

**A Late Holocene Paleoenvironmental Reconstruction of a Coastal Lake in Northeastern
Dominican Republic**

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Abstract

Coastal lakes, lagoons, and wetlands often provide excellent records of environmental change related to both marine and terrestrial processes. Although coastal paleoenvironments in the Caribbean have been a subject of increasing interest, long-term environmental reconstructions from lakes on the Atlantic side of the Caribbean islands are lacking. Laguna Limón is a freshwater lake in the El Seibo province of northeastern Dominican Republic. We collected a 315-cm sediment core from the center of the lake to examine lake evolution using loss-on-ignition and foraminiferal analysis. Loss-on-ignition results indicated the presence of a low-energy lagoon in the lake's present location between about 4700 and 1400 cal yr BP. During this period a foraminiferal assemblage dominated by the brackish-water *Ammonia parkinsoniana* but also containing relatively-abundant normal-marine salinity taxa (e.g., *Quinqueloculina* spp., *Archaias angulatus*, and *Trochulina rosea*) gradually was replaced by a low-diversity assemblage dominated by *Ammonia tepida* and *Ammonia parkinsoniana*, indicating a gradual decline in salinity due to the lagoon's growing isolation from the Atlantic Ocean. By 1400 cal. Yr. BP, the lake had become a shallow wetland, indicated by sediments with a high organic content. At 1200 cal. Yr. BP the lake flooded with freshwater, as it remains today. This study provides context for ongoing research into the environmental and human history of the Laguna Limón area.

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Attribution

This thesis would not have been possible without the assistance of several colleagues, who aided in data collection and interpretation for Chapter 2, *A late-Holocene paleoenvironmental reconstruction of a coastal lake in northeastern Dominican Republic*. These collaborators will be listed as co-authors on a manuscript that is in preparation for submission to the Caribbean Journal of Science.

Lisa M. Kennedy, PhD (Department of Geography, Virginia Tech) was a co-author on this paper, and assisted in collection of the LIM O500 core and interpretation of loss-on-ignition data. She also served as my advisor and the principal investigator for the grant that supported this research.

Stephen J. Culver, PhD (Department of Geology, East Carolina University) was a co-author on this paper, and helped identify foraminiferal specimens found in the LIM O500 core and surface samples.

Jason McVay was a co-author on this paper and assisted with the collection of the LIM O500 core, loss-on-ignition analysis of the core, and the initial interpretation of those results.

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Chapter 1: Introduction

1.1. Introduction

Due to their proximity to the ocean, coastal lakes experience both terrestrial (lacustrine) and marine phenomena. Multi-proxy studies of coastal lakes can highlight a variety of significant paleoenvironmental events and processes (e.g. sea-level fluctuations, climate variability, ecological change, environmental disturbance, changes in hydrology, and past human activity), and are therefore applicable to a wide range of disciplines, from archaeology to paleoclimatology. However, paleoenvironmental studies of freshwater coastal environments are especially limited in the tropics.

Coastal wetlands are not only important for the study of the past; they also host unique ecosystems. Salt marshes, mangrove forests, and other coastal wetlands provide habitat for birds and spawning grounds for fish and invertebrates. They also provide important ecosystem services for humans living near the coast; mangrove swamps and salt marshes, for example, play an important role in controlling erosion and buffering the storm surges resulting from hurricanes and tropical storms (Mitsch and Gosselink 2000, Morris et al. 2002, Zedler and Kercher 2005, McKee et al. 2007), and provide valuable fishing areas. Understanding long-term environmental change in coastal wetlands can therefore have widespread implications in many areas, from archaeology to economics.

Although Caribbean paleoenvironments have been the subject of increasing interest, paleolimnological studies of coastal lakes in the Caribbean are rare (Brenner and Binford 1988). This research reconstructs the paleoenvironmental history of Laguna Limón, a 5.1 km² freshwater lake on the northeastern coast of Hispaniola, the 2nd largest island in the Caribbean, using a multi-proxy approach. The objective of this study was to study the stratigraphy and foraminiferal record of a 3 m core from the center of Laguna Limon in eastern Dominican Republic to reconstruct the evolution of the lake. A clearer understanding of past environments at the Laguna Limon site can provide important context for paleoecological and archaeological research being conducted in the area.

This thesis presents a 4700-year history of Laguna Limón. The northern Caribbean region experienced climatic fluctuations, sea-level rise, and tectonic activity across this time frame. Spanning the same period (and before), the island of Hispaniola was inhabited by Pre-Columbian peoples, who were later largely displaced by Europeans, and experienced the expansion of intense agriculture all over the island. This study provides a preliminary framework for further paleoenvironmental and archaeological research on the northeastern coast of the Dominican Republic.

The following sections include background information on the study area and a brief literature review on the study of foraminifera. Chapter 2 is a manuscript in preparation for submission to the Caribbean Journal of Science.

1.2. Literature Review

1.2.1. Environmental Setting

The Caribbean is home to very few natural freshwater lakes that have received little study. There is little published work on lakes in the insular Caribbean in general. At present, published studies of lowland Caribbean lakes include Lake Miragoane in Haiti (Brenner and Binford 1988, Hodell et al. 1991, Higuera-Gundy et al. 1999), Wallywash Great Pond in Jamaica (Street-Perrott et al. 1993), Laguna de la Leche in Cuba (Peros et al. 2007), Laguna Tortuguero in Puerto Rico (Burney et al. 1994), and Laguna Saladilla in the Dominican Republic (Caffrey 2011). Paleoenvironmental histories have been published for montane wetlands (Kennedy et al. 2006) and mid-elevation lakes (Kennedy et al. 2006, Lane et al. 2009, Lane et al. 2011, Lane et al. 2014) of the Dominican Republic, but at present studies of coastal lakes are lacking.

Hispaniola is the second-largest Caribbean island, after Cuba, and encompasses both Haiti and the Dominican Republic. The island is extremely diverse in terms of relief; numerous mountain ranges traverse the length of the island, separated by deep valleys. The Cordillera Central, which occupies much of the island's interior, is the highest mountain range in the West Indies, with its tallest peaks exceeding 3,000 m (Orvis 2003).

The highly varied relief within the Dominican Republic results from its geological complexity. The northern part of the island of Hispaniola, including the Samaná Peninsula and the Cordillera Septentrional, consists of uplifted subduction zone rocks, overlain by Cenozoic shallow marine sediments (Mann et al. 1991). The highest range, the Cordillera Central, is the

core of a Cretaceous volcanic arc and is primarily composed of Cretaceous plutonic and volcanic rocks (Bolay 1997). The Cordillera Oriental in the east, like the Cordillera Central, is also composed of Cretaceous volcanic island arc rocks, as well as sediments derived from those rocks. The boundary between the North American and Caribbean plates, on which Hispaniola is located, is tectonically active; earthquakes are frequent along the many faults that transverse the length of Hispaniola, most trending east-west.

