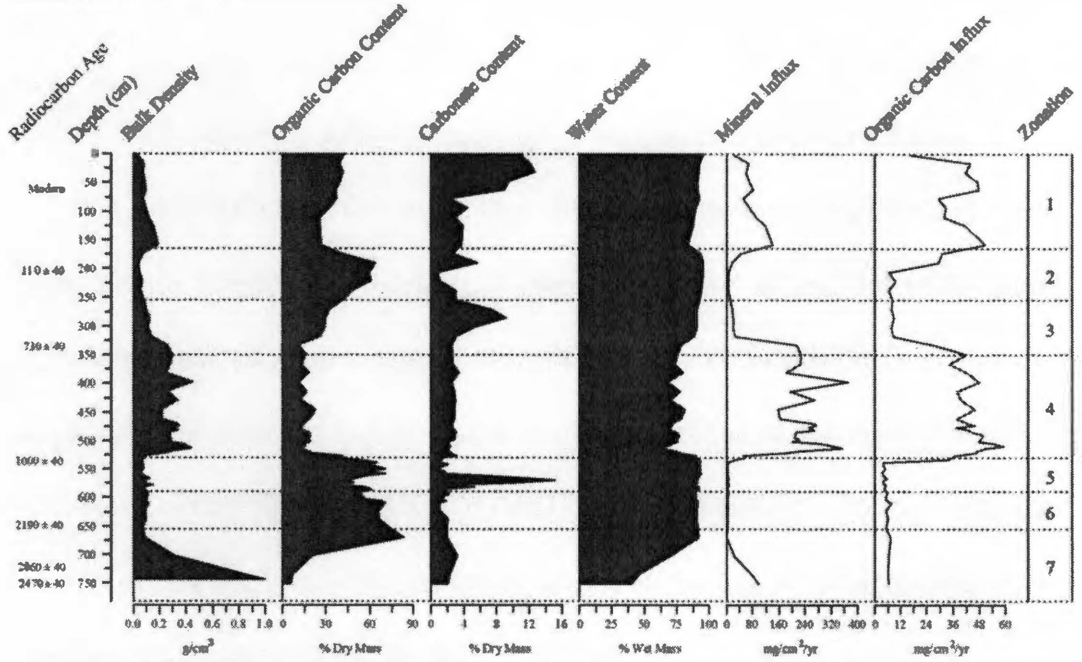


Figure 4.2. Sediment stratigraphy and chronology of the Laguna Castilla and Laguna de Salvador sediment cores. Radiocarbon dates (^{14}C yr B.P.) are italicized and the weighted means of the probability distributions for radiocarbon dates (cal yr B.P.) are in parentheses.

Figure 4.3. Diagram showing sediment bulk density (g/cm^3), organic content (% dry mass), carbonate content (% dry mass), water content (% wet mass), mineral influx (mg/cm^2/yr), and organic carbon influx (mg/cm^2/yr) for the Laguna Castilla and Laguna de Salvador sediment cores. Radiocarbon ages are uncalibrated.

Laguna Castilla



Laguna de Salvador

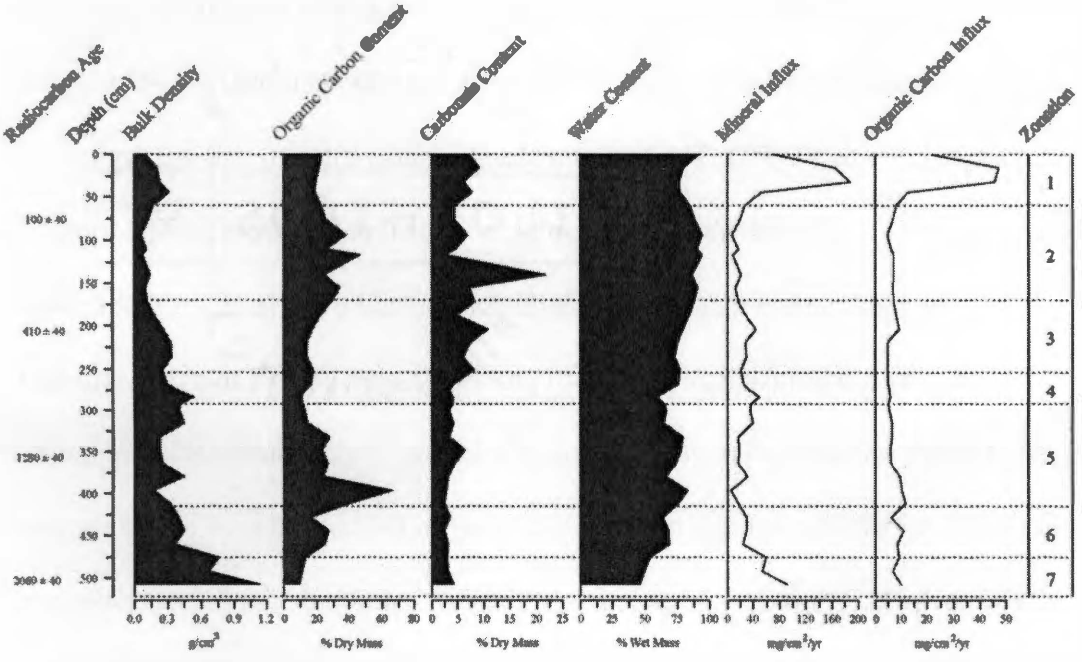


Figure 4.3. Continued.

consist of organic rich gyttja (2.5Y 3/1), with abundant fibrous organics between 334 and 155 cm.

Like the Castilla sediment core, the basal Salvador sediments (522−510 cm) consist of very coarse gravels, sands, and gleyed silts and clays (10Y 5/1). From 510 to 460 cm, the Salvador sediments consist of a mixture of organic and mineral clays and silts (2.5Y 4/1 to 10YR 2/1). Organic rich clay sediments (10YR 2/1) from 460 to 365 cm contain abundant fibrous organics and are capped by a thin layer of coagulated, ped-like clays (10Y 2/1; 365 to 359 cm). From 359 to 310 cm the Salvador sediments consist of organic rich clays and silts (5Y 2.5/1). At approximately 310 cm, we observed an abrupt transition from organic rich sediments to organic rich (2.5Y 2.5/1), mineral rich (5Y 6/2), and gleyed (10Y 2.5/1) clay laminae that extends to 265 cm. From 265 to 150 cm, the Salvador sediments consist of fine mineral silts and clays intermixed with organic clays (2.5Y 3/1 to 5Y 3/1). The uppermost sediments (150 to 0 cm) are organic rich gyttja (5Y 3/2), with abundant zooplankton fecal pellets from 150 to 50 cm.

The radiocarbon dates from Castilla and Salvador are in stratigraphic order except for the lowermost date (β-171501) in the Castilla core (Tables 4.1 and 4.2). The macrofossil dated may have been a root that penetrated older sediments; we have discounted it in our age model. According to the basal date, Castilla formed ~2983 cal yr B.P. Linear interpolation of the radiocarbon data indicates Salvador formed ~1870 cal yr B.P. Sedimentation rates (Figure 4.4) varied through time at both lakes, with higher and more variable sedimentation rates at Castilla.

Table 4.1. Radiocarbon determinations and calibrations for Laguna Castilla.

Lab Number[a]	Depth (cm)	δ^{13}C (‰)	Uncalibrated ^{14}C Age (^{14}C yr BP)	Calibrated Age Range[b] ± 2 σ (cal yr B.P.)	Area Under Probability Curve	Weighted Mean[c] (cal yr B.P.)
β-196817	66–68	–25.6	103.9% of Modern	–1.5 – –4.5*	1.000*	–3*
β-204702	204–207	–24.5	110 ± 40	–1 – –4	0.008	133
				150–10	0.651	
				178–174	0.007	
				273–185	0.333	
β-196818	329–331	–25.9	730 ± 40	585–567	0.063	674
				732–647	0.937	
β-171499	536–537	–24.2	1000 ± 40	975–795	1.000	899
β-192641	651–653	–23.8	2190 ± 40	2077–2070	0.009	2217
				2332–2113	0.991	
β-171500	724–725	–23.2	2860 ± 40	3080–2862	0.970	2983
				3109–3093	0.016	
				3140–3127	0.014	
β-171501	758–761	–25.3	2470 ± 40	2419–2363	0.118	2552
				2623–2428	0.600	
				2713–2628	0.282	

[a] Analyses were performed by Beta Analytic Laboratory. Samples β-196817, β-196818, and β-171499 consisted of bulk sediment; samples β-192641 and β-204702 consisted of a mixture of plant macroremains, insect parts, and charcoal; sample β-171501 consisted of plant macroremains; and sample β-171500 consisted of charcoal.

[b] Calibrations were calculated using Calib 5.0 (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004).

[c] Weighted mean of the calibrated age probability distribution curve.

*Dates were calibrated using the CALIBomb program (Reimer et al., 2004).

Table 4.2. Radiocarbon determinations and calibrations for Laguna de Salvador.

Lab Number[a]	Depth (cm)	$\delta^{13}C$ (‰)	Uncalibrated ^{14}C Age (^{14}C yr BP)	Calibrated Age Range[b] ± 2 σ (cal yr B.P.)	Area Under Probability Curve	Weighted Mean[c] (cal yr B.P.)
β-219035	76.5	–25.7	100 ± 40	–1 – –4	0.013	130
				149–11	0.673	
				270–187	0.315	
β-204696	204	–27.5	410 ± 40	392–319	0.243	446
				523–426	0.757	
β-196821	359	–29.8	1280 ± 40	1109–1089	0.028	1214
				1163–1126	0.065	
				1292–1167	0.907	
β-192645	504	–25.1	2060 ± 40	2133–1926	1.000	2029

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[a] Analyses were performed by Beta Analytic Laboratory. Samples β-219035, β-204696, and β-196821 consisted of wood fragments and sample β-192645 consisted of charcoal.

[b] Calibrations were calculated using Calib 5.0 (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004).

[c] Weighted mean of the calibrated age probability distribution curve.

Figure 4.4. The weighted mean of the calibrated radiocarbon ages (cal yr B.P.) plotted against depth for the Laguna Castilla and Laguna de Salvador sediment cores. Approximate sedimentation rates, labeled in italics and represented by the lines between dates, are estimated by linear interpolation between radiocarbon dates.

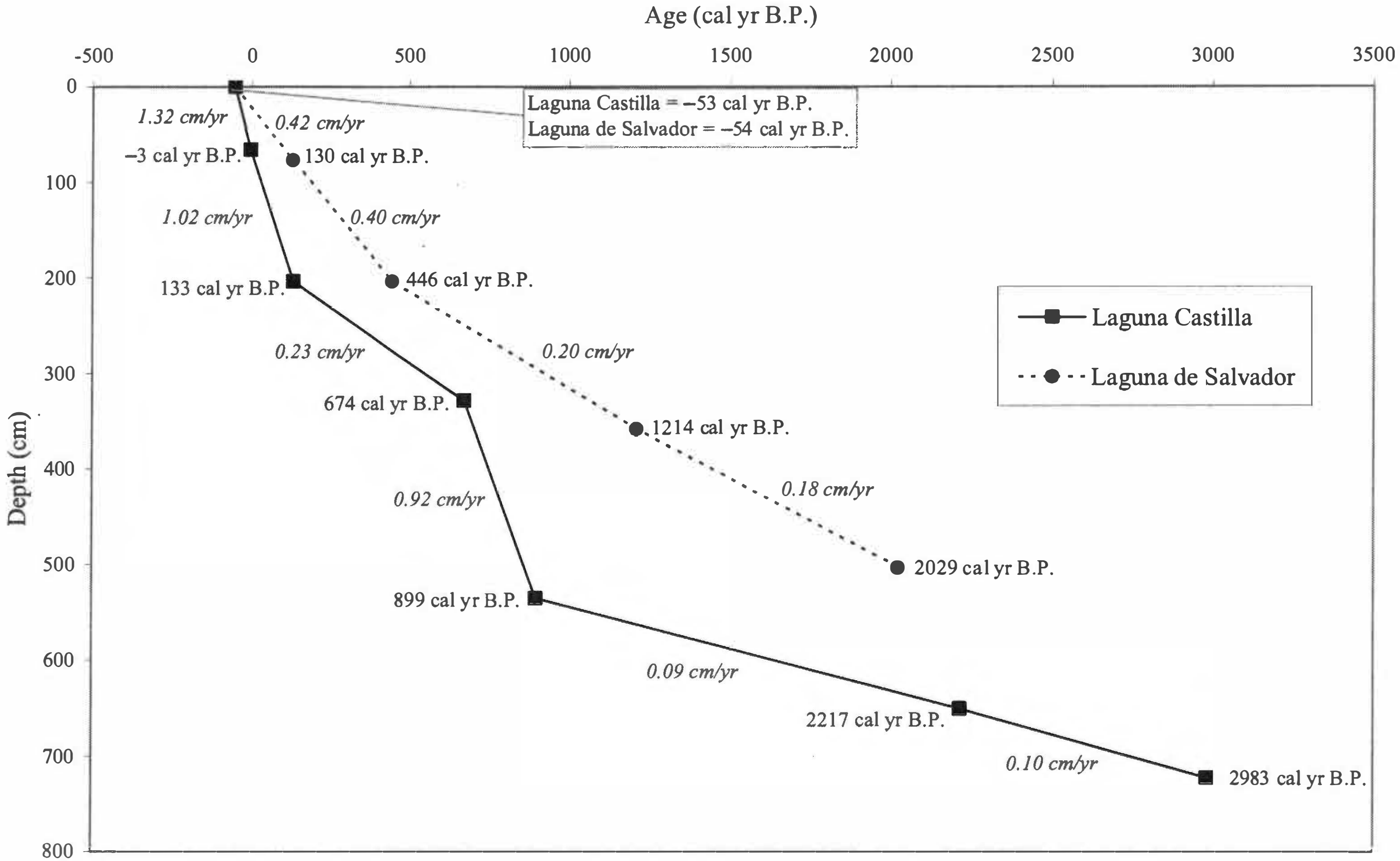


Figure 4.4. Continued.

Zonation

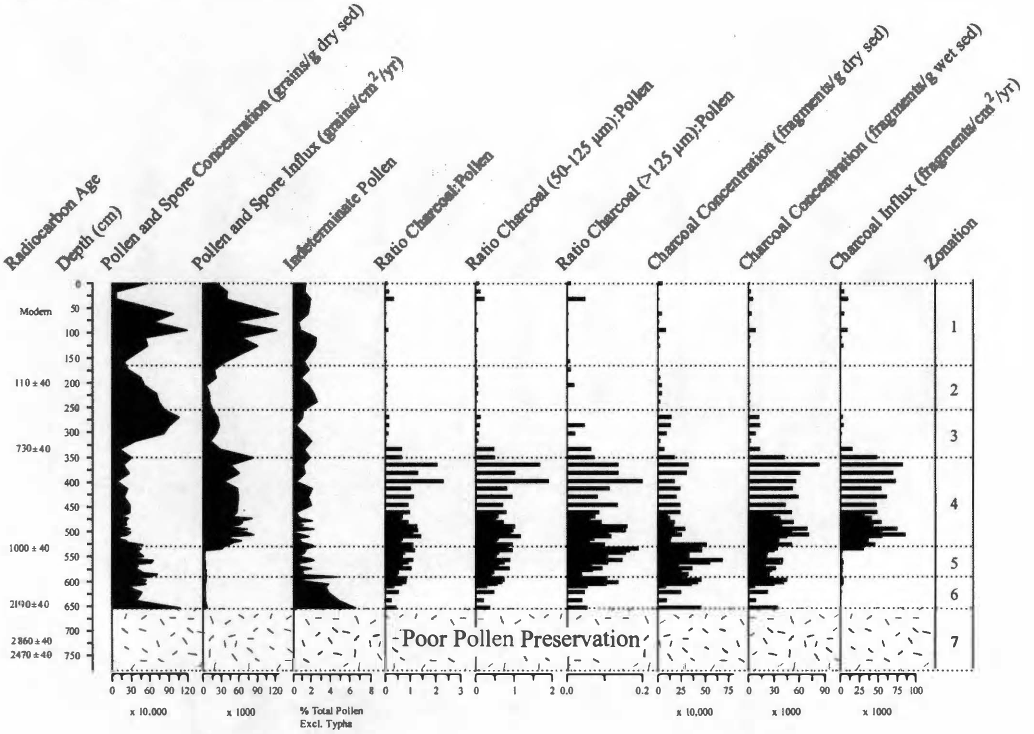
We delineated seven chronological zones across the two sediment records. These zones were based on the interrelationships of proxy data in the records but zone boundaries were positioned based on estimated ages and not correlation of proxy data. Our presentation of sediment stratigraphy did not make use of the zones, because of the complexity of the stratigraphy, but all other proxy data are presented by chronological zone. Zone 7 predates the formation of Salvador.