The climate of the Dominican Republic is tropical, being influenced primarily by northeasterly trade winds and the Intertropical Convergence Zone (ITCZ) (Horst 1992). At the outer reaches of the tropical zone, the Dominican Republic has a seasonal climate, with a rainy summer (ITCZ influence) and a drier winter under strong northeasterly trade winds (Hodell et al. 2000). Due to the orientation of Hispaniola's mountain ranges relative to the trade winds, precipitation on the island varies widely, from <500 mm in the valleys in the far southwest of the country to >2,500 mm on the windward side of the tallest mountain ranges (Bolay 1997). The high topography of the Cordillera Central creates a rainshadow effect, causing the northern, windward side of the mountain range to receive more than twice the amount of precipitation as the southern, leeward side (Horst 1992). Tropical storms commonly affect the Dominican Republic between March and November.

1.2.2. Quaternary Paleoenvironmental Research on Hispaniola

Late Quaternary climate history

Evidence for late Quaternary climate change has been well-documented in the Circum-Caribbean region, indicating intense climatic variability between wet and dry conditions (Hodell et al. 1991, Higuera-Gundy et al. 1999, Gischler et al. 2008, Escobar et al. 2012). The insular Caribbean has received comparatively less attention than mainland and marine sites; however, the island of Hispaniola has attracted more study than any other Caribbean island (Brenner and Binford 1988, Orvis et al. 1997, Higuera-Gundy et al. 1999, Kennedy et al. 2006, Lane et al. 2009).

Most paleoenvironmental studies on Hispaniola come from the island's interior, with Lake Miragoane in Haiti being the only lowland site receiving significant attention in the literature (Brenner and Binford 1988, Orvis et al. 1997, Higuera-Gundy et al. 1999, Kennedy et al. 2006, Lane et al. 2009). Highland and mid-elevation paleoenvironmental studies on Hispaniola reveal a climate history inconsistent of that from the lowland Caribbean, with evidence of sporadic human occupation (Kennedy et al., 2006; Lane et al., 2009). There is some evidence for the occurrence of large tropical storms (Kennedy et al., 2006).

Some of the longest continuous sediment records in the Circum-Caribbean come from the lowlands of Central America, in particular Lake Petén Itzá, Guatemala (Lea et al. 2003). A recent study by Escobar *et al.* (2012) examined stable isotopes ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) and lithology in a continuous, high-resolution sediment record from Petén Itzá that spanned approximately 85 ka, with the stable isotope record extending to ~42 ka. Trends in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, measured in the valves of the ostracod *Limnocythere opesta*, show a strong relationship to changes in lithology, with higher rates of gypsum deposition positively correlated with increased $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values (Escobar et al. 2012). These intervals, in which the lake's water was enriched in heavy isotopes, were interpreted to represent dry periods where evaporation exceeded precipitation and the lake

bottom was exposed to the atmosphere (Escobar et al. 2012). Conversely, low $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ are associated with clay deposition, and interpreted as an indicator of moister climates. The Petén Itzá record shows a shift away from the cool, dry conditions of the Pleistocene towards a warmer, wetter period between 15 and 13 ka. This warming trend was interrupted by the Younger Dryas and the Preboreal period between 13 and 10 ka, after which higher precipitation rates resumed, from the Pleistocene-Holocene transition until ~7 ka.

Geochemical and palynological analyses of sediment from Lake Miragoane, Haiti, generally agree with the Holocene Petén Itzá climate record. Oxygen isotopes, trace metals, and pollen suggest that the Pleistocene-Holocene transition was marked by a trend towards warmer temperatures and increased precipitation (Higuera-Gundy et al. 1999). Gradually declining $\delta^{18}\text{O}$ and trace metal concentration in Miragoane ostracods since the beginning of the Holocene indicates rising lake level, and therefore increasing precipitation (Higuera-Gundy et al. 1999). Holocene climate has not been constant, however; a rise in $\delta^{18}\text{O}$ indicates a return to a dryer climate around 3.2ka, which generally persisted (with some variation) throughout the late Holocene (Hodell et al. 1991). The pollen record is generally in accordance with the $\delta^{18}\text{O}$ record until ~1100 years BP, after which Lake Miragoane's watershed was extensively settled by Amerindian, and later European, populations (Higuera-Gundy et al. 1999). The inhabitants of the Miragoane watershed cleared forest to make way for agriculture, therefore removing climate-indicative forest pollen taxa from the sedimentary record (Higuera-Gundy et al. 1999).

Within the last millennium, Earth's climate has shown much variability (Jones et al. 2001). Natural and historical (documentary) proxy data indicate two distinct climatic epochs: the Medieval Warm Period (MWP) from ~900 AD to 1200 AD, and the Little Ice Age (LIA) from 1550 AD to 1900 AD (Jones et al. 2001). However, the majority of data from these periods

comes from the mid-latitudes of the Northern Hemisphere, which suggests that more data is needed from both the Southern Hemisphere and the tropics.

A 1500-year sediment core from the Great Blue Hole, Belize, reveals a $\delta^{18}\text{O}$ record in accordance with global climatic trends of the last millennium, including the increase in temperature occurring in the last several decades (Gischler et al. 2008). Also recorded in the Great Blue Hole core is a high-resolution record of tropical storms (Gischler et al. 2008). The frequency of storm deposits peaked from 650–850 AD, at approximately 1000 AD, 1200–1300 AD, and 1450–1550 AD (Gischler et al. 2008).

Sediment cores from the Cordillera Central of the Dominican Republic show strong fluctuations in precipitation throughout the Holocene (Kennedy et al. 2006, Lane et al. 2009). Proxy evidence from a core from a montane bog indicates periods of increased precipitation in the highlands of Hispaniola (Kennedy et al. 2006). Pine forests have mostly dominated high-elevation ecosystems of the Dominican Republic for at least the last 4000 years (Kennedy et al. 2006). However, spikes in the presence of pollen from deciduous taxa prior to 2500 years BP may be evidence for warmer or wetter conditions (Kennedy et al. 2006). Additionally, the formation of the bog around 4000 years BP, and its persistence throughout the mid-Holocene, seems paradoxical considering the dry conditions documented in lowland sediments (Kennedy et al. 2006). That the climate history of the Dominican highlands differs from lowland climate history suggests that the elevational climate gradient was different in the past than in the present (Kennedy et al. 2006).

Climate records have also been produced through analysis of sediment cores from mid-elevation lakes on the Caribbean slope of the Cordillera Central (Lane et al. 2009). Several discrete climatic episodes were interpreted to have occurred over the approximately 3000 years

recorded by the lake cores. Charcoal, pollen, and stable oxygen isotopes indicate a severe drought around 1200 yr BP, a wet Medieval Warm Period, and an arid Little Ice Age (LIA) (Lane et al. 2009). The timing and manifestation of these climatic events is consistent with the findings of Gischler et al. (2008). Further research on mid-elevation lakes in the Cordillera Central by Lane et al. (2011) supports the hypothesis of LIA aridity in the tropics. Evidence of aridity during the Terminal Classic Drought between ~1200 yrs BP and 800 yrs BP was also found in Lagunas Castilla and de Salvador in the interior of Hispaniola (Lane et al. 2014). Whereas this climatic pattern is widely thought to have contributed to the collapse of complex societies, such as the Maya, in the Yucatán Peninsula of Central America, the Terminal Classic Drought in Hispaniola coincided with major cultural shifts among smaller and less complex cultures (Lane et al. 2014).

Human history and prehistory

Archaeological sites in Trinidad place the earliest known human habitation of the insular Caribbean at around 7,000 years ago (5000 BC); these peoples, who are called the Otoiroids by archaeologists, were hunter-gatherers that can be directly traced to mainland South America (Keegan 1994). Casimiroid people first colonized Hispaniola, along with Cuba and Haiti, around a thousand years later (4000 BC), after migrating from Mesoamerica across the Yucatán channel (Keegan 1994). The exact timing of their arrival is complicated by archaeological sites that were dated as possibly up to 8,000 years old (6000 BC) (Saunders 2005). Around 4,000 yr BP (2000 BC), these early peoples shifted from hunting to extensive fishing societies (Wilson 2007). Around the same time, a new wave of colonization began as Otoiroid people from South

America and the islands closest to the mainland (e.g., Trinidad and Tobago) explored to the north. They colonized the Lesser Antilles and eventually made their way to the northern Lesser Antilles or even Puerto Rico, where they may have contacted the Casimiroid people (Wilson 2007).

Between 2,500 and 1,800 yr BP (500 BC–200 AD), Saladoid peoples migrated from northern Venezuela to Trinidad and then directly to the Greater Antilles (Saunders 2005). By 800 yr BP (1200 AD) their culture had transformed into the Chican Ostionoid culture, also known as the Taíno, through development of a new form of pottery (Rouse 1993). Unlike the Otoiroid and Casimiroid cultures before them, the Taíno practiced agriculture, produced ceramics and other material culture, and constructed monuments, ball courts, and religious plazas throughout their range (Saunders 2005). Macro- and microphytal evidence of maize consumption among these people has been found at both coastal and interior sites on Hispaniola and has been dated to as early as 980 yr BP (1020 AD) on the coast and 940 yr BP (1060 AD) in the interior (Lane et al. 2008). It is possible that the Chican Ostionoid culture resulted from the absorption of the preceramic Otoiroid cultures by the Saladoid, from the hybridization of the cultures, or from a complex interaction between diffusion, migration, and hybridization (Samson 2010). The eastern coastal plain was likely the most densely -populated area of the Dominican Republic prior to Spanish conquest (Samson 2010).

The arrival of Europeans in the late 15th century AD marked the beginning of dramatic social and environmental change in Hispaniola and the rest of the Caribbean (Wilson 2007). Christopher Columbus established the first European settlement in the Americas in 1492 at La Navidad on the northern coast of what is now Haiti. Subsequent to cultural contact, Old World diseases such as smallpox and measles spread through the Caribbean, killing up to 80% of the

indigenous population within a period of 30 years (Wilson 2007). Sugar cane became an important agricultural product in the Greater Antilles and plantations were founded throughout the islands, employing African and indigenous slave labor to fuel European demand (Saunders 2005). With the abolition of slavery in the 19th century, the plantation system disintegrated and other industries arose, with tourism being one of the most influential.

Fire and disturbance history on Hispaniola

The Caribbean archaeological record from the preceramic period of human settlement is sparse, and is additionally complicated by a combination of sea-level rise and tectonic activity (Keegan 1994). This issue magnifies the value of indirect (proxy) evidence of human occupation that can more thoroughly reconstruct the prehistoric human history of the Caribbean, as well as gauge the impact of preColumbian and modern societies on island ecosystems.

Sedimentary records from island lakes can provide paleoecological clues to the timing and extent of human settlement. For example, a sudden spike in charcoal in a core from Laguna Tortuguero, Puerto Rico suggests the beginning of human-caused fire on the island around 5300 years BP (Burney et al. 1994). Although wildfires of natural origin must be taken into account, a similar pattern, in which sudden increases in sedimentary charcoal occur coeval to human arrival, can be found on many oceanic islands around the world (Burney 1997).

Several studies of sedimentary charcoal from Hispaniola have been undertaken in order to better understand fire history on the island, especially in relation to Holocene climate change (Brenner and Binford 1988, Kennedy et al. 2006, Lane et al. 2009). Charcoal records from a

highland bog on the windward side of the Cordillera Central, Dominican Republic, suggest that fire has been a natural and consistent disturbance of the pine forests for at least the past 4000 years (Kennedy et al. 2006). In a study of mid-elevation lakes on the leeward side of the Cordillera Central, (Lane et al. 2009) documented a spike in sedimentary charcoal coeval with the first appearance of maize (*Zea mays*) pollen, indicating the arrival of humans to the area. However, a decline in sedimentary charcoal concentrations, within certain contexts, may also be indicative of an increase in human impact. For example, charcoal and pollen both decrease suddenly and exponentially in sediment from Lake Miragoane after the time of the Spanish conquest of Hispaniola, reflecting a historically documented period of deforestation (Brenner and Binford 1988). A study of macro- and microcharcoal in a core from Laguna Limón found a charcoal record of increasing aridity over the late Holocene, suggesting a southward migration of the ITCZ (McVay 2013). Additionally, high charcoal concentrations in the topmost 20 cm of the core were interpreted to result from the clearing of land in the lake's watershed through burning.

Pollen and spores in sediment may also provide clues to human modification of landscape and ecology. For instance, the presence of *Zea mays* (maize) pollen, as mentioned above, is an indication of human agriculture (Keegan and Diamond 1987, Hodell et al. 2000, Bell and Walker 2005, Wahl et al. 2006, Anderson et al. 2007, Wahl et al. 2007). Wahl et al. (2006) examined the history of human settlement and abandonment in the Petén region of Guatemala, and found that the first instance of maize pollen occurred together with a decrease in forest taxa and an increase in sedimentation rate. This finding suggests that early agriculturists in the Guatemalan lowlands cleared areas of forest for cultivation. Cores from a northern Yucatán mangrove swamp also reveal human settlement coeval with the appearance of maize pollen (Aragon-Moreno et al. 2012).

1.2.3. Modern foraminifera as a paleoenvironmental proxy

Overview of modern foraminifera

Foraminifera are the largest and most diverse group of shelled microorganisms alive today (Sen Gupta 1999). There are estimated to be more than 4,000 extant species of foraminifera, the great majority of which are benthic (Sen Gupta 1999). They live primarily in marine and marginal-marine environments, with very few fresh water species, and are distributed globally (Sen Gupta 1999). The diversity of foraminifera and their ubiquity around the world, as well as through geologic time, makes them an excellent tool in the investigation of paleoenvironments.

Like other amoeboid protists, foraminifera possess pseudopodia: anastomosing protrusions of the cell wall used for feeding, locomotion, and other life processes (Goldstein 1999). However, the most important feature distinguishing foraminifera from the rest of the protists is their test, or shell. Because foraminifera reproduce both sexually and asexually, biological species are difficult to identify without the aid of genetics. Therefore, species are defined primarily by the physical features of the test (Murray 2006). There are two main ways in which foraminifera construct their tests. Agglutinated foraminifera build a test of foreign sedimentary particles cemented together. Calcareous foraminifera secrete a wall of CaCO_3 (calcite or aragonite), produced entirely by the organism. Calcareous taxa can be further subdivided according to the structure of the test wall: porcellaneous, consisting of a homogenous

surface of calcite; and hyaline, wherein the wall is perforate, and occasionally ornamented (Sen Gupta 1999). Although most foraminifera are either agglutinated or calcareous, a few secrete an organic test, particularly those in the order Allogromiida. One order, Silicoloculinida, which lives below the depth of calcite compensation (the depth at which calcite will dissolve faster than it can precipitate), builds a siliceous test (Sen Gupta 1999).