Pollen and Charcoal

Pollen is poorly preserved in the basal sediments of both cores, but overlying sediments contain abundant and well preserved pollen. Pollen spectra in both cores are generally dominated by *Pinus* and Poaceae, but there is considerable variability in pollen assemblages through time (Figures 4.5–4.7). Zone 6 (~2250–1520 cal yr B.P.) in both records is dominated by arboreal taxa, especially *Pinus*, Urticales, and other broadleaved trees and shrubs. On average, arboreal taxa decrease gradually through Zone 5 (~1520–890 cal yr B.P.), and herbaceous pollen, such as Poaceae and Asteraceae, and charcoal concentrations, influx, and charcoal:pollen ratios increase. Zone 4 (~890–700 cal yr B.P.) marks the first appearance of maize pollen in both sediment records. The appearance of maize pollen in Zone 4 is accompanied by decreases in pollen percentages of arboreal taxa, especially *Pinus*, sharp increases in the percentages of Poaceae and Asteraceae pollen, and increases in charcoal concentrations and influx, particularly in the Castilla record.

Figure 4.5. Diagram showing pollen and spore concentrations, influx, and indeterminate pollen percentages for the Laguna Castilla and Laguna de Salvador sediment records. This diagram also includes charcoal fragments expressed as charcoal:pollen ratios for the >50 µm, >50–125 µm, and >125 µm size categories. Total charcoal concentrations are also expressed as fragments per g dry sediment and fragments per g wet sediment. Total charcoal influx is expressed as fragments per cm^2 per year. Radiocarbon ages are uncalibrated.

Laguna Castilla



Laguna de Salvador

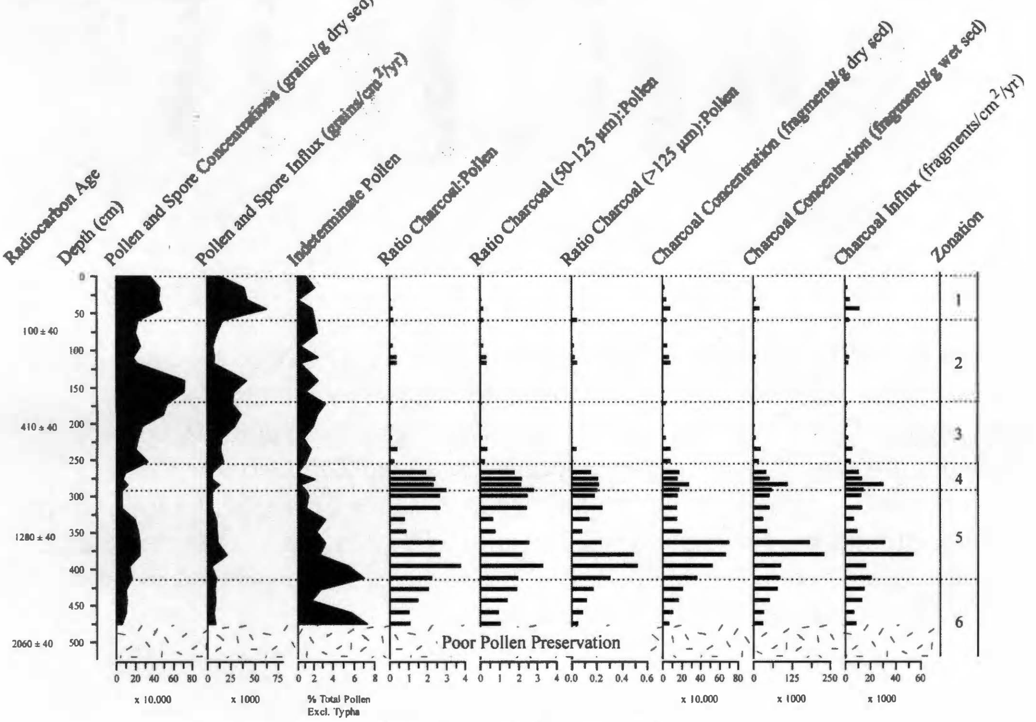


Figure 4.5. Continued.

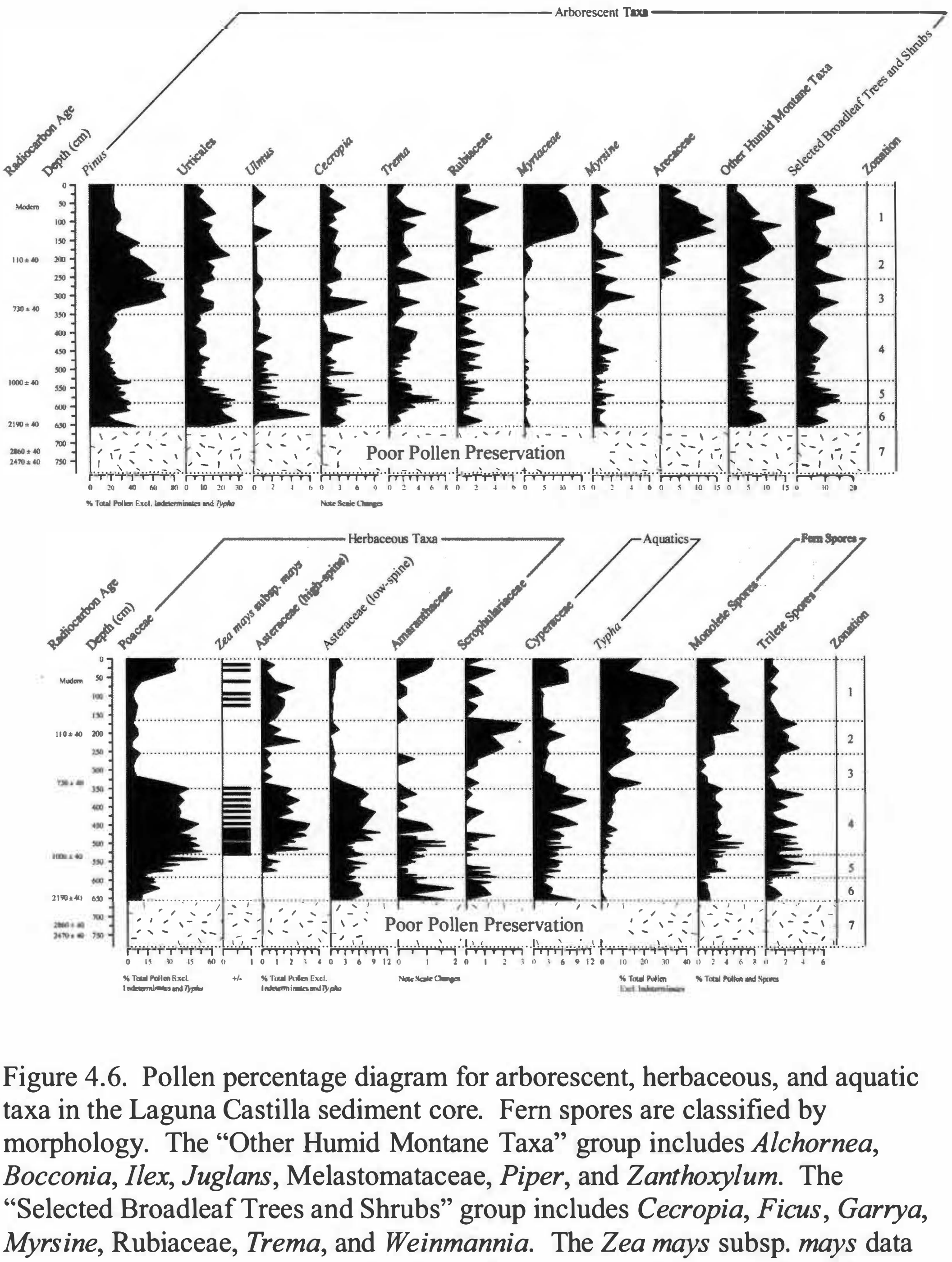


Figure 4.6. Pollen percentage diagram for arborescent, herbaceous, and aquatic taxa in the Laguna Castilla sediment core. Fern spores are classified by morphology. The "Other Humid Montane Taxa" group includes *Alchornea*, *Bocconia*, *Ilex*, *Juglans*, Melastomataceae, *Piper*, and *Zanthoxylum*. The "Selected Broadleaf Trees and Shrubs" group includes *Cecropia*, *Ficus*, *Garrya*, *Myrsine*, Rubiaceae, *Trema*, and *Weinmannia*. The *Zea mays* subsp. *mays* data show the presence or absence of maize pollen on two slides scanned in their entirety. Radiocarbon ages are uncalibrated.

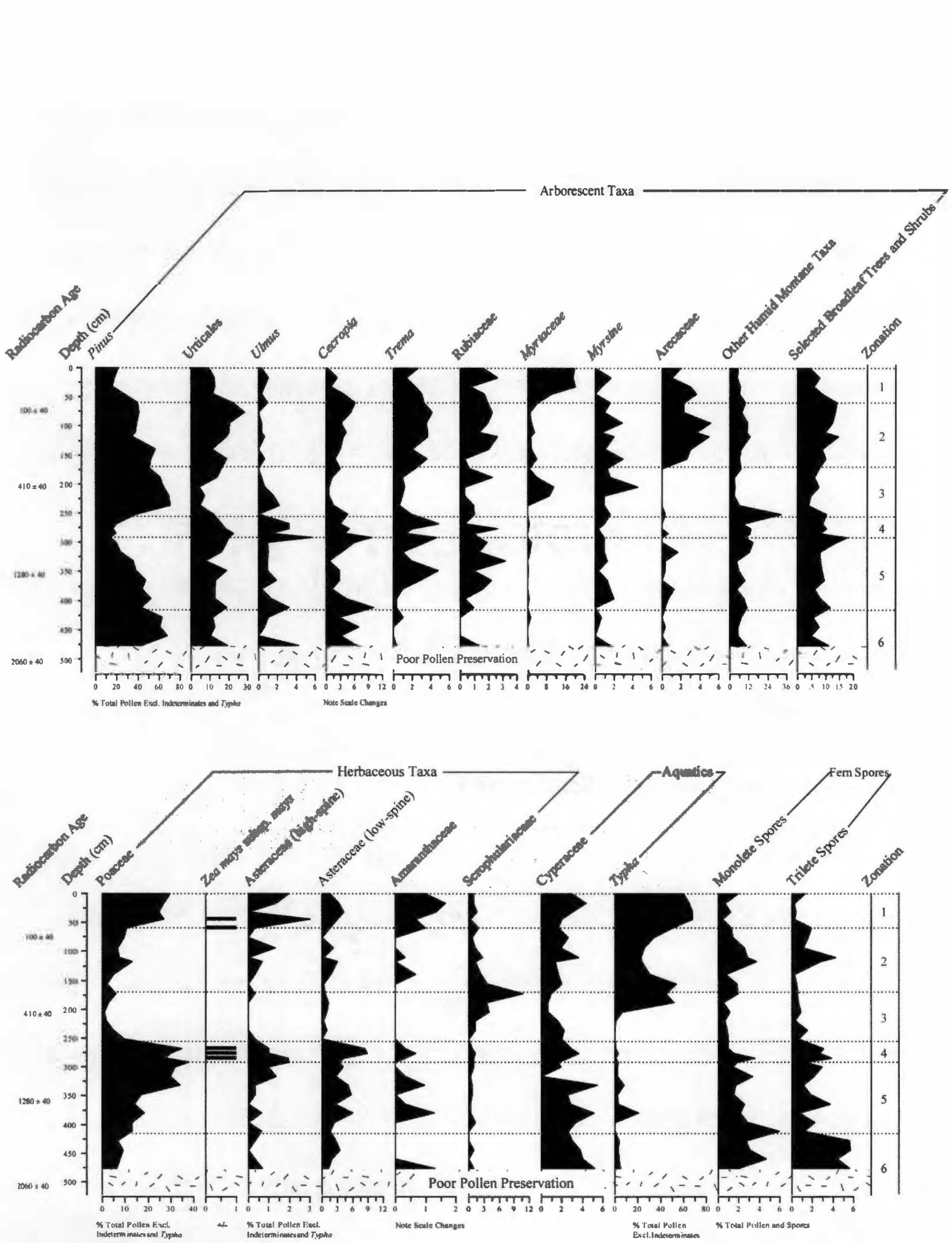


Figure 4.7. Pollen percentage diagram for arborescent, herbaceous, and aquatic taxa of the Laguna de Salvador sediment core. Fern spores are classified by morphology. The "Other Humid Montane Taxa" group includes *Alchornea*, *Bocconia*, *Ilex*, *Juglans*, Melastomataceae, *Piper*, and *Zanthoxylum*. The "Selected Broadleaf Trees and Shrubs" group includes *Cecropia*, *Ficus*, *Garrya*, *Myrsine*, Rubiaceae, *Trema*, and *Weinmannia*. The *Zea mays* subsp. *mays* data show the presence or absence of maize pollen on two slides scanned in their entirety. Radiocarbon ages are uncalibrated.

Zone 3 (700–350 cal yr B.P.) marks the disappearance of maize pollen, a sharp decrease in the abundance of herbaceous pollen, the highest percentages of *Pinus* pollen in the entirety of the sediment records (~70%), and a sharp decrease in the amount of charcoal entering the lakes (Figure 4.5). Zone 2 (~350–95 cal yr B.P.) encompasses a period of decreasing *Pinus* percentages and increasing percentages of pollen of broadleaf trees and shrubs (e.g. Urticales, *Cecropia*, *Trema*, Rubiaceae, Arecaceae). Zone 1 (~95 to –54 cal yr B.P.) marks the reappearance of maize and a subsequent decrease in pollen of arboreal taxa. Zone 1 also includes a conspicuous peak in the abundance of Myrtaceae and *Typha* pollen in both sediment records.