Foraminifera as a paleoenvironmental proxy

As a proxy, foraminifera can be used in multiple ways. Analysis of stable isotopes in foraminiferal tests is a staple in the field of paleoclimatology. $\delta^{18}\text{O}$ is primarily employed as an indicator of a) global ice volume, b) input from different seawater reservoirs, and c) local variations in evaporation/precipitation (Katz et al. 2010). $\delta^{13}\text{C}$ provides information about paleoenvironments. In addition to helping to identify seawater reservoirs, carbon isotopes can be used as a proxy for paleoproductivity and temperature (Katz et al. 2010). Other geochemical evidence, such as trace element signatures, can act as a proxy for paleoproductivity, nutrient levels, pH, and atmospheric CO_2 (Katz et al. 2010).

Since foraminifera are sensitive to environmental and ecological change, any study of foraminifera must take into account the ecology of each species, genus, or faunal assemblage. An understanding of how faunal changes reflect environmental change can make foraminiferal assemblages themselves useful as a paleoenvironmental proxy. This approach is especially useful in marginal marine environments, where the environment is highly sensitive and influenced by

both marine and non-marine factors. Faunal changes can reflect changes in salinity, oxygen concentration, sea-level, and temperature, among other environmental factors (Scott et al. 2001).

In coastal settings, foraminiferal assemblages are largely controlled by the varying influences of marine and non-marine factors. For instance, the relationship between foraminiferal diversity and salinity has been well-documented, as has the relationship between test wall structure and salinity (Murray 2006). In low-salinity estuarine waters, foraminiferal assemblages are generally of low diversity and comprise predominantly agglutinated taxa (Murray 2006). Higher-salinity marine environments typically have a greater number of porcellaneous and hyaline taxa as well as larger species such as symbiont-hosting soritiids (Murray 2006). Hypersaline environments, on the other hand, host a greater variety of porcellaneous taxa (Debenay et al. 2001, Murray 2006). In coastal settings, calcareous (both porcellaneous and hyaline) species dominate the nearshore biofacies, whereas a greater proportion of agglutinated species is typically observed in estuarine and marsh areas: this trend is exhibited in numerous studies of coastal lakes, lagoons, and wetlands (Culver 1990, Sen Gupta 1999, Murray 2006).

Faunal changes can also occur due to environmental stress. Pollution, increased turbidity due to deforestation and runoff, and ecosystem disturbance can all affect the ecology of foraminifera. For instance, impacts of growing populations and industrialization after European settlement of the Chesapeake Bay watershed were reflected in cores from the Chesapeake Bay (Karlsen et al. 2000). The rapid increase in *Ammonia parkinsoniana* counts in the 1970s, as well as a shift from *Elphidium*-dominated assemblages to *Ammonia*-dominated assemblages, is attributed to an increase in nutrient flux in the watershed (Karlsen et al. 2000). The relationship between *Ammonia* species abundances and *Elphidium* species abundances has also been shown to be indicative of hypoxic conditions (Sen Gupta et al. 1996, Sen Gupta and Platon 2006).

Ammonia species are common and are more tolerant of low-oxygen conditions than *Elphidium* species, which are also common, found in the same geographic range. Therefore, a greater abundance of *Ammonia* relative to *Elphidium* The *Ammonia-Elphidium* index was first used in as a tracer of bottom-water dysoxia in response to pollutants in the northern Gulf of Mexico (Sen Gupta et al. 1996).

Modern foraminifera of the Caribbean region

The earliest descriptions of the taxonomy and ecology of Caribbean foraminifera come from as early as the 19th century. D'Orbigny included an early description of Cuban foraminifera in a natural history of the island (d'Orbigny 1839); later, Flint dedicated a volume to describing the foraminifera of Puerto Rico (Flint 1900). Foraminiferal taxa from the Caribbean, including Jamaica and Trinidad, were more thoroughly documented by Cushman after 1920 (Cushman 1921, Cushman 1922, Cushman 1948). Distribution data from all published literature concerning Caribbean benthic foraminifera were compiled and mapped by Culver and Buzas , who determined that the shelf waters of the Caribbean islands, the Caribbean coast of Central America, Southern Florida, and the Bahamas comprise a distinct biogeographic province which is distinct from both the Gulf of Mexico and the subtropical Atlantic coast of North America (Culver and Buzas 1999).

Paleoenvironmental research involving foraminifera in the Caribbean and the tropical North Atlantic is abundant and has tended to focus heavily on mangrove swamps, hypersaline lagoons, and coral reef systems (Brasier 1975, Culver 1990, Li et al. 1997, Debenay et al. 2001,

Schultz et al. 2010). A wealth of studies of Puerto Rican foraminifera was published by Sieglie in the 1970s, focusing primarily on the bays in the western part of the country, as well as on coral reefs (e.g., Sieglie 1970, Sieglie 1971, Sieglie 1975). Brooks (1973) also conducted a study of the distribution of foraminifera in the coastal waters of southern Puerto Rico, grouping taxa into a series of “thanatofacies” characteristic of different environments.

A survey of benthic foraminifera within and surrounding a Puerto Rican mangrove swamp (Culver 1990) documented several trends that may be applicable to paleoenvironmental research at Laguna Limón: predominance of agglutinated foraminiferal taxa within the mangrove swamp; sharp distinctions between offshore, inshore, and mangrove swamp faunas; and (in general) increasing diversity with water depth (Culver 1990). Other research from a carbonate platform off the Caribbean coast of Belize suggests that the diversity of foraminiferal assemblages may be correlated with the degree of water circulation, with the low-diversity lagoonal and mangrove swamp faunas due in part to the inhibition of water movement caused by thick vegetation (Gischler et al. 2003). Conversely, the highest diversity was found in high wave-energy areas open to the sea. The low-energy of mangrove swamp environments also helps sustain populations of delicate agglutinated taxa (Gischler et al. 2003, Schultz et al. 2010). Foraminiferal distribution in Caribbean marginal-marine environments has also been demonstrated to be influenced by substrate and submerged vegetation, with “weed-typical” assemblages appearing in areas covered by sea grasses such as *Thalassia* (Brasier 1975).

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Chapter 2: Manuscript

A late-Holocene paleoenvironmental reconstruction of a coastal lake in northeastern Dominican Republic

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2.1. Abstract

Coastal lakes, lagoons, and wetlands often provide excellent records of environmental change related to both marine and terrestrial processes. Although coastal paleoenvironments in the Caribbean have been a subject of increasing interest, long-term environmental reconstructions from lakes on the Atlantic side of the Caribbean islands are lacking. Laguna Limón is a freshwater lake in the El Seibo province of northeastern Dominican Republic. We collected a 315-cm sediment core from the center of the lake to examine lake evolution using loss-on-ignition and foraminiferal analysis. Loss-on-ignition results indicated the presence of a low-energy lagoon in the lake's present location between about 4700 and 1400 cal yr BP. During this period a foraminiferal assemblage dominated by the brackish-water *Ammonia parkinsoniana* but also containing relatively-abundant normal-marine salinity taxa (e.g., *Quinqueloculina* spp., *Archaias angulatus*, and *Trochulina rosea*) gradually was replaced by a low-diversity assemblage dominated by *Ammonia tepida* and *Ammonia parkinsoniana*, indicating a gradual decline in salinity due to the lagoon's growing isolation from the Atlantic Ocean. By 1400 cal. Yr. BP, the lake had become a shallow wetland, indicated by sediments with a high organic

content. At 1200 cal. Yr. BP the lake flooded with freshwater, as it remains today. This study provides context for ongoing research into the environmental and human history of the Laguna Limón area.

2.2. Introduction

Due to their proximity to the ocean, coastal lakes experience both terrestrial and marine phenomena. Multi-proxy studies of coastal lakes can highlight a variety of significant paleoenvironmental events and processes (e.g., sea-level fluctuations, climate variability, ecological change, environmental disturbance, changes in hydrology, and even historical human activity), and are therefore applicable to a wide range of disciplines, from archaeology to paleoclimatology. However, there are limited studies of freshwater coastal environments, especially in the tropics.

Although Caribbean paleoenvironments have been the subject of increasing interest, paleolimnological studies of coastal lakes in the Caribbean are rare (Brenner and Binford 1988). So far, environmental reconstructions from lake and wetland sediments on Hispaniola have focused primarily on pollen, charcoal, stable isotopes, and loss-on-ignition (LOI) (Brenner and Binford 1988, Higuera-Gundy et al. 1999, Kennedy et al. 2006, Lane et al. 2009, Lane et al. 2011); there are no published studies examining foraminifera as part of a multi-proxy paleoenvironmental reconstructions from Hispaniola.

This research aimed to construct a paleoenvironmental history of Laguna Limón, a freshwater lake on the northeastern coast of the Dominican Republic (Figure 1), using a multi-

proxy approach. In this study we analyzed the physical properties (i.e., color, loss-on-ignition, lithology) of sediment from a core taken from Laguna Limón, in addition to conducting foraminiferal analysis.

Foraminifera have long been used in the reconstruction of tropical-subtropical paleoenvironments, due to their sensitivity to zonations in vegetation, salinity, temperature, depth, and other ecological factors (e.g., Cushman 1921, Phleger 1966, Culver 1990, Debenay et al. 2001, Gischler et al. 2003, Sen Gupta and Platon 2006). The largest and most diverse group of shelled microorganisms alive today (Sen Gupta 1999), foraminifera can serve as useful proxies for reconstruction of long-term environmental history from coastal lake and wetland sediments. The earliest descriptions of the taxonomy and ecology of Caribbean foraminifera come from as early as the 19th century (d'Orbigny 1839, Goës 1882, Flint 1900), with these species being more thoroughly documented by Cushman after 1920 (Cushman 1921, Cushman 1922). The majority of research on Quaternary Caribbean paleoenvironments that has used foraminifera as a proxy has focused on mangrove swamps, coral reefs and reef lagoons, and hypersaline lagoons (e.g., Culver 1990, Debenay et al. 2001, Peros et al. 2007, Schultz et al. 2010, Cheng et al. 2012). Very little work has been done concerning lakes, however. Although Laguna Limón is currently a freshwater environment where we did not expect living foraminifera to occur, its proximity to the ocean indicates that it likely experienced marine influence at times in the past; the foraminiferal assemblages found in the Limón core helped us understand the degree of marine influence within the lake over time.

We present a paleoenvironmental history of Laguna Limón from ~4,700 cal. Yr. BP to the present, during which the Caribbean region was experiencing climatic fluctuations, sea-level rise, and tectonic activity. This time period also includes Pre-Columbian indigenous habitation of

Hispaniola, European invasion, and the expansion of intense agriculture all over the island. This study provides a preliminary framework for further paleoenvironmental and archaeological research on the northeastern coast of the Dominican Republic.

2.3. Methods

2.3.1. Study Area

The Dominican Republic (D.R.) is located on the island of Hispaniola (19°N, 70°W), which lies between Cuba and Puerto Rico (Figure 1). These islands, along with Jamaica, make up the Greater Antilles island chain, forming the northern border of the Caribbean Sea. The second largest country in the insular Caribbean, the D.R. makes up the eastern two-thirds of Hispaniola, with Haiti occupying the western third. The island's terrain is generally mountainous and rugged, with a wide range of relief. The Cordillera Central is notable for having the tallest mountain peaks in the Caribbean, with Pico Duarte reaching 3,098 m above sea-level (Orvis 2003).

The climate of the Dominican Republic is tropical, being influenced primarily by northeasterly trade winds and the Intertropical Convergence Zone (ITCZ) (Horst 1992). At the outer reaches of the tropical zone, the Dominican Republic has a seasonal climate, with a rainy summer (ITCZ influence) and a drier winter under strong northeasterly trade winds (Hodell et al. 2000). Due to the orientation of Hispaniola's mountain ranges relative to the trade winds, precipitation on the island varies widely, from <500 mm in the valleys in the far southwest of the

country to >2,500 mm on the windward side of the tallest mountain ranges (Bolay 1997). The northeastern Dominican Republic experiences a tropical wet climate, with a mean annual temperature of 25.6 °C and a mean annual precipitation total of 1758.1 mm. Hurricanes and tropical storms are common from March to November, and contribute significantly to the amount of rainfall received (Bolay 1997).

The sediments under study for this project were collected within and around Laguna Limón, a ~5 km² freshwater lake on the northeastern coast of the Dominican Republic in the province of El Seibo, near the town of Las Lisas (Figure 2). Limón lies on the narrow coastal plain between the Cordillera Oriental and the Atlantic Ocean. The Quaternary colluvium of the coastal plain surrounds Limón to the south, east, and north. The western side of the lake is bounded by the Upper Cretaceous Las Guayabas Formation, which is characterized primarily by sandstones and siltstones, with some interbedded limestone. A Quaternary alluvial fan associated with these Cretaceous rocks also borders the lake on its western shore. The alluvial fan outcrops on the beach to the north of the lake.

Laguna Limón is shallow, with an average depth of 1.5 m from our dry season observations at several points. It is situated ~2 m above mean sea-level and separated from the Atlantic by ~200 m of dry land at its closest point. The water is fresh to oligohaline, with salinities ranging from 0 to 0.5. Flooded pasture surrounds the lake on its southern and eastern shores and substantial fringes of mangrove forest cover most of the seaward lake shores (Figure 2). A narrow, storm-derived channel, maintained by local fishermen, connects the lake to the ocean, cutting across Playa Limón and through mangrove forest (Figure 1). The lake is connected to the ocean through this inlet only at high tide.

Playa Limón, the sandy beach fringing the coast between Punta la Pasa de Limón and the mouth of Río Cedro, experiences moderate wave energy, with the largest swells from the open ocean being interrupted by a reef lying approximately 500 m offshore. Waves observed at Playa Limón were estimated to be around 1 m in height at times during our January and March fieldwork. The flat, dry land adjacent to Limón is occupied by moist tropical lowland forest and managed forests of coconut palm. Two rivers and several streams empty into the lake, originating on the northern (windward) slope of the Cordillera Oriental, to the south of Laguna Limón. Drainage from these hills is the source of the fresh water filling both Limón and nearby Laguna Redonda (Figure 1).