Bulk Sedimentary Stable Carbon Isotopes

The $\delta^{13}C_{TOC}$ values in both cores vary markedly with depth (Figure 4.8). On average, the Salvador sediments have more negative $\delta^{13}C_{TOC}$ values (avg = –26.0‰) than do the Castilla sediments (avg = –24.6‰). Zone 7 (~2980–2250 cal yr B.P.) in Castilla is typified by relatively high $\delta^{13}C_{TOC}$ values (approximately –19‰) followed by a gradual decrease through Zone 6 (~2250–1520 cal yr B.P.) to around –27.5‰. Salvador $\delta^{13}C_{TOC}$ values are also relatively high in the lowermost sediments of Zone 6 (approximately –18‰) and decrease steadily upcore to around –25.5‰ at the Zone 6/Zone 5 boundary. The $\delta^{13}C_{TOC}$ values then increase steadily in both Castilla and Salvador through Zone 5 (~1520–890 cal yr B.P.), with the exception of a large negative excursion in the Salvador $\delta^{13}C_{TOC}$ record around 350 cm depth. The $\delta^{13}C_{TOC}$ record becomes increasingly complex in Zone 4 (~890–700 cal yr B.P.), especially in the Castilla profile where

Figure 4.8. Stable carbon isotope composition of bulk sediments from Laguna Castilla (A) and Laguna de Salvador (B) plotted against depth and plotted against calibrated age (C). Radiocarbon ages in A and B are uncalibrated.

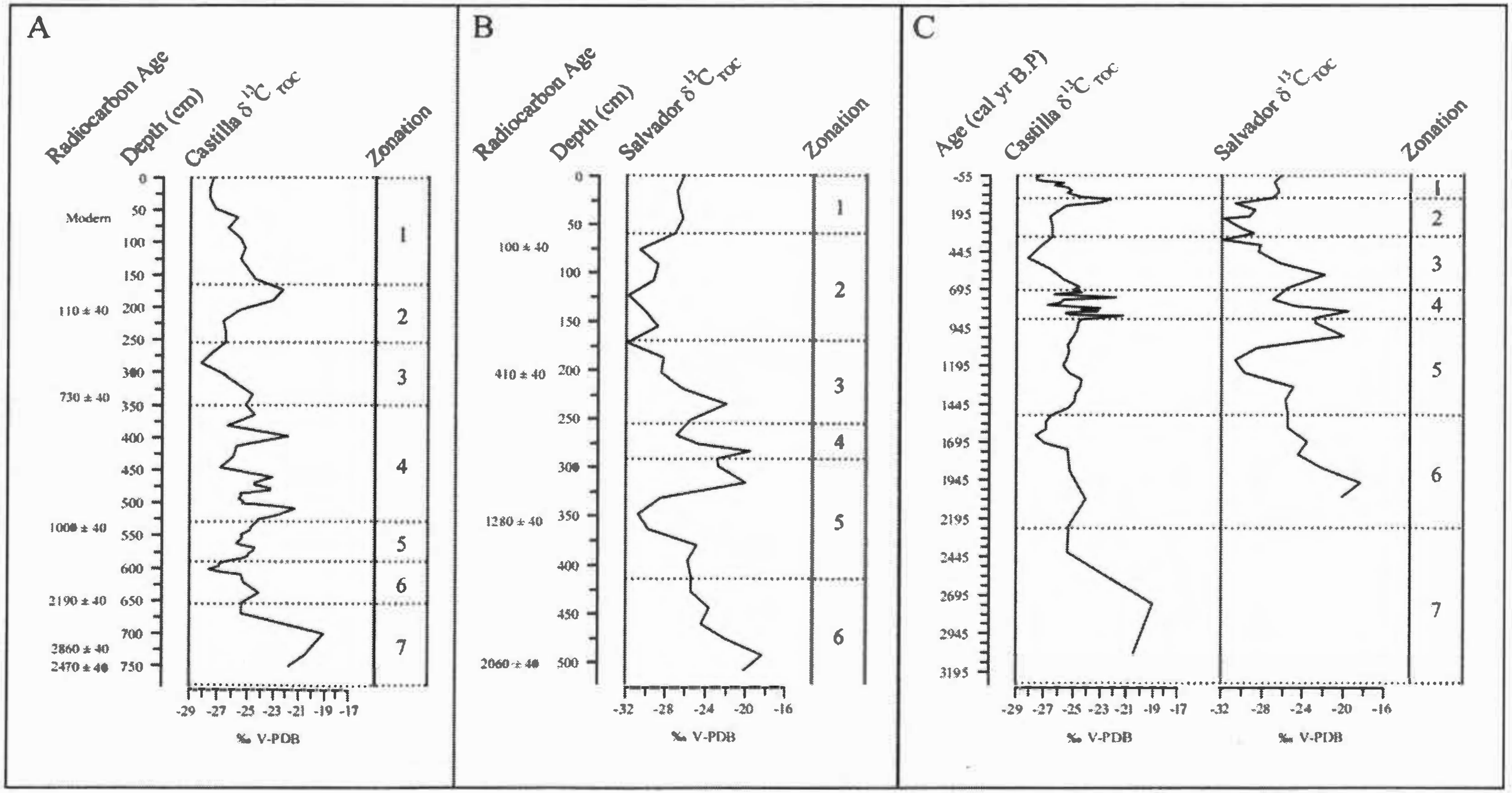


Figure 4.8. Continued.

$\delta^{13}C_{TOC}$ values range from a minimum of –26.5‰ to a maximum of –20.9‰ and are highly variable. The $\delta^{13}C_{TOC}$ values decrease through Zone 3 (700–350 cal yr B.P.) in both profiles, reaching a minimum of –31.9‰ in the Salvador record, but then increase in Zone 2 (350–95 cal yr B.P.), reaching a maximum of –21.8‰ in the Castilla record. Finally, in Zone 1 (95 to –54 cal yr B.P.) there is a decrease in the $\delta^{13}C_{TOC}$ signatures of Castilla from –21.8 to –27.3‰ and an increase in the $\delta^{13}C_{TOC}$ signatures of the Salvador sediments from –27.1 to –26.2‰.

Aquatic Macrofossils

Four different types of aquatic macrofossils were isolated from the Castilla and Salvador sediments, each occurring in only limited portions of the cores. The Castilla sediments contain only fossil valves and carapaces of the benthic ostracod *Cythridella boldii* Purper. The Salvador sediment record contains a greater variety of aquatic macrofossils, including *C. boldii* and *Candona* sp. ostracod valves and carapaces, calcified and non-calcified oospores from the charophyte *Chara haitensis* Turpin, and a very limited number of unidentified gastropods.

In the Castilla sediment core, *Cythridella boldii* valves are found exclusively in Zones 2–5, clustered in three distinct depth intervals (Figure 4.9). Valve concentrations of *C. boldii* reach their maximum values in the Castilla sediment record (~2.6 valves/cc wet sediment) between 600 and 515 cm depth. Between 300 and 265 cm, *C. boldii* valve concentrations range from 0 to 0.3 valves/cc wet sediment. From 240 to 190 cm, *C. boldii* valve concentrations range from 0 to 0.7 valves/cc wet sediment.

Figure 4.9. (A) Concentration (valves per cm^3 wet sediment) of *Cythridella boldii* ostracod valves and the carbon and oxygen isotope composition of *C. boldii* valves in the Laguna Castilla sediment core. Dashed lines indicate sections of discontinuous fossil occurrence where *C. boldii* valves were too sparse for isotopic analysis. Radiocarbon ages are uncalibrated. (B) Carbon and oxygen isotope composition of *C. boldii* valves in Zones 2 and 3 of the Castilla sediment record. (C) Carbon and oxygen isotope composition of *C. boldii* valves in Zones 4 and 5 of the Castilla sediment record. Error bar symbols in graphs B and C indicate the interval sampled to obtain enough material for isotopic analysis.

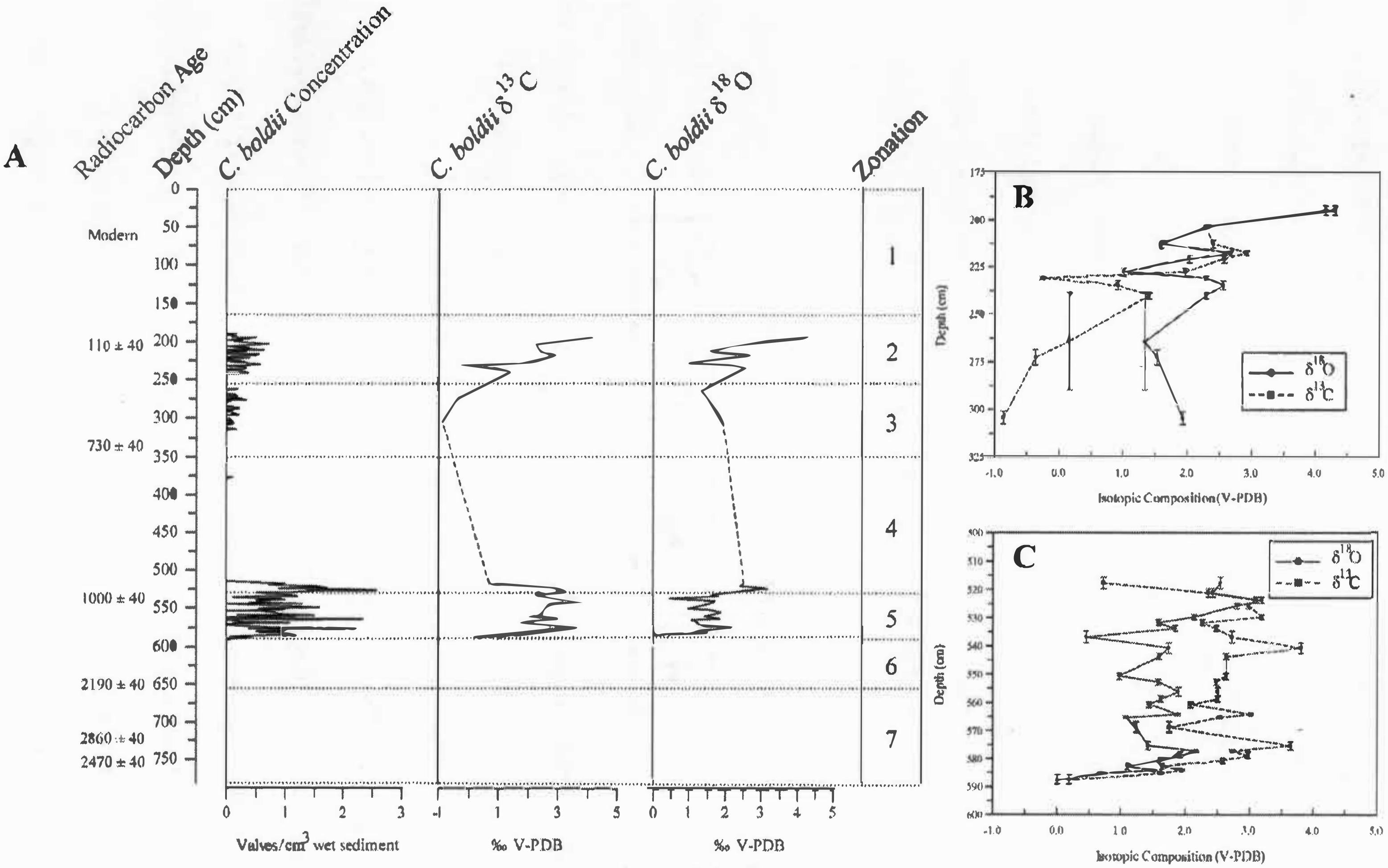


Figure 4.9. Continued.

Biogenic carbonates are found in Zones 1–5 in the Salvador sediment core. The most abundant aquatic macrofossils in the Salvador sediment core are from the charophyte *Chara haitensis* (Figure 4.10), some of which are encrusted in calcium carbonate. Oospore concentrations reach their maximum (~19 oospores/cc wet sediment) between 50 and 110 cm depth. *Chara* oospores are also present in the 185−130 and 375−320 cm depth intervals. *Candona* sp. ostracod valves also occur sporadically throughout much of the Salvador sediment core in relatively low concentrations (Figure 4.10). *Cythridella boldii* ostracod valves are only present in the Salvador sediment core between 150 and 45 cm depth.

Isotopic Analyses of Biogenic Carbonates

The low concentrations of biogenic carbonates in the Castilla and Salvador sediment cores made it necessary to combine monospecific biogenic carbonates from adjacent sub-samples to obtain adequate masses for isotopic analysis (Table 4.3). The oxygen ($\delta^{18}O_{cyth}$) and carbon ($\delta^{13}C_{cyth}$) isotopic composition of *Cythridella boldii* ostracod valves varies markedly throughout the Castilla sediment record (Figure 4.9), with $\delta^{18}O_{cyth}$ values from 0.0 to 4.3‰ and $\delta^{13}C_{cyth}$ values from –0.9 to 4.2‰. The $\delta^{18}O_{cyth}$ and $\delta^{13}C_{cyth}$ values of valves isolated from the Salvador sediment core (Figure 4.10) tend to be more negative, varying between –2.2 and 4.1‰ and –6.8 to –2.8‰, respectively. For the most part, the $\delta^{18}O$ and $\delta^{13}C$ trends covary in each of the sediment cores (Figures 4.9 and 4.10). This covariation is typical of carbonates forming in closed basin lakes (Talbot, 1990).

Figure 4.10. (A) Concentration (valves per cm^3 wet sediment) of *Cythridella boldii* and *Candona* sp. ostracod valves and the carbon and oxygen isotope composition of *C. boldii* and *Candona* sp. valves in the Laguna de Salvador sediment core. Also included are the concentrations of *Chara haitensis* oospores (oospores per cm^3 wet sediment), calcified oospores, and non-calcified oospores, and the carbon and oxygen isotope composition of calcified oospores. Dashed lines indicate sections of discontinuous fossil occurrence where biogenic carbonates were too sparse for isotopic analysis. Radiocarbon ages are uncalibrated. (B) Stable carbon and oxygen composition of *C. boldii* valves in the Laguna de Salvador sediment record. (C) Stable carbon and oxygen isotope composition of *Candona sp.* valves in the Laguna de Salvador sediment record. (D) Stable carbon and oxygen isotope composition of calcified *C. haitensis* oospores in the Laguna de Salvador sediment record. Error bar symbols in graphs B, C, and D indicate the interval sampled to obtain enough material for isotopic analysis.