2.3.2. Field Methods

In March 2013, surface samples were collected at 12 sampling sites in and around Laguna Limón (Figure 1). We obtained material from dry land and shallow water by scooping the top 1-2 cm of sediment into a collection bag. In deeper water, we used a snapper-type dredge to collect sediment. For the subtidal samples, we dove to the seabed (approximately 4 m deep) to manually scoop the surface sediment into a sample bag; high wave energy made it difficult to guarantee collection of only the top 1–2 cm of sediment. The LIMO500 sediment core was collected in January 2012 using a Livingstone drive rod piston corer. The core, which measures about 3.2 meters in length, was taken from the approximate center of the lake in 335 cm of water (Figure 1). The core and sample locations were recorded by GPS. We measured salinity at several sites around the lake, including the artificially-maintained inlet that connects Laguna

Limón to the ocean, the approximate center of the lake, and the mouth of a stream entering the lake.

2.3.3. Laboratory Methods

Sediment samples of 1 cc were removed at 1 cm intervals throughout the LIMO500 core for loss-on-ignition analysis following standard techniques (Dean, 1974). Weighed samples were dried overnight in an oven at 100 °C, then reweighed to determine water content. Samples were then burned at 500 °C for 2 hours and at 1000 °C for 1 hour, cooling and reweighing after each step, to determine organic and carbonate fractions respectively. After combustion at 1000 °C, remaining material comprised non-carbonate inorganic sediment, primarily silicates (Dean 1974). We described the core using the Munsell soil color chart system, comparing Munsell color tiles to the wet sediment in the core, and by observing texture and shell content. Four samples of charcoal and one sample of wood were isolated and submitted for radiocarbon dating by Woods Hole Oceanographic Institute National Ocean Sciences Mass Spectrometry Facility (Table 1). Radiocarbon dates were calibrated using Calib 6.1 (Stuiver and Reimer 1993).

To study the down-core distribution of foraminifera, we subsampled the sediment core at 2 cm intervals, collecting 20 cc samples at each interval. High clay content required that both core samples and surface sediment samples be soaked overnight in a 10% solution of sodium metaphosphate and caustic soda to disaggregate fine sediment particles (Abbene et al. 2006). Samples were washed through a 63- μ m copper mesh sieve using tap water to remove clay and silt; the sand fraction was then rinsed with distilled water into a labeled weigh boat and dried at 40° C. Between samples, sieves were rinsed with a methylene blue solution to stain any foraminiferal tests that were left behind. Any blue-stained foraminifera were disregarded for

analysis due to their presence resulting from contamination by a previous sample. We dried sieved samples overnight at 40° C and split them with a microsampler into aliquots for counting.

We studied foraminifera from 12 down-core sediment samples spaced 16-cm apart, as well as from 12 surface samples collected from in and around Laguna Limón (Figure 1). We employed a systematic process to randomize picking of the foraminifera from the samples. Each sediment sample was sprinkled evenly over a gridded tray, and all of the foraminifera from each randomly-selected grid square were picked until about 200 specimens were counted. The approximately 200 picked specimens were affixed to a microslide with gum tragacanth.

Specimens were identified by comparison to published literature, including publications focusing on Caribbean and other tropical to sub-tropical locations (e.g. Cushman 1922, Loeblich and Tappan 1964, Jones and Bock 1971, Hottinger et al. 1993, Javaux and Scott 2003, Culver et al. 2013). After preliminary identification, the species were confirmed against type specimens at the Smithsonian Institution. Taxon names were checked against the World Register of Marine Species (WoRMS).

We performed non-stratigraphically-constrained Q-mode cluster analysis on relative abundance data using the JMP statistical program. Prior to cluster analysis, the data were transformed with the arcsine-square root transformation, described by the equation $2\arcsin\sqrt{p}$ (p = relative abundance) (Buzas 1979, Culver et al. 2012). The arcsine-square root transformation is frequently used in ecological studies to normalize skewed proportion data, increasing the emphasis on both high and low proportion values (McCune et al. 2002). Species represented by only one specimen in only one sample were excluded from the cluster analysis.

2.4. Results

2.4.1. Core chronology

Five AMS radiocarbon dates (Woods Hole Oceanographic Institute National Ocean Sciences Accelerator Mass Spectrometry Facility) on organic material (four charcoal fragments and one piece of wood) provided a chronology for the LIMO500 sediment core (Table 1). All dates were in order and sediment influx averaged 0.7 mm per year. Age estimates ranged from 616 cal yr BP on charcoal from 54 cm core depth to 4697 cal yr BP on wood at 313 cm core depth.

2.4.2. Core and surface sample description

Sediments in the core ranged from organic-rich mud to sand. Basal sand present at the bottom of the core was too compacted to core through. We identified distinct “zones” in the core based on sediment color, texture, and composition as determined by LOI analysis (Figure 2; Table 2).

Zone I(a) (315–226 cm), the oldest (~4700–3200 cal. Yr. BP) portion of the core, was gray (5YR 5/1) to dark gray (5YR 4/1) in color and featured sandy, relatively dry sediment. Macrofloral remains were present, but rare. The carbonate fraction (mean ~25%) of samples in Zone I(a) were about two to five times higher than in samples from zones higher in the core, whereas the organic fraction was low (mean ~5%) (Figure 2; Table 2). The transition between

Zone I(a) and I(b) was gradual, characterized by a steady decline in carbonate content and a corresponding increase in silicate content. Organic content in zone I(b) remained low, averaging ~6% (Table 2). The abundance of sand declined upcore until it nearly disappeared at the transition between Zone I(b) and Zone II. Sediment in Zone I(b) (226–126 cm, 3200–1400 cal. Yr. BP) had a higher clay content than sediment in zone I(a), and had an olive gray color (5YR 5/2). Insect and plant remains were abundant in Zone I(b), particularly grass and algae. Many foraminiferal tests in Zone I(b) were pyritized, especially *Ammonia tepida*. In both Zone I(a) and Zone I(b) mollusk shells, including oysters, clams, and gastropods, were common and often large and intact.

Zone II (126 cm–111 cm, 1400–1200 cal. Yr. BP) was characterized by a sharp transition from the olive gray of Zone I(b) to black (2.5YR 2/). Sediments were mostly fine silt and clay, with a small component of fine sand, and abundant organic material. LOI analysis confirmed an increase in organic content in Zone II, revealing a spike to about 40% followed by a decline to around 20% at the expense of silicates (Figure 2). Carbonate content averaged ~5% across the interval. Shells were also common in Zone II, but not as abundant as in Zones I(a) and (b).

Zone III (111 cm–surface) represents the most recent portion of the core dating from approximately 1200 cal. Yr. BP to the present. Sediments in Zone III transitioned from the black of Zone II to dark gray (5YR 4/2). Organic content dropped quickly at the boundary between Zone II and Zone III, and then generally increased towards the top of the core (Figure 2). Silicate content mirrored organic content at the transition between Zone II and Zone III. In the top 40 cm of the core, sand was almost absent, with the bulk of the material >63 μ m comprising plant fibers, particularly aquatic grasses, and algae. An increase in organic content also began around 40 cm

depth. Samples from Zone III, once sieved, contained very little material >63µm. Ostracod valves, diatoms, fish teeth, and insect remains were common in Zone III.

Surface samples from the lake were rich in organic material, particularly grass, algae, ostracod valves, and insect remains, and contained no sand. Samples taken from the beach, ocean, mangroves, and channels around the lake contained abundant medium-grained, sub-angular to sub-rounded sand of both biogenic (carbonate) and silicic composition. Fragments of marine invertebrates, such as sponge spicules, coral, and echinoid spines, were common.

2.4.3. Foraminiferal analysis

We identified 40 foraminiferal taxa, including 19 species from 38 families from the LIMO500 sediment core and surface samples

Cluster analysis of transformed abundance data revealed that all surface samples containing foraminifera (8 of 12) clustered separately from the core samples (Figure 3). The foraminifera-bearing surface samples contained abundant sand and were rich in *Trochulina rosea* (formerly *Discorbis rosea*) and *Archaias angulatus*, as well as miliolid species. Many specimens were abraded and rounded and could not be identified beyond the generic level. None of the surface samples taken from Laguna Limón contained any foraminifera, except for LF-08, which was collected in the channel between the lake and the ocean, where there is interaction between the two.

In the LIMO500 sediment core, foraminifera were present only in samples between 306 (near the bottom) and 128 cm core depth. Cluster analysis defined two groups of samples, herein

termed biofacies, which did not overlap stratigraphically (Figure 2). Biofacies A was characterized by a relatively low-diversity assemblage dominated by *Ammonia tepida* and *Ammonia parkinsoniana* (Table 3). Biofacies B contained a more diverse assemblage that, while still dominated by *A. tepida* and *A. parkinsoniana*, also contained a significant proportion of *Quinqueloculina* species (Table 3). Biofacies A samples ranged from 306 and 256 cm core depth and Biofacies B samples from 242 to 126 cm (Figure 3). Cluster analysis indicated distinct separation between the surface and core samples, with all of the foraminifera-bearing surface samples defining Biofacies C (Figure 3). All foraminifera-bearing surface samples contained a diverse assemblage dominated by *Trochulina rosea* and *Archaias angulatus* and with a high proportion of *Quinqueloculina*; we did not find a similar assemblage in any of the core samples (Table 3).

Biofacies B generally coincides with Zone 1(a). The foraminifera of this zone were diverse, and included *Quinqueloculina* species, *Trochulina rosea*, *Elphidium mexicanum*, *Archaias angulatus*, *Amphistegina lessonii*, *Cibicides* species, and *Triloculina* species (Table 3). *Ammonia* species were present in all of the foraminifera-bearing core samples, but *Ammonia* species strongly dominate in Biofacies A, which generally coincides with Zone 1(b) between 242 cm and 128 cm. This assemblage was characterized by its lower diversity relative to that defining Biofacies A, and by the strong dominance of both *Ammonia tepida* and *Ammonia parkinsoniana*. Foraminifera from the genus *Criboelphidium* were found throughout the core, including *C. kugleri*, *C. poeyanum*, and *C. vadescens*.

Very few specimens of agglutinated taxa (<1% abundance in any sample) were found in both the core samples and the surface samples. The only agglutinated specimens found were of the genus *Textularia*.

2.5. Discussion

2.5.1. Environmental Interpretation

Surface Samples

All surface samples contained a large component of carbonate sand, pointing to a marine origin such as that found on Playa Limón. The foraminiferal assemblages in the surface samples also support a marine origin for this sand. *Trochulina rosea*, the most abundant species, is characteristic of high-energy inner-shelf marine environments, such as that found offshore of Playa Limón (Gischler et al. 2003). The prevalence of these *Trochulina rosea*-*Archaias angulatus*-dominated assemblages in and around the lake may be due to movement of beach sand by tropical storm surges, or by human activities, such as the dredging of channels between the lake and the ocean. The surface samples that contained foraminifera clustered apart from the core samples (Figure 3) implying that none of the surface environments sampled, including beach, mangrove swamp, or inlet, were ever present at the core site (near the present center of the lake) when the foraminifera-containing sediments were deposited.

It is notable that we did not find characteristic mangrove swamp agglutinated foraminifera in any of the samples, either from the core or the surface (Culver 1990, Sen Gupta 1999, Murray 2006). In addition, the core provided no evidence of a mangrove environment, such as peat or leaf remains; thus, mangrove vegetation was likely never present at the coring site.

Zone I(a) (4700 – 3200 Cal. Yr. BP)

We interpret Zone I(a) to represent a low-energy bay that was gradually becoming isolated from the ocean. The change from Biofacies A, dominated by *Ammonia* species with abundant *Quinqueloculina* species to the lower-diversity, strongly *Ammonia*-dominated Biofacies B near the boundary between Zone I(a) and (b) indicates decreasing marine influence between 4700 Cal. Yr. BP and 3200 Cal yr BP. *Quinqueloculina* species are associated with shallow, normal-marine conditions, while *Ammonia* species are largely indicative of shallow, low-energy, brackish-water settings such as sheltered bays, lagoons, marshes, and mangrove environments, and are highly tolerant of environmental stress (Culver 1990, Williams 1995, Sen Gupta et al. 1996, Debenay et al. 1998, Sen Gupta 1999, Debenay et al. 2001, Murray 2006, Sen Gupta and Platon 2006, Cheng et al. 2012, Culver et al. 2012).

The high carbonate content of sediments in Zone 1(a) (Table 2, Figure 2) points to a dominantly marine origin for the sediment. The geology of Limón's watershed is mainly composed mostly of silicate-bearing rocks such as sandstones and volcanics that would have a low carbonate content. The rise in silicate content over time in Zone I(a) (at the expense of carbonate) demonstrates a decreasing marine influence and an increasing terrestrial influence within the system. Laguna Limón's watershed is primarily underlain by the Río Chavón Formation (Upper Cretaceous), comprising sandy marls, siltstones, and limestones, and the volcanic Las Guayabas Formation. Sediments entering the lake via rivers and streams would contain carbonate minerals, but still would have a greater silicate content than the marine sands offshore of Limón.

Zone I(b) (3200 – 1400 Cal. Yr. BP)

Zone I(b) represents a period of shallowing and freshening of a low-energy bay as marine influence decreased. During the deposition of Zone I(b) sediments, the bay was becoming less marine-influenced, with freshwater input exceeding marine input. Carbonate content continued to steadily decline, indicating a gradual increase in terrestrial influence. The olive-gray sediment color in this interval (Munsell 5YR 4/2) suggests hypoxic to anoxic conditions that made anaerobic respiration possible (Pomeroy and Wiegert 1981). The pyritization of foraminiferal tests in this interval supports the interpretation of anoxia in the sediment, as does the increased proportion of *Ammonia tepida* in Biofacies A as compared to Biofacies B (Sen Gupta et al. 1996) (Table 3). The greater abundance of macrofloral remains in Zone I(b) than Zone I(a) suggests a decreased energy level in the system, as moving water would sweep away dead vegetation.