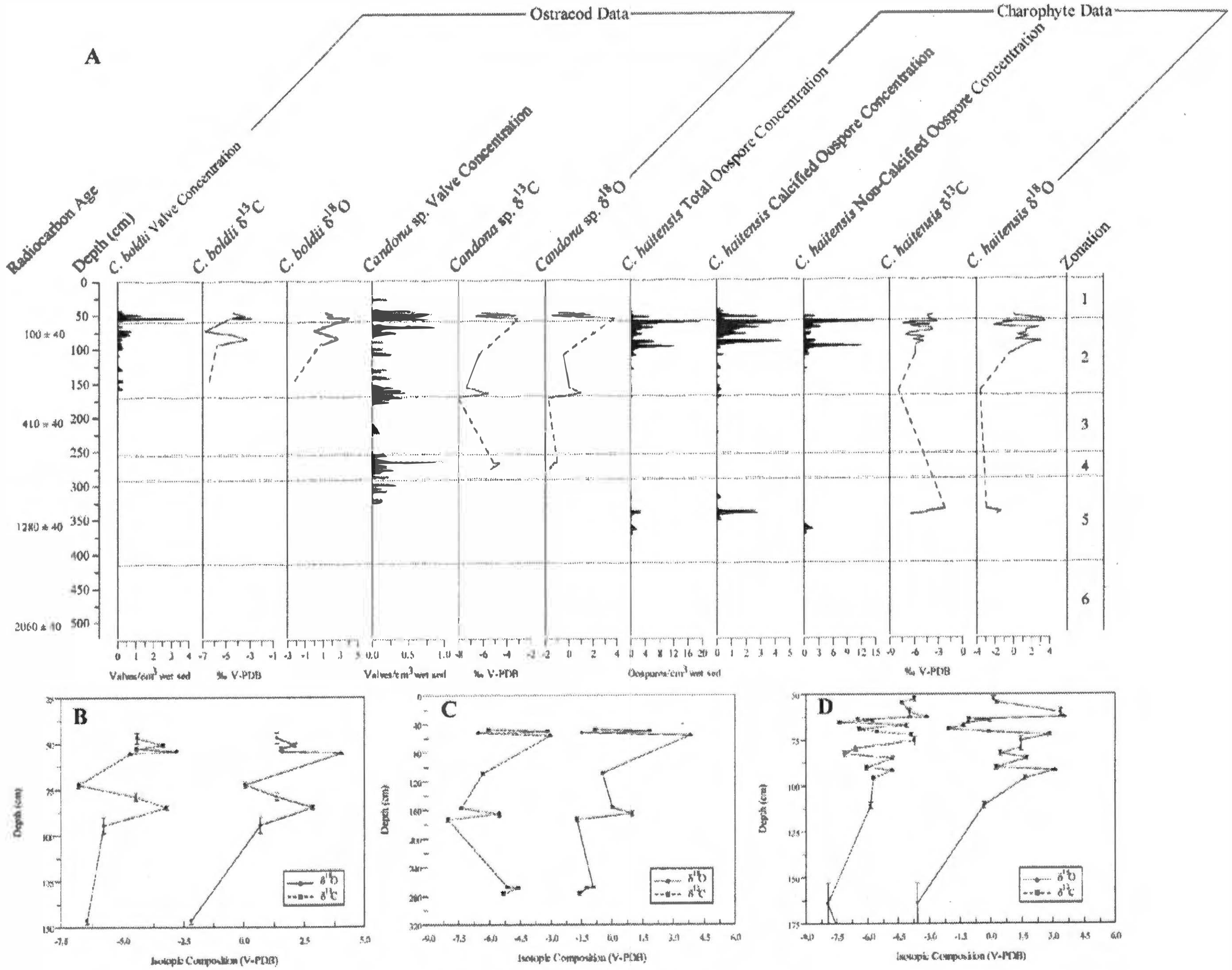


Figure 4.10. Continued.

Table 4.3. Biogenic carbonate isotope sampling information.

Lake		Average Sample Depth Interval (cm)	Average Sample Age Interval (cal yrs)
Laguna Castilla			
	Cythridella boldii	4.1	23.5
Laguna de Salvador			
	Cythridella boldii	3.3	8.1
	Chara haitensis	3.0	8.6
	Candona sp.	3.1	9.1

The oxygen ($\delta^{18}O_{chara}$) and carbon ($\delta^{13}C_{chara}$) isotopic composition of calcified *Chara haitensis* oospores vary markedly throughout the Salvador record. The $\delta^{18}O_{chara}$ values range from a minimum of –3.6 to a maximum 3.5‰ and the $\delta^{13}C_{chara}$ values range from –7.4 to –3.1‰. The oxygen ($\delta^{18}O_{cand}$) and carbon ($\delta^{13}C_{cand}$) isotopic composition of *Candona* sp. ostracod valves in the Salvador record are also highly variable, ranging from –1.7 to 3.9‰.

Discussion

Proxy Interpretation

Pollen

Modern pollen studies are rare in the Caribbean and only one modern pollen study has been undertaken on the island of Hispaniola. Kennedy et al. (2005) investigated modern pollen rain as revealed by surface samples collected in the high elevations of the Cordillera Central in the Dominican Republic. Two sample sites were in humid montane broadleaf forest located ~30 km north of Las Lagunas. Due to the similar elevations and climates of these humid montane broadleaf forest modern pollen sample sites and the Las Lagunas lakes, we expect similar vegetation assemblages and pollen rain at both locations. Arboreal pollen rain at the humid montane broadleaf forest sites was dominated by *Pinus*, *Myrsine*, *Brunellia/Weinmannia*, *Ilex*, and Urticales pollen, and herbaceous pollen rain was dominated by Poaceae, Amaranthaceae, and *Begonia* pollen. The samples also contained relatively high fern spore concentrations compared to surface pollen samples from other high-elevation sites analyzed by Kennedy et al. (2005). Kennedy et al. also reported high percentages of *Pinus* pollen from all of their surface pollen sampling sites regardless of the local importance of *Pinus occidentalis*, and attributed this to long-distance transport of pine pollen.

Stable Carbon Isotopes

Analyses of the carbon isotopic compositions of lacustrine sediments require an understanding of the possible sources of carbon entering a lake or bog. Stuiver (1975) suggested three sources of organic carbon that can be incorporated into lake sediments: terrestrial plants, submerged aquatic organisms, and pondweeds or other emergent plants. The isotopic composition of these organic carbon sources typically determines the $\delta^{13}C_{TOC}$ value of lake sediments, and the type of photosynthetic pathway used by these various carbon sources is of particular importance.

The Poaceae family, and a few other plant families such as the Cyperaceae (Deines, 1980; Boom et al., 2001), contain genera that utilize the C_4 photosynthetic pathway. This mode of photosynthesis seems to be most advantageous under warm and dry conditions, in periods of decreased partial pressures of atmospheric CO_2 (Ehleringer et al., 1997; Collatz et al., 1998), and also possibly in locations where warm season precipitation dominates (Huang et al., 2001). The C_4 photosynthetic pathway may also be favored in tropical localities following land clearance and crop cultivation by humans (Lane et al., 2004; in press). Plants using the C_4 photosynthetic pathway produce carbon isotopic compositions distinct from those of plants using the more common C_3 pathway or the somewhat rare CAM photosynthetic pathway. The distinct carbon isotope ratios of these plants are then incorporated in the terrestrial component of the sedimentary organic carbon pool. Although some plants using the CAM photosynthetic pathway can produce organic matter with $\delta^{13}C$ values that overlap with that of organic matter produced by C_4 plants, CAM plants are typically small contributors to the terrestrial organic carbon pool in mesic tropical forests.

Plants using the C_4 pathway produce organic tissues with $\delta^{13}C$ values ranging from –17 to –9‰, averaging –12‰, while C_3 species produce a $\delta^{13}C$ value ranging from –32 to –20‰, averaging –27‰ (Bender, 1971; O'Leary, 1981). Plants using CAM photosynthesis typically produce values intermediate between these two ranges, but CAM plants are typically small contributors to the organic carbon pool of most ecosystems. The distinct ranges of these carbon isotope ratios allow for the evaluation of the past abundances of C_3 vs. C_4 plants in the watershed of a particular lake or bog from sediment isotope profiles as long as those plants contribute to the organic matter contained in the lake or bog sediments.

Terrestrial vegetation is not the only organic carbon source contributing to lake sediments. Autochthonous organic matter from aquatic organisms is also present and can confound $\delta^{13}C_{TOC}$ records. Talbot and Johannessen (1992) pointed out one such complication produced by aquatic organisms capable of using a HCO^-_3-based metabolism. Under highly alkaline or saline conditions, some aquatic plants and algae will begin to utilize a HCO^-_3-based metabolism (Smith and Walker, 1980; Lucas, 1983). Photosynthesis utilizing this metabolic pathway can produces organic matter that is enriched in ^{13}C (Smith and Walker, 1980), mimicking the composition of C_4 terrestrial material. Under arid conditions, when lake levels drop, increased alkalinity and salinity may promote HCO^-_3-based photosynthesis. The resulting isotopic enrichment in $\delta^{13}C_{TOC}$ may result in an overestimation of C_4 plant dominance (Brincat et al., 2000).

Aquatic Macrofossils

The modern distribution and habitat preference of the ostracod *Cythridella boldii* has not been well defined. Specimens of *C. boldii* have been collected from Lake Valencia, Venezuela (Curtis et al., 1999) and from the Enriquillo Valley, Dominican Republic (Purper, 1974). *Cythridella boldii* is known to be a non-swimming species of ostracod and a profundal burrower (Curtis et al., 1999). Curtis et al. (1999) documented the presence of *C. boldii* valves at a water depth of 9.4 m in Lake Valencia.

The cogener *Cythridella illosvayi* has been studied in more detail and used in several paleolimnological studies. Holmes (1997) documented the presence of *C. illosvayi* along the coastal margin of Wallywash Great Pond, Jamaica, where emergent macrophytes dominate the shallow waters. Based on this modern distribution, Holmes (1998) used the presence of *C. illosvayi* in the Wallywash Great Pond sediment record as an indicator of decreased water levels. However, *C. illosvayi* ostracod valves have also been recovered from greater depths in Lake Punta Laguna, Mexico (6.3 m; Curtis et al., 1996), Lake Peten-Itza, Guatemala (7.6 m; Curtis et al., 1998), and Little Salt Spring, Florida (70 m; Zarikian et al., 2005). Thus, it seems that water depth alone does not control the distribution of *C. illosvayi*.

The identification of ostracod species in the genus *Candona* from shell morphology alone is difficult, and we lack collections of living specimens from the Las Lagunas lakes that would make species identification possible. Species of *Candona* are found throughout the world in a wide variety of habitats, thus their occurrence does not constrain paleolimnological conditions in Castilla or Salvador. However, variable preservation and changes in the isotopic composition of these valves may indicate shifting hydrological conditions in the lakes (see discussion below).

The habitat preference and geographic distribution of the charophyte *Chara haitensis* are also poorly understood and we have not made any paleolimnological interpretations based on its occurrence. The type specimen of *C. haitensis* was collected in Haiti. Proctor et al. (1971) suggested that the geographic range of *C. haitensis* is centered in the neotropics and that the species is restricted to the western hemisphere.

Preliminary analyses of aquatic macrofossils in near-surface sediments collected from all four lakes in the Las Lagunas area (Laguna Castilla, Laguna de Salvador, Laguna de Felipe, and Laguna Clara) indicate that the presence of ostracods and charophytes is probably more dependent upon water chemistry than habitat availability (Thomason et al., 2007). The presence of calcified oospores and calcite-encrusted charophytes is likely to be indicative of Ca^{2+} ion saturation in the water column (Dean, 1981; Delorme, 1991). Currently, ostracod and charophyte macrofossils are only found in significant numbers in the near-surface sediments of Laguna de Felipe, which has the highest Ca^{2+} ion concentrations of

Table 4.4. Selected limnological data for the lakes of Las Lagunas. Water samples were collected in January 2004

	Laguna Castilla	Laguna de Salvador	Laguna de Felipe	Laguna Clara
Surface Area[a]	1.2 ha	0.5 ha	0.8 ha	0.4 ha
Water Depth	4.5 m	2.8 m	1.8 m	1.1 m
Water Temperature[b]	21.7 °C	20.2 °C	20.3 °C	20.0 °C
pH[c]	7.9	8.1	7.6	6.8
Ca^{2+} Ion Concentration[d]	32.9 ppm	52.4 ppm	88.1 ppm	15.2 ppm
$\delta^{18}O$ (V-SMOW)[e]	−27.6‰	−28.1‰	−32.7‰	−32.5‰
$\delta^{18}O$ (V-PDB)[e]	2.4‰	1.9‰	−2.8‰	−2.5‰
Biogenic Carbonates[f]	No	No	Yes	No

[a] Surface areas were estimated based on GPS measurements by K. Orvis.

[b] Water temperature was measured using a YSI model 55 meter.

[c] pH was measured with an Oakton pH meter.

[d] Chemical analyses were conducted by the University of Wisconsin Soil and Plant Analysis Lab.

[e] Isotope measurements were conducted by the Department of Earth and Planetary Sciences Stable Isotope Lab at the University of Tennessee.

[f] Presence or absence in the uppermost surface sediments.

the four Las Lagunas lakes (Table 4.4). Thus, we interpret the presence of ostracod and charophyte macrofossils in the Castilla and Salvador sediment records as an indication of increased Ca^{2+} ion concentrations, which were, in turn, variations most likely controlled by changing lake levels, with decreased lake levels increasing the concentration of Ca^{2+} ions in the water column and vice versa.

Oxygen and Carbon Isotope Composition of Biogenic Carbonates

The oxygen isotope composition of an ostracod carapace is primarily dependent on the $\delta^{18}O$ composition of the water and the temperature at which carbonate precipitation occurs (Craig, 1965; Stuiver, 1970). In tropical, closed-basin lakes with a seasonally dry climate, the $\delta^{18}O$ value of the lake water is controlled primarily by the evaporation to precipitation ratio (E/P) of the lake (Fontes and Gonfiantini, 1967; Gasse et al., 1990). In some cases, landscape changes, such as widespread watershed deforestation, can also affect the $\delta^{18}O$ value of lake water (Rosenmeier et al., 2002b). During periods of increased (decreased) E/P ratios, the $\delta^{18}O$ value of lake water will go up (down) as kinetic fractionation processes lead to an increase (decrease) in the relative concentrations of ^{18}O compared to ^{16}O. Assuming that long-term temperature changes in the tropics are less likely to affect $\delta^{18}O$ values in the lake than are changes in the E/P ratio (Covich and Stuiver, 1974; Curtis and Hodell, 1993), the $\delta^{18}O$ value of ostracod carapaces should be most indicative of variations in the E/P ratio of the lake.

Young ostracod instars have been shown to assimilate carapaces with trace element chemistries and isotopic compositions that differ from those of adults of the same species under the same conditions (Chivas et al., 1986; Engstrom and Nelson, 1991; Keatings et al., 2002). The $\delta^{18}O$ composition of ostracod valves is also affected by species-specific "vital effects" (von Grafenstein et al., 1999; Keatings et al., 2002) and microhabitats (Heaton et al., 1995; Ito et al., 2003), but these problems can be minimized by analyzing numerous monospecific adult specimens.

The $\delta^{13}C$ composition of lacustrine biogenic carbonates depends mainly upon the $\delta^{13}C$ value of dissolved inorganic carbon (DIC) within the lake. This value, in turn, is controlled by a variety of factors including atmospheric CO_2 concentration, dissolution of carbonate rocks in the watershed, root respiration, watershed vegetation, and the bacterial decay of humus (Lister, 1988). In productive freshwater lakes, the most important factor in determining the $\delta^{13}C_{DIC}$ is the photosynthetic activity of aquatic organisms (Oana and Deevey, 1960). During photosynthesis, most aquatic organisms preferentially take up ^{12}C from the DIC pool, thereby increasing the $\delta^{13}C$ value of the remaining DIC. In light of the small water volumes and high biologic productivity of Castilla and Salvador, we interpret the $\delta^{13}C$ value of biogenic carbonates produced in these lakes as a proxy of paleoproductivity.

In a recent study, Pentecost et al. (2006) documented extreme isotopic disequilibrium between the carbon and oxygen isotope compositions of the calcite encrusting specimens of *Chara hispida* and the isotopic composition of lake water in shallow, highly productive lakes. Pentecost et al. attribute this disequilibrium to the direct combination of atmospheric CO_2 with hydroxide ions under high pH conditions. With this in mind, we interpret the Chara isotopic data from Salvador only in the context of other proxy indicators of paleolimnological and paleoclimatological variability.

Paleoenvironmental Reconstruction and Regional Context

Zone 7 (~2980–2250 cal yr B.P.)

The apparent formation of Laguna Castilla is marked by deposits of organic rich sediments dating back to ~2980 cal yr B.P. The material underlying these sediments has low pollen concentrations, high bulk densities, low organic carbon content, and large grain sizes, suggesting that the lake developed on landslide material (Figures 4.2, 4.3, and 4.6).

Some of the most positive $\delta^{13}C_{TOC}$ values in the Castilla sediment record are within Zone 7. There are two possible explanations for this. First, it is possible that much of the organic carbon carried within the landslide material was produced by C_4 plants or that C_4 plants initially colonized the basin prior to lake formation. An alternative explanation is that the basin was a shallow water environment early in its history, that may have stagnated seasonally, leading to methane production and outgassing. Degassing of ^{12}C-enriched methane leaves the residual sediments enriched in ^{13}C and, thus, anomalously positive $\delta^{13}C_{TOC}$ values (Ogrinc et al., 2002). This interpretation is supported by the similar $\delta^{13}C_{TOC}$ pattern (Figure 4.8) and poor pollen preservation in the basal Salvador sediments (Figure 4.7), which may have undergone a similar genesis at a later date.

The soils in the Las Lagunas area are porous and well-drained (pers. observation). It is possible that water in the Castilla basin had a very short residence time until a clay seal formed and cut off any subsurface drainage from the basin. These conditions could have potentially led to the development of a highly productive methanogenic shallow water, or seasonally inundated, ecosystem. In either case, the sediments would have been prone to drying, which could lead to the observed fossil pollen degradation in Zone 7.

Zone 6 (~2250–1520 cal yr B.P.)

Pollen preservation improves markedly in the Castilla sediments around 2250 cal yr B.P. (Figure 4.6) and in the Salvador sediments around 1870 cal yr B.P. (Figure 4.7). Improvement in pollen preservation suggests more mesic conditions. The dominance of *Pinus*, Urticales, and a variety of other broadleaf pollen through Zone 6 indicates the presence of humid montane broadleaf forest (Kennedy et al. 2005) near the lakes. Moderately high microscopic charcoal concentrations (Figure 4.5) indicate that fires were common in the region during this period. The $\delta^{13}C_{TOC}$ records for both lakes indicate a dominance of C_3 plants in the two watersheds (Figure 4.8), as expected for a humid montane broadleaf forest.

Other paleoclimate records from the circum-Caribbean region also indicate that this was a relatively moist period of the late Holocene. Trace metal concentrations in the sediments of the Cariaco Basin are relatively high and steady, indicating consistently high rainfall in northern South America (Figure 4.11; Haug et al., 2001). Relatively high lake levels are indicated for the Yucatan Peninsula (Hodell et al., 1995; 2005a) and Lake Valencia (Curtis et al., 1999). High moisture delivery to all of these sites has been interpreted as an indication of a more northerly mean boreal summer position of the ITCZ (Haug et al, 2003). A more northerly mean position of the ITCZ during the boreal summer would also yield increased precipitation for the Las Lagunas area as the proximal doldrum conditions would promote enhanced delivery of sea breeze moisture into the area.

Zone 5 (~1520–890 cal yr B.P.)

The decline in pollen from arboreal taxa and increase in herbaceous pollen in Zone 5 of both sediment records (Figures 4.6 and 4.7) indicate a period of increasing aridity at Las Lagunas. While an increase in the dominance of herbaceous plants might also be attributed to deforestation, lack of an associated increase in mineral influx into either lake suggests deforestation was not the cause (Figure 4.3; also see Zone 4 discussion below). The steady increase in the $\delta^{13}C_{TOC}$ compositions in both sediment records more likely indicates a local increase in the proportion of C_4 plants, which tend to be more drought tolerant than C_3 plants (Figure 4.8). Charcoal concentrations in both records reach some of their highest levels, possibly indicating an increase in fire return intervals or fire intensity as a result of more arid conditions (Figure 4.5; Martin and Fahey, 2006). Zone 5 also includes the first appearance of biogenic carbonates in the two sediment records (Figures 4.9 and 4.10). We interpret the presence of *Cythridella boldii* valves and *Chara haitensis* oospores as an indication of increased Ca^{2+} ion

Figure 4.11. Comparison of selected Laguna Castilla and Laguna de Salvador proxy data with titanium concentrations from the Cariaco Basin (ODP Site 1002; 10°42'44" N, 65°10'11" W; Haug et al. 2001; 2003). Increased Ti concentrations in the Cariaco Basin sediments indicate increased terrigenous input from rivers draining northern South America as a result of increased precipitation. Haug et al. (2001; 2003) hypothesized that variations in precipitation are closely tied to the mean boreal summer position of the Intertropical Convergence Zone (ITCZ). A more northerly mean position of the ITCZ yields higher precipitation totals in northern South America and the Las Lagunas area. The age model for the Cariaco Basin data has been adjusted slightly from cal yr before A.D. 2000 to cal yr before A.D. 1950 for comparison to the Castilla and Salvador sediment records.

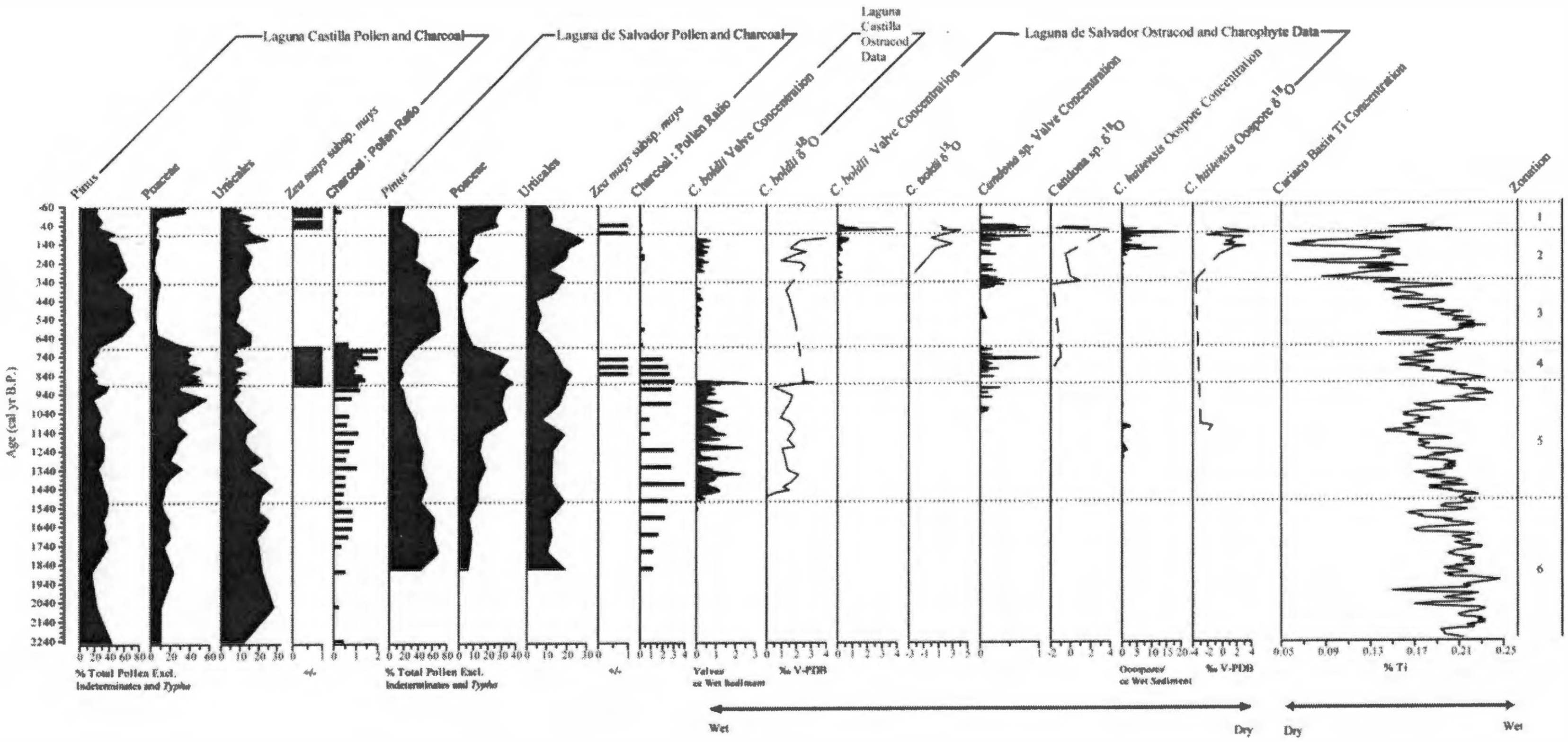


Figure 4.11. Continued.

concentrations resulting from decreased lake levels. The Cariaco Basin trace element records also indicate steady decreases in precipitation delivery for northern South America during this period (Figure 4.11; Haug et al., 2001; 2003).

One of the most striking features of Zone 5 is evidence of early pedogenesis at around 360 cm depth in the Salvador record (Figure 4.2). The high organic carbon content (~27% by mass; Figure 4.3) and small grain sizes of the peds indicate that they most likely formed in-situ and were not eroded and transported into the lake from the surrounding hillslopes. We interpret this ped layer to represent a short period when water levels in Salvador were sufficiently low to expose surface sediments at the core location to the atmosphere at least episodically, if not for an extended period. *Chara haitensis* oospores were deposited immediately before and immediately after the formation of these peds (Figure 4.10), providing supporting evidence that this may have been a period of severely depressed water levels in Salvador. Woody organic macrofossils preserved in the peds and decreased $\delta^{13}C_{TOC}$ values in this section of the Salvador sediment core indicate that the exposed lake floor may have been colonized by woody C_3 plants (Figure 4.8). These organic macrofossils date to ~1210 cal yr B.P. (Table 4.2).

Castilla is a deeper lake than Salvador (Table 4.4) and there is no evidence that Castilla sediments also dried out during this time. A spike in sedimentary carbonate concentrations at 570 cm in the Castilla sediment core may reflect increased Ca^{2+} ion saturation in the water column and consequent $CaCO_3$ precipitation, driven by a decrease in lake level (Figure 4.3). The $\delta^{18}O_{Cyth}$ record from Castilla displays an ~1‰ increase around 1220 cal yr B.P., which may indicate decreased lake levels; however, this increase is relatively minor compared to variations in Castilla $\delta^{18}O_{Cyth}$ values in other intervals that do not show evidence of sediment desiccation (Figure 4.9). It is possible that this drought was relatively short-lived, or was a series of short-lived events, that went unrecorded in the Castilla $\delta^{18}O_{Cyth}$ record, which has a resolution of ~20–40 years through this section of the sediment core. It is also possible that the drying at Salvador was seasonal, whereas the time-averaging of Castilla $\delta^{18}O_{Cyth}$ values caused by sampling methods is insensitive to fluctuations at this temporal scale.

Taking into account the errors associated with radiocarbon dating, the interval of apparent desiccation of the Salvador sediments correlates to an extended period of increased regional aridity and a series of severe drought events between ~1000 and ~1200 cal yr B.P. that have been documented at numerous sites in the circum-Caribbean region. Increased aridity at this time has been linked to the Terminal Classic Collapse of the Mayan civilization by numerous researchers. Hodell et al. (1995; 2001; 2005a) presented isotopic and sedimentary geochemical evidence of drought at around this time from lakes throughout the Yucatan Peninsula. Haug et al. (2003) reported a series of three droughts during this interval dating to around 810 (1140), 860 (1090), and 910 A.D. (1040 cal yr B.P.) in their high resolution trace-metal record from the Cariaco Basin. Nyberg et al. (2001) reported an increase in the magnetic susceptibility of marine sediments off the coast of Puerto Rico during this time that they associated with an increase in the deposition of hematite-rich dust from Saharan Africa due to intensified trade wind strength. Beets et al. (2006) reported an increase in dune activity and increase in the $\delta^{18}O$ composition of landsnail shells on the Caribbean island of Guadeloupe, suggesting increased tradewind activity and decreased precipitation at this time. All of these findings indicate a more southerly mean boreal summer position of the ITCZ, which would have also decreased precipitation for the Las Lagunas area. The geographic diversity of these sites points to a regionally pervasive change in climate that may be indicative of a larger shift in the global climate system (Mayewski et al., 2004).

Zone 4 (~890–700 cal yr B.P.)

Zone 4 includes the first evidence of human activity in the Castilla and Salvador records. Maize grains deposited ~890 cal yr B.P. in Castilla represent the earliest evidence of maize agriculture from the interior of Hispaniola (Figures 4.6 and 4.7; Chapter 2). Decreased concentrations of arboreal pollen types, increases in pollen concentrations of herbaceous taxa, and marked increases in charcoal influx in both lakes (particularly Castilla) indicate deforestation and the establishment of agricultural fields. Sedimentation rates (Figure 4.4) and mineral influx (Figure 4.3) increase by two orders of magnitude in the Castilla sediment record, suggesting major increases in soil erosion in the watershed, possibly coupled with increased algal productivity in the lake.

The overall indication is that the prehistoric populations that settled the Las Lagunas area had a greater impact on the landscape than did earlier episodes of climate variability or later activities by modern humans (see Zone 1 discussion below). Due to the lack of archaeological research in this interior region of

Hispaniola, we can only guess as to the identity of prehistoric settlers. Based on existing archaeological chronologies for the island, these early settlers were most likely Ostionoid. According to Wilson (1997), the Ostionoid archaeological period extends from ~1450 to 450 cal yr B.P. on the island of Hispaniola.

Based on the higher sedimentation rates, mineral and charcoal influx, $\delta^{13}C_{TOC}$ values, and lower concentrations of arboreal pollen in the Castilla record compared to the Salvador record, it appears that land was used more intensively in the Castilla watershed (Figures 4.3–4.8). Salvador is surrounded on three sides by steep slopes unfavorable for agriculture, but Castilla occupies a relatively flat area that would have been suitable for a variety of agricultural uses including maize agriculture. The large (~6‰) swings in the Castilla $\delta^{13}C_{TOC}$ record throughout Zone 4 correlate well with variations in maize pollen concentrations, indicating the $\delta^{13}C_{TOC}$ variability is most likely responding to variations in the abundance of maize being cultivated in the Castilla watershed (Figure 4.8; Chapter 3; Lane et al., 2006).

A spike in the abundance of *Cythridella boldii* valves early in Zone 4 of the Castilla record correlates with one of the largest increases in $\delta^{18}O_{Cyth}$ values in the record at around 890 cal yr. B.P. Increases in Castilla $\delta^{18}O_{Cyth}$ values from ~0.5‰ to ~3.2‰ in less than 25 years indicate an abrupt and severe increase in lake E/P ratios. This peak in $\delta^{18}O_{Cyth}$ values corresponds to the first appearance of maize in the pollen record and indicates that Castilla and Salvador were settled by prehistoric populations during, or immediately after, an apparently severe period of drought. The absence of biogenic carbonates in the Castilla record throughout the remainder of Zone 4 make it difficult to infer any climate variability that may have affected the prehistoric populations after their initial settlement of the area (Figure 4.9).

Human activity in the watershed of a lake can affect the $\delta^{18}O$ value of lake water through the modification of watershed hydrology, but the typical isotopic shift would be in the opposite direction than that of the $\delta^{18}O_{Cyth}$ record presented here. Rosenmeier et al. (2002b) documented a decrease in the $\delta^{18}O$ composition of lake water following severe deforestation of a watershed as a consequence of the decreased residence time of water in the soils and consequent reduction in the evaporative enrichment of the water prior to delivery to the lake itself.

While it is unlikely that human modification of the watershed could have caused the positive isotopic shift in the $\delta^{18}O_{Cyth}$ record, human activity could explain the absence of *Cythridella boldii* valves for the remainder of Zone 4. Ostracods are very sensitive to turbidity (e.g. Belis et al., 1999) and *C. boldii* valves disappear from the Castilla record just as mineral influx is peaking (Figure 4.12). A large increase in mineral influx would have increased the turbidity of Castilla during this time and could explain the temporary disappearance of *C. boldii* from the sediment record.

The apparently mild human impacts in the Salvador watershed do not appear to have affected ostracod communities of the lake. Valves of *Candona* sp. are present in the record through Zone 4, but not in sufficient concentrations for high-resolution isotopic analysis. The preservation of valves of *Candona* sp. in Zone 4 of the Salvador record indicates decreased lake levels and increased Ca^{2+}

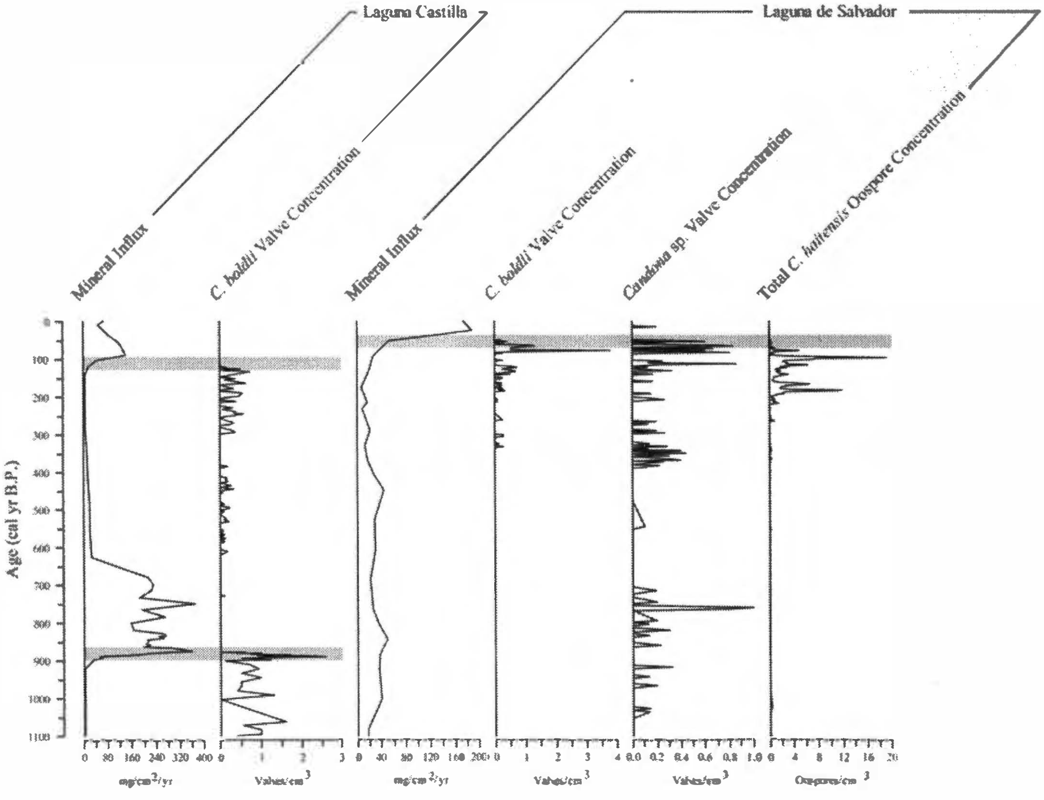


Figure 4.12. Comparison of mineral influx and biogenic carbonate concentrations for Laguna Castilla and Laguna de Salvador. Highlighted sections indicate periods of increased mineral influx and decreased biogenic carbonate concentrations.

ion concentrations as compared to Zone 6. However, the absence of charophyte oospores and *C. boldii* valves indicates higher lake levels during Zone 4 than during the time encompassed by Zone 5.

Zone 3 (~700–350 cal yr B.P.)

Zone 3 marks a period of ecosystem recovery after human abandonment of the Castilla and Salvador watersheds around 700 cal yr B.P. Maize pollen drops out of the records, and pollen percentages for herbs in the Poaceae, Cyperaceae, and Asteraceae families decline along with sedimentation rates, charcoal influx, mineral influx, and $\delta^{13}C_{TOC}$ values (Figures 4.3–4.8). Arboreal pollen types increase, especially *Pinus* and those in the "Other Humid Montane Taxa" category, indicating at least some forest recovery after human abandonment of the watersheds (Figures 4.6 and 4.7).

Why humans abandoned the two watersheds at this time is unclear. A conspicuous (~5 cm) mineral clay deposit in the Castilla record punctuates the period of human occupation (Figure 4.2). It is possible that this is a storm deposit, but no similar deposit was found in the Salvador record that would be expected if a tropical storm or hurricane had affected the area.

Pines readily colonize and dominate poor soils at middle and high elevations in Hispaniola (Darrow and Zanoni, 1991), and the dominance of *Pinus* pollen through Zone 3 (Figures 4.6 and 4.7) may reflect the deterioration of soil quality in the Las Lagunas area due to the activities of prehistoric humans. A concomitant increase in the abundance of pine stomata in pollen samples from Zone 3 argues for a local increase in the abundance of pine (Remus et al., 2006).

Pine stomata are not effectively dispersed over long distances and the presence of stomata in lake sediments is generally interpreted to indicate the local presence of pines (Gervais and MacDonald, 2001). Kennedy et al. (2005) found this to be true in their study of modern surface pollen samples in the highlands of the Cordillera Central. Surface pollen samples from forest stands including pines contained pine stomata, while samples from grasslands lacking pine did not. An increase in the pines near the lake shore, along with their prodigious pollen production, may explain the decline in Urticales pollen percentages in the Salvador record at this time.

The conspicuous decrease in *Candona* sp. valves in the Salvador record (Figure 4.10), absence of *Cythridella boldii* valves in Castilla (Figure 4.9), and the sharp decline in herbaceous pollen types in both records (Figures 4.6 and 4.7) indicate wetter conditions, increased lake levels, and decreased salinity at both Castilla and Salvador in Zone 4, compared to Zone 5. While the absence of ostracods in Zone 3 of the Castilla record might have been a consequence of the drastic anthropogenic watershed impacts incurred in Zone 4, the absence of *Candona* sp. valves in the Salvador record, which were present in Zone 4 despite the impacts of human activity, indicate that it was likely a shift in lake hydrology and chemistry that caused a decrease in ostracod abundance (Figures 4.9 and 4.10).

High-resolution records of paleoprecipitation from the Cariaco Basin (Haug et al., 2001), the Florida Everglades (Winkler et al., 2001), the Caribbean island of Guadeloupe (Beets et al., 2006), and the coast of Puerto Rico (Nyberg et al., 2001) also indicate that the period between ~350 and ~700 cal yr B.P. was relatively wet (Figure 4.11). As described previously, a concurrent increase in precipitation at all of these sites is typically ascribed to a more northerly mean boreal summer position of the ITCZ and/or higher Caribbean sea surface temperatures (SSTs).

Zone 3 is roughly coincident with the latest stages of the Medieval Warm Period (MWP; ~950–650 cal yr B.P.), but precedes the coldest periods of the Little Ice Age (LIA; ~450–150 cal yr B.P.). This is generally a time associated with relatively high late Holocene average temperatures globally (Jones et al., 1998; 2001; Moberg et al., 2005). The very earliest stages of this relative increase in global temperatures have been linked to an increase in solar output called the "Medieval Maximum" (Jirikowic and Damon, 1994; Stuiver et al., 1998). An increase in solar activity and related seasonal increase in Northern Hemisphere solar insolation may have "pulled" the ITCZ to a more northerly mean boreal summer position during this time (Peterson and Haug, 2006). Caribbean SST reconstructions also indicate a general increase in warm season SSTs between 700 and 550 cal yr B.P. that could have enhanced convective activity and atmospheric moisture availability in the region (Nyberg et al., 2002). In addition, lake sediment records from South America (Moy et al., 2002) indicate decreasing El Niño frequency and more persistent La Niña conditions during this period that would have also led to a more northerly mean boreal summer position of the ITCZ (Fedorov and Philander, 2000), warmer SSTs in the Caribbean (Giannini et al., 2000), and wetter conditions in the Las Lagunas area.

Zone 2 (~350–95 cal yr B.P.)

The decreased dominance of *Pinus* pollen and slight increases in broadleaf arboreal pollen (Urticales, *Cecropia*, *Trema*, and Arecaceae) in Zone 2 of both records may signal further recovery of forests from the impacts of prehistoric humans some 350 years earlier (Figures 4.6 and 4.7). One of the most conspicuous aspects of Zone 2 in the Castilla and Salvador sediment records is the abundance and variety of biogenic carbonates deposited during this interval (Figures 4.9 and 4.10), including the reappearance of *Chara haitensis* oospores in the Salvador record. The only other stratigraphic level with *C. haitensis* oospores in the Salvador record is associated with evidence of very low lake levels and desiccation of the Salvador sediments. The high abundance of oospores in Zone 2 also likely indicates low water levels. The increased abundance of *C. boldii* ostracod valves in the Castilla sediment record also indicates decreased water levels.

Zone 2 roughly overlaps the coldest periods of the LIA, which have only recently been recognized in paleoclimate records from the tropics (Thompson et al., 1995; deMenocal et al., 2000; Alin and Cohen, 2003; Behling et al., 2004; Brown and Johnson, 2005; Liu et al., 2005). Trace metal concentrations in the sediments of the Cariaco Basin reach their lowest levels since the Younger Dryas during the LIA, indicating extraordinarily dry conditions for northern South America (Figure 4.11; Haug et al., 2001; Peterson and Haug, 2006). Paleolimnological records from Aguada X'caamal, Mexico also indicate increased aridity and decreased lake levels during the LIA (Hodell et al., 2005b).

Meteorological records from Nassau, Bahamas extending back to A.D. 1811, which includes the latest stages of the LIA, indicate that the early 1800s included some of the coldest and driest conditions for the area in the last 200 years (Chenoweth, 1998). Caribbean SST reconstructions based on the oxygen isotope compositions of foraminifera and corals indicate a possible decrease of Caribbean SSTs of up to 3 °C (Winter et al., 2000; Watanabe et al., 2001; Nyberg et al., 2002; Haase-Schramm et al., 2003). A large decrease in SSTs certainly would have decreased evaporation and convective activity in the region (Hodell et al., 2005b). Furthermore, correlations between LIA records from the tropics and those from the high latitudes indicate intensified meridional airflow and increased meridional temperature gradient during this time that would have led to a more southerly mean boreal summer position of the ITCZ (Kreutz et al., 1997; Hodell et al., 2005b; Peterson and Haug, 2006). A decrease in Caribbean SSTs and a suppression of the annual cycle are the likely mechanisms responsible for increased aridity in the Las Lagunas area at this time.

The oxygen isotope signatures of biogenic carbonates in Zone 2 of the Castilla and Salvador records also indicate increasing aridity and decreased lake levels (Figures 4.9 and 4.10). For example, in the Castilla record, $\delta^{18}O_{Cyth}$ values reach as high as ~4.0‰. This is an increase of ~2‰ over the average $\delta^{18}O_{Cyth}$ values with the Castilla record. Although biogenic carbonates in Zone 2 have some of the highest $\delta^{18}O$ values on record, there is no indication that either lake dried out completely, as Salvador apparently did during Zone 5.

If the $\delta^{18}O$ values reflect E/P ratios, and presumably lake level variability, why don't we see more positive $\delta^{18}O$ values in the carbonate record in Zone 5? Based on the data presented here and other paleoclimate records from the region, we believe that the fundamental characteristics of these two arid periods may have differed. High-resolution records of the arid period around 1000–1200 cal yr B.P. indicate this was a period of generally arid conditions interrupted by a series of high-amplitude, extended drought events that occurred as often as once every 50 years (Haug et al., 2003; Hodell et al., 2005a). High-resolution records of the LIA in the circum-Caribbean seem to indicate a more prolonged and severe period of aridity, perhaps lasting 400 years, again interrupted by extreme drought events, but with these events perhaps only occurring once every 100 years (Hodell et al., 2005b; Peterson and Haug, 2006).

A more prolonged period of arid conditions during the LIA, perhaps accompanied by less seasonal or inter-annual variability, could have severely depressed lake levels over long intervals, leading to more positive $\delta^{18}O$ values in the time-averaged biogenic carbonate record compared to the 1000–1200 cal yr B.P. drought. The 1000–1200 cal yr B.P. drought might have included one or more extreme short-term drought events, leading to the desiccation of Salvador, but lacked the long-term lake level draw down necessary to increase the time-averaged $\delta^{18}O$ values to the levels observed during the LIA. Oxygen isotope records from Lake Valencia, Venezuela also display a larger shift in $\delta^{18}O$ values during the LIA than during the 1000–1200 cal yr B.P. period (Curtis et al., 1999), and sediment density records from Lake Chichancanab, Mexico, indicate the occurrence of more severe individual drought events during the 1000–1200 cal yr B.P. interval than at any other time in the last 2000 years (Hodell et al., 2005a). Thus, we propose that extreme drought events during the arid period from 1000–1200 cal yr B.P. were more severe than those that occurred during the LIA, but that the LIA was, on average, a drier interval of time in the Las Lagunas area, and potentially the circum-Caribbean as a whole.

This interpretation is supported by foraminiferal isotope records collected off the coast of Puerto Rico. Nyberg et al. (2002) presented isotopic evidence of high Caribbean SSTs and high sea surface salinities (SSSs) off the coast of Puerto Rico between 1000 and 1250 cal yr B.P. This pattern of increased SSTs and increased SSSs is unique because modern increases in SSTs typically result in increased evaporation and convective activity in the Caribbean and a decrease in SSSs. Nyberg et al. suggested that this unexpected pattern may be the result of more frequent or intensified El Niño events, which can cause a rise in Caribbean SSTs, but also suppress convective activity and precipitation, thereby increasing Caribbean SSSs (Giannini et al., 2000). It is interesting to note that multiple researchers have provided evidence of anomalously frequent and powerful El Niño events around 1200 cal yr B.P. (Quinn, 1992; Ely et al., 1993; Moy et al., 2002; Rein et al., 2004; Mohtadi et al., in press).

Nyberg et al. (2002) presented evidence of systematically different climate dynamics in the Caribbean during the LIA. Isotopic and foraminiferal faunal assemblage records from the coastal sediments of Puerto Rico indicate a ~2 °C drop in mean SSTs and an increase in SSSs during the LIA, which is the expected pattern. According to the results of their artificial neural network analysis, the decrease in mean SSTs during the LIA were primarily attributable to significantly cooler SSTs during the winter, which Nyberg et al. primarily associated with intensified polar air outbreaks into the Caribbean. Nyberg et al. also suggested that increased upwelling, as a result of intensified trade winds, and decreased deep water formation in the North Atlantic, could have led to the decreased Caribbean SSTs during the LIA.

In any case, the data and interpretations presented by Nyberg et al. (2002) point to fundamentally different climatic conditions in the Caribbean between 1000 and 1250 cal yr B.P. and during the LIA, in line with the Castilla and Salvador records presented here. Intensified El Niño events around 1200 cal yr B.P. (Quinn, 1992; Ely et al., 1993; Moy et al., 2002; Rein et al., 2004; Mohtadi et al., in press) could have produced drought events severe enough to lead to the desiccation of Salvador. However, El Niño events are relatively short-lived climatic events and may not be recorded in the relatively coarse oxygen isotope records of Castilla and Salvador, leading to the relatively lower $\delta^{18}O$ values in the Castilla and Salvador records around 1200 cal yr B.P., compared to the LIA. On the other hand, longer-term shifts in the Caribbean climate or ocean systems, such as the influence of more powerful polar fronts, decreased SSTs as a result of increased upwelling, or a decrease in warm water import from the tropical Atlantic as a result of decreased deep water formation in the North Atlantic (Nyberg et al. 2002), may have led to more consistently arid conditions on the island of Hispaniola during the LIA. These longer-term signals could be captured in the time-averaged carbonate $\delta^{18}O$ records of Castilla and Salvador and could explain the relatively higher average $\delta^{18}O$ values recorded during the LIA compared to the period between 1250 and 1000 cal yr B.P., when lake levels were apparently lower.

Zone 1 (~95 to –54 cal yr B.P.)

Zone 1, the period of most recent human occupation of the Las Lagunas watersheds, shows near-synchronous increases in mineral influx in both Castilla and Salvador, indicating increases in watershed erosion likely tied to historic human settlement and land use (Figure 4.3). Increases in herbaceous pollen types, particularly Poaceae and Amaranthaceae (Figures 4.6 and 4.7), also indicate human settlement and deforestation in both watersheds.

The pollen records of both Castilla and Salvador also include abrupt increases in the percentages of Myrtaceae pollen in Zone 1 (Figures 4.6 and 4.7). While other Myrtaceae are native to the mid-elevations of Hispaniola, most of the Myrtaceae pollen in the upper sediments is most likely the pollen of *Syzyygium jambos* Alston. (rose apple), which is currently the dominant arboreal species along the shores of both lakes. The morphology of fossil Myrtaceae pollen isolated from the sediment cores is identical to that of modern pollen collected from the rose apple trees currently surrounding the lakes. The rose apple is an invasive tree that was introduced to the Caribbean in A.D. 1762 (Morton, 1987). Rose apple produces abundant fruit and may have been purposefully introduced to the Las Lagunas area as a source of food and possibly firewood.

The marked increase in the abundance of *Typha* pollen in Zone 1 is also noteworthy (Figures 4.6 and 4.7). *Typha domingensis* is an emergent aquatic plant that currently grows along the shores of both Castilla and Salvador. Increased dominance of *Typha* after historic human settlement may relate to increased nutrient availability. A large increase in the abundance of algal remains, particularly those from algae in the genus *Pediastrum*, through Zone 1 may indicate increasing eutrophication of the lake after human settlement and the introduction of livestock to the area (data not shown; Bradshaw et al., 2005). Local inhabitants have also reported an increase in aquatic plant biomass that they associate with the introduction of livestock to the area.

The $\delta^{13}C_{TOC}$ signatures of both Castilla and Salvador increase sharply at the beginning of Zone 1, most likely as a result of deforestation and the reintroduction of maize to the landscape (Figure 4.8; Lane et al., 2004). Castilla $\delta^{13}C_{TOC}$ values decline steadily through Zone 1 while Salvador $\delta^{13}C_{TOC}$ values remain high up until the present. This discrepancy may reflect the modern distribution of maize fields near the lakes. Maize fields are presently located relatively far away from the shore of Castilla, but are just a few meters away from the shore of Salvador. Considering the close proximity of the maize fields at Salvador, it is unclear why there are no maize pollen grains in the uppermost sediments of the Salvador core.

The sudden rise in mineral influx into both lakes associated with the modern occupation of the watersheds is coincident with a disappearance of ostracod valves from the Castilla sediment record, as was the case during the prehistoric occupation of the Laguna Castilla watershed (Figure 4.12). Unlike the period of prehistoric occupation in Zone 4, the modern rise in mineral influx into Salvador is also coincident with the disappearance of ostracod valves. This is probably because modern mineral influxes into Salvador, and presumably human impacts in the Salvador watershed, are much higher than they ever were at any other time in the Salvador sediment record (Figure 4.12).

Much like the transition from Zone 5 to Zone 4, the transition from Zone 2 to Zone 1 includes some of the most extreme positive oxygen isotope excursions on record (Figures 4.9 and 4.10). This is the case for all of the biogenic carbonates present at this time. In the Salvador record, the $\delta^{18}O_{Cyth}$ values reach a maximum of 4.0‰, the $\delta^{18}O_{Cand}$ values reach a maximum of 3.9‰, and the $\delta^{18}O_{Chara}$ values reach a maximum of 3.5‰ all at around 80 cal yr B.P. The peak in $\delta^{18}O_{Cyth}$ values in the Castilla record at around 196 cm (124 cal yr B.P. according to the Castilla age model) appears to occur ~40 years prior to the peaks in the Salvador sediments (Figure 4.12). Considering the rapidly changing sedimentation rates through this section of the two records, errors associated with radiocarbon dating, and the difficulty in calibrating radiocarbon dates of this young age, it is quite possible that the positive excursion in the Castilla $\delta^{18}O_{Cyth}$ record actually corresponds to the positive excursions in the Salvador carbonate records at around 80 cal yr B.P. This is further supported by the fact that the rise in mineral influx into both lakes occurs just after the positive peak in $\delta^{18}O_{Cyth}$ values (Figures 4.3, 4.9, and 4.10). If one assumes that both lakes were settled at roughly the same time, which is likely considering their close proximity, then a simultaneous increase in mineral influx would be expected.

Synchronous shifts in proxy indicators of human presence and two periods of drought in the sediment records of the two lakes (Zones 1 and 4) are consistent with population migrations during severe drought events to land with perennially dependable water sources. According to archaeologists and historians, both prehistoric and historic humans appear to have primarily settled the coasts and fertile valleys of the island of Hispaniola (Rouse, 1992; Bolay, 1997; Wilson, 1997). Hispaniola as a whole has very few natural lakes or other sources of fresh water other than rivers, which are not necessarily annually dependable sources of water and are less than ideal for maintaining livestock during historic times. In times of severe drought, it is possible that humans were driven inland and into the highlands in search of water bodies such as the regionally unique lakes of Las Lagunas.

Summary and Conclusions

Climate History

Isolating climate signals in sediment records affected by human activity can be difficult (Horn, in press). The multi-proxy, multi-site approach we have employed here has improved our ability to separate anthropogenic and climate signals in the Castilla and Salvador sediment records. Figure 4.11 and Table 4.5 summarize the general climate variability for the Las Lagunas area over the last ~3000 years.

Table 4.5. Climate summary for the Las Lagunas area.

Zone	Age (cal yr B.P.)	Age (AD/BC)	Climate Conditions	Notes
1	95 to−54 cal yr B.P.	A.D. 1855 to 2004	Arid (?)	Increased calcium carbonate content in the sediments; paleoshorelines indicate higher lake levels in the past; record obscured by human activity
2	350 to 95 cal yr B.P.	A.D. 1600 to 1855	Arid	Abundant biogenic carbonates; increased $\delta^{18}O$ values
3	700 to 350 cal yr B.P.	A.D. 1250 to 1600	Mesic	Absence of biogenic carbonates; high arboreal pollen concentrations
4	890 to 700 cal yr B.P.	A.D. 1060 to 1250	Increasingly Mesic (?)	Presence of *Candona* valves in the Laguna de Salvador sediment record; record obscured by human activity
5	1520 to 890 cal yr B.P.	A.D. 430 to 1060	Arid	*Cythridlella boldii* present in the Laguna Castilla sedimentary record; progressive decrease in arboreal pollen concentrations and increase in herbaceous pollen; evidence of desiccation in the Laguna de Salvador sedimentary record
6	2250 to 1520 cal yr B.P.	300 B.C. to A.D. 430	Mesic	Absence of biogenic carbonates; high arboreal pollen concentrations
7	2980 to 2250 cal yr B.P.	1030 to 300 B.C.	Variable (?)	Poor pollen preservation; well-preserved roots; positive $\delta^{13}C$ values indicative of methanogenesis

The precipitation regime of the Las Lagunas area is controlled primarily by the seasonal proximity of the ITCZ. When the ITCZ is displaced southwards, high pressure dominates the Las Lagunas area, limiting convective activity and the onshore flow of moisture from the Caribbean Sea. When the ITCZ reaches a more northerly mean position, the proximal-doldrum conditions enhance convective activity and onshore transport of moisture onto the Caribbean slope of the Cordillera Central. The close correlations between the Las Lagunas climate proxy records and proxy records of mean ITCZ position from throughout the circum-Caribbean, especially those from the Cariaco Basin (Figure 4.11), provide further support that shifts in the mean boreal summer position of the ITCZ over the last few millennia have been the primary driver of late Holocene climate variability in the region.

The Las Lagunas sediment records provide some of the best terrestrial records of discrete climatic "events"' in the northeastern Caribbean. The first was a severe drought ~1210 cal yr B.P., possibly one of the most severe drought "events" of the last 2000 years. This drought led to the apparent desiccation of Salvador and may be related to the series of droughts linked to the Terminal Collapse of the Maya civilization on the Yucatan Peninsula. The Las Lagunas sediment records also provide evidence of a relatively wet Medieval Warm Period (MWP) in the eastern Caribbean. Zone 3 of the Castilla and Salvador proxy records coincides with the latest stages of the MWP and includes evidence of increased lake levels and C_3 forest dominance. Zone 2 in both records provides further evidence that the Little Ice Age (LIA) may have been, on average, one of the most arid periods in the circum-Caribbean in the last 2000 years. There is no evidence that Castilla or Salvador ever dried out completely during the LIA, but high concentrations of *C. haitensis* oospores and other biogenic carbonates, as well as maximum $\delta^{18}O$ values, indicate an extended period of depressed lake levels during the LIA. These three discrete climatic "events" appear to have had profound impacts on both the natural vegetation and disturbance regimes of the region and thus likely affected human populations that occupied the area, as well.

Human-Environment Interactions

Lake sediments have long been recognized as excellent archives of the environmental impacts of prehistoric human populations and societies. Over the last decade, lake sediments have also been increasingly recognized as excellent archives of information regarding the impact of climate change on human populations (e.g. deMenocal, 2001). The paleolimnological histories of Castilla and Salvador provide us with new information regarding both the environmental impacts of prehistoric and modern human populations in the interior of Hispaniola, and on the impacts of circum-Caribbean climate change on human populations.

The Las Lagunas lakes are marked by two distinct periods of human occupation over the last ~2000 years. The first occupation, commencing ~890 cal yr B.P., was coincident with what was apparently a severe drought "event" that punctuated an extended period of aridity for the region. The second occupation, commencing ~95 cal yr B.P., was also coincident with an apparently severe drought "event" punctuating an extended period of drought during the LIA.

Unlike most other records of prehistoric cultural responses to climate variability, such as those from the Yucatan Peninsula (Hodell et al., 1995) and the island of Guadeloupe (Beets et al., 2006), some of the most severe periods of drought in the Las Lagunas area appear to be associated with human occupation, as opposed to abandonment.

The limited number and size of lakes, steep topography, and poor soils of Las Lagunas probably made the area unsuitable or undesirable as a large population center at any point in time. However, freshwater lakes are rare on the island of Hispaniola and the Las Lagunas lakes represent a uniquely dependable inland water source. It is possible that humans were migrating out of large regional population centers on the island during periods of increased aridity and smaller populations were resettling in areas with dependable water sources, such as Las Lagunas. This hypothesis could explain the unexpected pattern of human settlement as opposed to abandonment during drought for the Las Lagunas area, but further research is necessary to verify this hypothesis and to place these potential population migrations into archaeological and historical context. While abundant attention has been devoted to the inter-island migrations of prehistoric Caribbean populations, very little attention has been devoted to the intra-island migrations of these same populations.

The activities of prehistoric populations had long lasting effects on the vegetation and disturbance regimes of the Las Lagunas area as well as aquatic organisms in Castilla. It appears as though the natural vegetation of the area had only just begun to recover some 350 years after prehistoric human abandonment only to be disturbed once again by the more recent occupation ~95 cal yr B.P. The benthic ostracod *Cythridella boldii* disappears completely from the Castilla sediment record following prehistoric human occupation, most likely due to increased lake turbidity from increased mineral influx. It was not until some 100 years later that *C. boldii* finally returned to the Castilla sediment record.

After prehistoric site abandonment, charcoal values in both sediment records never approach earlier levels. This decrease in charcoal abundance in the Las Lagunas area may have been the result of a significant decrease in soil fertility due to prehistoric erosion and a subsequent decrease in plant biomass. While it is also possible that a shift in climate could lead to decreased charcoal abundance as a result of decreased fire occurrence, paleolimnological evidence indicates similar hydrological conditions both prior to and following human settlement in the area. These potentially long-lasting impacts of prehistoric human populations on vegetation and fire regimes should be kept in mind by researchers analyzing modern day “natural” fire regimes and land managers interested in instituting prescribed burns on Caribbean islands to recreate “natural” fire regimes and maintain “natural” vegetation assemblages.

The most recent occupation of the Las Lagunas watersheds has also had significant impacts on the landscape and the lakes. Like the prehistoric occupation, the most recent occupation of the Las Lagunas area is associated with deforestation and an increase in mineral influx into both lakes. Once again, this increase in mineral influx is coincident with the disappearance of ostracods from both sediment records. The increased abundance of the alga *Pediastrum* sp. and increased dominance of *Typha domingensis* in the pollen record may indicate increased eutrophication in both lakes.

Conclusions

Terrestrial records of environmental change from the islands of the Caribbean are of great importance because of the unique biology, climatology, and history of these island settings. Despite the importance of these islands, the long-term environmental histories of most Caribbean islands remain poorly understood. The Castilla and Salvador sediment records provide evidence of regionally coherent climate variability that affected the interior of Hispaniola during the late Holocene and support for the hypothesis that variations in the mean latitudinal position of the ITCZ have been a primary driver of Holocene climate change in the circum-Caribbean region. The multi-proxy paleoenvironmental records of Castilla and Salvador also provide some of the first insights into prehistoric human-environment interactions in the interior of Hispaniola and provide testable hypotheses regarding the cultural response of Caribbean islanders to rapid climate change.

CHAPTER 5

Conclusions and Summary

This study has provided insights into late Holocene climate, vegetation, and human history in Hispaniola, and has contributed to methods for studying prehistoric agriculture using stable carbon isotopes. My dissertation research includes the earliest evidence of maize agriculture from the interior of Hispaniola (Chapter 2), evidence that the stable carbon isotope composition of bulk sediments can be used to estimate, at high temporal resolution, relative shifts in the abundance of maize being cultivated in a small neotropical watershed (Chapter 3), and a ~3000 cal yr B.P. multi-proxy record of paleoenvironmental change from two small lakes in the mid-elevations of the Cordillera Central of the Dominican Republic (Chapter 4).

Combined, these three studies have yielded new information regarding the geographic distribution of maize agriculture and importance of maize agriculture to prehistoric populations of Hispaniola, the impacts of both modern and prehistoric humans on the natural environment of the island of Hispaniola, and the impacts of climate change on the natural ecosystems and human populations of the island of Hispaniola. When compared with other records of climate change from the region, the multiproxy record of paleoenvironmental change that I have produced contributes insight into the regional coherence of, and possible mechanisms responsible for, late-Holocene climate changes in the circum-Caribbean region.

Maize pollen isolated from the sediments of Laguna Castilla and Laguna de Salvador dates back to ~ A.D. 1060 and represents the earliest and most securely dated evidence of maize agriculture from the interior of Hispaniola. Based on evidence preserved in archaeological sites throughout the Caribbean, many archaeologists and ethnobotanists believe that maize was a very minor component in the diets of prehistoric Caribbean populations. The abundance of maize pollen grains preserved in the Laguna Castilla and Laguna de Salvador sediments, combined with skeletal isotopic evidence from the interior of Puerto Rico (Stokes, 1998), indicate maize consumption may have been more prevalent in the interiors of Caribbean islands where marine resources were unavailable or too distant to be exploited efficiently. This finding emphasizes the need for more archaeological and ethnobotanical studies in the interiors of Caribbean islands.

The abundance of maize pollen in the Laguna Castilla sediment core, combined with high sedimentation rates during this period of prehistoric occupation, provided the necessary conditions to test the sensitivity of a relatively new proxy of forest clearance and maize agriculture. The stable carbon isotope composition of bulk sediments ($\delta^{13}C_{TOC}$) proved to be an effective proxy for the occurrence of prehistoric forest clearance and maize agriculture in the mesic neotropics. The stable isotope composition of sediments is sensitive to these activities because agricultural settings tend to be dominated by C_4 plants, which have stable carbon isotope compositions distinct from those of the C_3 plants that dominate undisturbed neotropical forests (Lane et al., 2004). Theoretically, the relative shift in $\delta^{13}C_{TOC}$ signatures through time may be indicative of the relative extent of maize agriculture within a particular watershed (Lane et al., in review). My high-resolution analyses of $\delta^{13}C_{TOC}$ values, maize pollen concentrations, and mineral influx into Laguna Castilla document the sensitivity of $\delta^{13}C_{TOC}$ signatures to the amount of maize being cultivated within a small tropical watershed. Shifts in the $\delta^{13}C_{TOC}$ record lag shifts in maize pollen concentrations by a few years, perhaps due to the time required for the breakdown of maize tissues and subsequent transport of this carbon to the sedimentary basin. In addition, the relative shifts in $\delta^{13}C_{TOC}$ values ($\Delta^{13}C_{TOC}$) appear to be sensitive to variations in allochthonous carbon influx, something that must be considered in any future models intended to reconstruct the spatial scale of maize agriculture in a watershed using the $\delta^{13}C$ signature of lake sediments.

My 3000 cal yr B.P. multi-proxy paleoenvironmental reconstruction indicates that the Laguna Castilla and Laguna de Salvador lake basins formed at different times and were initially probably shallow water, methanogenic environments prone to desiccation. Pollen assemblages indicate that the mid-elevations of the Cordillera Central were relatively moist from 2250 to 1520 cal yr B.P. Decreasing abundances of arboreal pollen types, increasing grass pollen concentrations, increasing $\delta^{13}C_{TOC}$ values, and sedimentary evidence that Laguna Salvador may have dried out completely, all indicate increasingly arid conditions for the region between 1520 and 890 cal yr B.P. The later portions of this arid period correspond well with regional evidence of drought from throughout the circum-Caribbean and may have been produced by the same shifts in atmospheric circulation that are associated with droughts on the Yucatan Peninsula that are implicated in the collapse of the Mayan civilization (Hodell et al., 1995; 2005a Gill, 2000; Haug et al., 2003).

Humans settled the Laguna Castilla and Laguna de Salvador watersheds around 890 cal yr B.P. Drastic increases in mineral influx, charcoal influx, and sedimentation rates at Laguna Castilla, combined with the appearance of maize pollen at both sites and increases in weedy herbaceous pollen at the expense of arboreal taxa, indicate prehistoric forest clearance and agriculture. These prehistoric environmental impacts appear to have been more severe than other natural or anthropogenic disturbance over the last two millennia, especially in the Laguna Castilla basin. At ~700 cal yr B.P., all of these proxies reverse, indicating abandonment of the watersheds by humans for reasons that remain unclear.

Following abandonment of the Laguna Castilla and Laguna de Salvador watersheds, pines became the dominant arboreal species in the area, possibly as a result of decreased soil fertility due to the high erosion rates associated with the period of prehistoric human agriculture. The pollen records of both lakes indicate that arboreal taxa typical of the native lower montane moist forest, such as *Trema*, *Cecropia*, other genera in the Urticales order, and *Myrsine*, did not reach pre-occupation levels in the area for some 350 years following site abandonment. In addition, charcoal concentrations never again reached pre-occupation levels in either sediment record.

The most recent (and ongoing) occupation of the Laguna Castilla and Laguna de Salvador watersheds began ~95 cal yr B.P. and is also associated with increased erosion, deforestation, and possibly increased eutrophication of the lakes as a result of livestock maintained in the area. The increased abundance of *Typha domingensis* pollen in the two sediment records and the appearance of the alga *Pediastrum* sp. likely indicate increased nutrient availability in the lakes. Local inhabitants have also reported an increase in aquatic plant biomass that they associate with the introduction of livestock to the area.

The presence of biogenic carbonates in the sediments of Laguna Castilla and Laguna de Salvador allowed the reconstruction of prehistoric evaporation/precipitation (E/P) ratios for both lakes using stable oxygen isotope ($\delta^{18}O$) analyses. The prehistoric and modern occupations of the Laguna Castilla and Laguna de Salvador watersheds coincide with the two largest positive oxygen isotope excursions on record. The synchronous shifts in proxy indicators of human occupation and drought twice in the sediment records of the two lakes may indicate population migration into the interior of Hispaniola in search of perennially dependable water sources during severe drought events. This pattern of occupation is opposite of that in most other circum-Caribbean geoarchaelogical records, such as those from the Yucatan Peninsula (Hodell et al., 2005a) and the island of Guadaloupe (Beets et al., 2006), where drought is typically associated with site abandonment rather than occupation. Further paleolimnological studies of small lakes in the interior of Hispaniola and other Caribbean islands will be necessary to see if this pattern of climatically induced human migrations was common in the region.

The $\delta^{18}O$ records of Laguna Castilla and Laguna de Salvador may also provide insights into regional climate changes and the mechanisms responsible for these changes. For example, the most positive $\delta^{18}O$ values on record in both lakes occurred during the Little Ice Age (LIA), indicating this period may have been one of the driest periods in the region over the last 3000 cal yr B.P. A positive, but relatively smaller, excursion in $\delta^{18}O$ values is also evident around 1210 cal yr B.P. in the Laguna Castilla $\delta^{18}O$ record and is accompanied by evidence of desiccation in the Laguna de Salvador sediment record.

The maximum $\delta^{18}O$ values during the LIA are not associated with any evidence of lake desiccation in the Laguna Castilla or Laguna de Salvador sediment records. This shift in the relationship between these two proxy indicators may be indicating a fundamental shift in climate dynamics. The biogenic carbonate $\delta^{18}O$ record is time-averaged because it consists of carbonates produced and deposited over an extended period of time; thus any short-lived droughts would be hard to detect using the $\delta^{18}O$ record. If the drought, or series of droughts, that led to the desiccation of Laguna de Salvador ~1210 cal yr B.P. was short-lived, perhaps related to intensified El Niño events (Nyberg et al., 2002), it may not be detectable in the time-averaged $\delta^{18}O$ record. However, longer-lived droughts would be detectable in the $\delta^{18}O$ record. Nyberg et al. (2002) have proposed that the LIA may have consisted of a fundamental shift in the climate regime of the Caribbean as a result of intensified polar air outbreaks, intensified tradewinds, and/or decreased deep water formation in the North Atlantic. These types of changes could have lead to longer-lived (multi-decadal) droughts in the Caribbean as opposed to the short-term (annual) changes related to increased El Niño intensity or frequency.

On longer timescales, the paleoprecipitation records of Laguna Castilla and Laguna de Salvador correlate well with regional paleoprecipitation records, especially those from the Yucatan Peninsula and the Cariaco Basin. The correlation of these records provide further evidence that variations in the mean annual position of the Intertropical Convergence Zone (ITCZ) have been a primary driver of circum-Caribbean climate change throughout the Holocene (Hodell et al., 1991; Haug et al., 2001) and provide further evidence that the tropics were not immune to global climate change events (Mayewski et al., 2004) once thought to have affected only the high latitudes.

Despite the rapidly increasing number of paleoenvironmental records available from throughout the neotropics, voids still exist in our understanding of Holocene climate change, the impacts of these changes on ecosystems and human populations, and the impacts of prehistoric human populations on the natural environment, especially in the eastern Caribbean and tropical North Atlantic. This dissertation has contributed to an understanding of all of these topics and represents one of the very few paleoenvironmental reconstructions from the interior of any Caribbean island. Future high-resolution paleoenvironmental studies using new techniques, such as compound-specific isotopic analyses, will help to resolve and further refine the environmental history of the circum-Caribbean and the role of the neotropics in global climate change.

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LIST OF REFERENCES

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APPENDIX A

APPENDIX A

POLLEN PROCESSING SCHEDULE FOR SEDIMENTS FROM LAS LAGUNAS, DOMINICAN REPUBLIC

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

1. Place wet sediment (sample volumes for the uppermost, watery sediments of Laguna Castilla and Laguna Salvador were 2.5 cc, and sample volumes for deeper sediments were 0.5 cc) in pre-weighed, 15 ml polypropylene centrifuge tubes and reweigh.
2. Add 1 tablet *Lycopodium* spores to each tube (Batch # 710961 = 13,911 spores/tablet).
3. Add a few ml 10% HCl, and let reaction proceed; slowly fill tubes until there is about 10 ml in each tube. Stir well, remove stirring sticks, and place in hot water bath for 3 minutes. Remove from bath, centrifuge, and decant.
4. Add 10 ml hot distilled water, stir, centrifuge and decant. Repeat for a total of two washes.

5. Add about 10 ml 5% KOH, stir, remove stirring sticks, and place in boiling bath for 10 minutes; stir again after 5 minutes. Remove from bath and stir again. Centrifuge and decant.
6. Add 10 ml hot distilled water, stir, centrifuge, and decant. Repeat for a total of 4 washes.
7. Fill tubes about ½ way with distilled water, stir, and pour through 125 µm mesh screen, collecting liquid in a labeled beaker underneath. Use a squirt bottle of distilled water to wash the screen, and to wash out any material remaining in the centrifuge tube.
8. Centrifuge down material in beaker by repeatedly pouring beaker contents into correct tube, centrifuging, and decanting.
9. Add 8 ml of 49–52% HF and stir. Place tubes in boiling bath for 20 minutes, stirring after 10 minutes. Remove from bath and centrifuge and decant.
10. Add 10 ml hot Alconox solution (made by dissolving 4.9 cm^3 commercial Alconox® powder in 1000 ml distilled water). Stir well and let sit for 5 minutes. Centrifuge and decant.
11. Add more than 10 ml hot distilled water to each tube, so that top of water comes close to top of tube. Stir, centrifuge, and decant. Check top of tubes for oily residue after decanting. If present, remove carefully with wadded paper towel. Also at this time, examine the tubes to see if they still contain silica. If silica is present, repeat steps 9–11. Assuming that

no samples need retreatment with HF, continue washing with hot distilled water as above for a total of 3 hot water washes.

12. Add 10 ml of glacial acetic acid, stir, centrifuge, and decant.
13. Make acetolysis mixture by mixing together 9 parts acetic anhydride and 1 part concentrated sulfuric acid. Add about 8 ml to each tube and stir. Remove stirring sticks and place in boiling bath for 5 minutes. Stir again after 2.5 minutes. Remove from bath and centrifuge and decant.
14. Add 10 ml glacial acetic acid, stir, centrifuge, and decant.
15. Add 10 ml hot distilled water, stir, centrifuge, and decant.
16. Add 10 ml 5% KOH, stir, remove stirring sticks, and heat in vigorously boiling bath for 5 minutes. Stir again after 2.5 minutes, then remove sticks. After 5 minutes, centrifuge and decant.
17. Add 10 ml hot distilled water, stir, centrifuge, and decant. Repeat for a total of 3 washes.
18. After decanting last water wash, use vortex mixer for 20 seconds to mix sediment in tube.
19. Add 1 drop 1% safranin stain to each tube. Use vortex mixer for 10 seconds. Add distilled water to make 10 ml. Stir, centrifuge, and decant.
20. Add a few ml tertiary-butyl alcohol (TBA), use vortex mixer for 20 seconds. Fill to 10 ml with TBA, stir, centrifuge, and decant.
21. Add 10 ml TBA, stir, centrifuge, and decant.
22. Vibrate samples using the vortex mixer to mix the small amount of TBA left in the tubes with the microfossils. Carefully transfer the liquid to

precleaned and labeled glass vials. Centrifuge down residue in vials and decant. Repeat as necessary until all material is transferred from tubes to vials.

23. Add several drops of silicone oil (2000 cs viscosity) to each vial, more if a lot of residue remains. Stir with a clean toothpick.
24. Place uncorked samples in a dust-free cabinet to let the residual TBA evaporate.
25. Stir again after 1 hour, adding more silicone oil if necessary.
26. Check the samples after 24 hours; if there is no alcohol smell, cap the vials. If the alcohol smell persists, allow more time for evaporation.

VITA

Chad Steven Lane was born in Santa Maria, California in 1979. He attended the University of Denver in Denver, Colorado and graduated in 2001 *magna cum laude* with a Bachelor of Science degree in Environmental Sciences and a minor in Physics. Chad was introduced to the subjects of paleoecology, paleoclimatology, and biogeography by his undergraduate advisor, Dr. Donald Sullivan, who graciously invited Chad to work in his laboratory. Chad's initial research focused on lacustrine sedimentary records of climate and vegetation change over the last 20,000 years collected from the lakes of Grand Mesa, Colorado.

In 2001 Chad entered the graduate program in geography at the University of Tennessee, and began studying paleoecology and paleoclimatology in Costa Rica under the direction of Dr. Sally Horn in Geography and Dr. Claudia Mora of the Department of Earth and Planetary Science. Chad pursued several research projects as a masters student, including exploring the potential for using stable carbon isotopes in sediment records as a proxy for prehistoric agriculture and tropical forest clearance in the Costa Rican lowlands and the development of a method for the controlled laboratory production of reference charcoal. Chad's masters thesis, co-directed by Drs. Horn and Mora, focused on stable carbon isotope signatures in the sediments of a glacial lake within the high-elevation páramo surrounding Cerro Chirripó, Costa Rica's highest mountain peak. As a Master's student, Chad was funded as a teaching assistant in Geography and as a research assistant with the Global Environmental Change Research Group, composed of faculty from the departments of Geography, Earth and Planetary Sciences, and Ecology and Evolutionary Biology.

In July 2002 Chad assisted Dr. Sally Horn and Dr. Kenneth Orvis with field work in the Dominican Republic funded by the National Geographic Society. This work included a trip to the small town of Las Lagunas in the mid-elevations of the Cordillera Central to core Laguna Castilla. Chad deeply enjoyed his time in Las Lagunas and found the location a compelling study site. His desire to conduct Ph.D. research in the area led to further field work at the site funded by the Global Environmental Change Research Group, and ultimately to the NSF grant project at Las Lagunas and Saladillo of which his dissertation is a part. During his dissertation work, Chad was funded by the NSF grant and as an instructor and head graduate teaching assistant for introductory physical geography courses. He also had Yates and Hilton Smith Fellowships from the University of Tennessee. In the future, Chad plans to remain in the world of academia where he can continue to research environmental change in the circum-Caribbean and other regions of the world, and to share his enthusiasm for science with undergraduate and graduate students.