The abundance curves (Figure 4) for the several *Criboelphidium* species as well as *Elphidium mexicanum* in zones I(a) and (b) show a different trend to that of the *Ammonia* species, as well as *Quinqueloculina* species, *Archaias angulatus*, *Amphistegina lessonii*, *Cibicides* species, *Trochulina rosea*, and *Triloculina* species. The *Ammonia* species became increasingly dominant over time, whereas abundances of *Quinqueloculina*, *Triloculina*, *Archaias angulatus*, and the offshore rotaliids declined. *Criboelphidium vadesens*, *kugleri*, and *poeyanum* also show a general decrease in abundance, but their decline occurs at a later time than the miliolids and offshore rotaliids. *Elphidium* and *Criboelphidium* species often serve as valuable environmental indicators due to their sensitivity to variations in salinity, temperature, oxygen, nutrient levels, and substrate in shallow marine environments (Gischler et al. 2003, Eichler et al. 2010, Pruitt et al. 2010). We can conclude that the variations seen in abundance of

species likely reflect subtle, local changes in environment. For example, the greater abundance of *C. poeyanum* in Zone 1(a) than in Zone 1(b) (Figure 4) is likely due to a reduction in depth over time, as *C. poeyanum* and *kugleri* have been demonstrated to be associated with relatively deep, low-energy, polyhaline bays and lagoons (Culver 1990, Debenay et al. 2001, Gischler et al. 2008), and *C. vadescens* with shallower, low energy brackish water (Cushman 1948). *Elphidium mexicanum*, which peaks at 256 cm and then declines, commonly occurs in relatively shallow, warm, brackish water (Culver 1990, Cheng et al. 2012). Because the decrease in the abundance of normal-marine salinity species occurs before the decrease in abundance of the brackish-water *Criboelphidium* and *Elphidium* species, we can conclude that salinity began to decline before the lake shallowed, with both shallowing and freshening continuing until ~1400 cal yr BP (Figure 2).

Zone II (1400 cal. Yr. BP – 1200 cal. Yr. BP)

Zone II records the process of Laguna Limón's isolation from the ocean. The data suggest the presence of a low-energy freshwater, herbaceous wetland during this time period. The abundance of organic material in the sediments, mostly grasses and sedges, indicates a very low energy system with plants growing *in situ*. Low carbonate levels in this interval support the idea that marine influence on this environment had ceased completely, with all water entering the system from either the basin's watershed or groundwater. The sharp drop in silicates at 120 cm (~1300 cal. Yr. BP) and the coeval spike in organics denotes a sudden reduction in fluvial input, as water entering the wetland from streams would be carrying silicate-dominated sediment. At this point, the wetland shallowed to the point that it may not have been continuously submerged.

Zone III (1200 cal. Yr. BP – Present)

Over the interval represented by Zone III, the freshwater herbaceous wetland represented in Zone II flooded with freshwater, bringing an increased flux of terrigenous sediment into the system. *In situ* biomass rose over time, replacing silicate content in the sediment. Around 500 cal. Yr. BP, the rate of *in situ* biomass production increased. The timing of the increase in organic matter coincides with the invasion of the El Seibo province by Europeans (Bolay 1997), and may be due to increased nutrient runoff related to the establishment of cattle ranching in Limón's watershed.

2.5.2. Possible mechanisms of change

Zones I(a) and (b) in the LIMO500 core record a bay gradually becoming restricted from the ocean, until the basin became completely isolated from marine influence around 1400 cal yr BP. Over time, a surplus of sediment supply would have filled the basin, enhanced by the establishment of sediment-trapping vegetation, causing shallowing (Ramcharan and McAndrews 2006). There are a number of ways the basin could have become isolated from the ocean. The establishment of a mangrove forest could have stabilized the shoreline, allowing for beach closure. Mangrove-related lagoon closure has been hypothesized for various sites around the Caribbean, including Maracas Bay in Trinidad (Ramcharan and McAndrews 2006) and Laguna de Leche, Cuba (Peros et al. 2007).

Alternatively, tectonic uplift related to the Septentrional Fault Zone (SFZ) may have caused the lake to evolve from a wetland open to the sea to a freshwater lake (McVay 2013). The SFZ is a part of the transform boundary between the North American and Caribbean Plates, and traverses the northern part of Hispaniola, running through the Bahía de Samaná to the north of Laguna Limón. This plate boundary is tectonically active, and earthquakes associated with the SFZ have been recorded in the Cibao Valley of the Dominican Republic (Mann et al. 1991, Prentice et al. 2003). Even a slight amount of uplift could have initiated the isolation of the low-lying Laguna Limón basin from the ocean as sea-level fell relative to the lake. It is unlikely that eustatic sea-level change played a role in this process, as it has been well established that an increase in mean sea level has occurred worldwide over the last ~20 kyr (e.g.; Milliman and Emery 1968, Fleming et al. 1998).

Tectonic movement associated with the SFZ may have had the additional consequence of changing the course of rivers and streams in Laguna Limón's watershed, causing more fresh water and terrigenous sediment to enter the lake (McVay 2013). At 1200 cal. Yr. BP, Laguna Limón flooded with fresh water, changing from a shallow wetland to a lake. A freshening of Laguna Saladilla in northwestern Dominican Republic has been hypothesized to have resulted from a shift in the course of the Masacre River, causing it to flow into the lake (Caffrey 2011). However, the closest recorded incidence of streams changing course due to tectonic activity during the Holocene is from the Cibao Valley, over 100 km away from the Laguna Limón site (Mann et al. 1991, Prentice et al. 2003).

2.5.3. Conclusion and Implications

This study of stratigraphy and foraminifera in a 315 cm core from the center of Laguna Limón provided a 4700 year record of lake evolution. Although Laguna Limón is currently a freshwater lake, a shallow, low-energy bay connected to the ocean and containing water at normal-marine salinity existed in the lake's present location. Between 4700 cal yr BP and 1400 cal yr BP the bay shallowed and freshened as it became increasingly isolated from the Atlantic Ocean. Marine influence over the bay ceased completely between 1400 and 1200 cal yr BP, during which time a freshwater, herbaceous wetland occupied the area. After 1200 cal yr. BP., the wetland flooded with fresh water of fluvial origin and became a lake.

The results of this study have clear implications for both ecological and archaeological research on the northeastern coast of the Dominican Republic. A general freshening of the wetlands surrounding the area would have drastically changed the region's plant communities, replacing salt-tolerant marsh vegetation with fresh water plants. Future palynological research could provide a window on vegetation dynamics around Limón.

If the formation of Laguna Limón were indeed due to uplift, much of the coastal plain on the northeastern coast of the Dominican Republic would have been affected. At the time of the lake's formation, a large marsh might have existed in the area. Ongoing archaeological research confirms preColombian human habitation in the area of Laguna Limón (Alice Samson, personal communication, 2014); abundant archaeological evidence including dwellings, plazas, and human remains, as well as palynological proxy data supporting human agricultural practices, have been found in Higüey, the province neighboring El Seibo to the east (Samson 2010). The lifeways of the early inhabitants of the region would have certainly been affected by the environmental change recorded by the core. If a salt marsh existed where there is now flooded pasture, it may have influenced the types of food that were eaten and types of natural resources

available. Future research combining archaeology with continued paleoenvironmental study could more fully illuminate the history of Laguna Limón and the influence of environmental change on the biotic and human communities nearby.

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Chapter 2 Figures

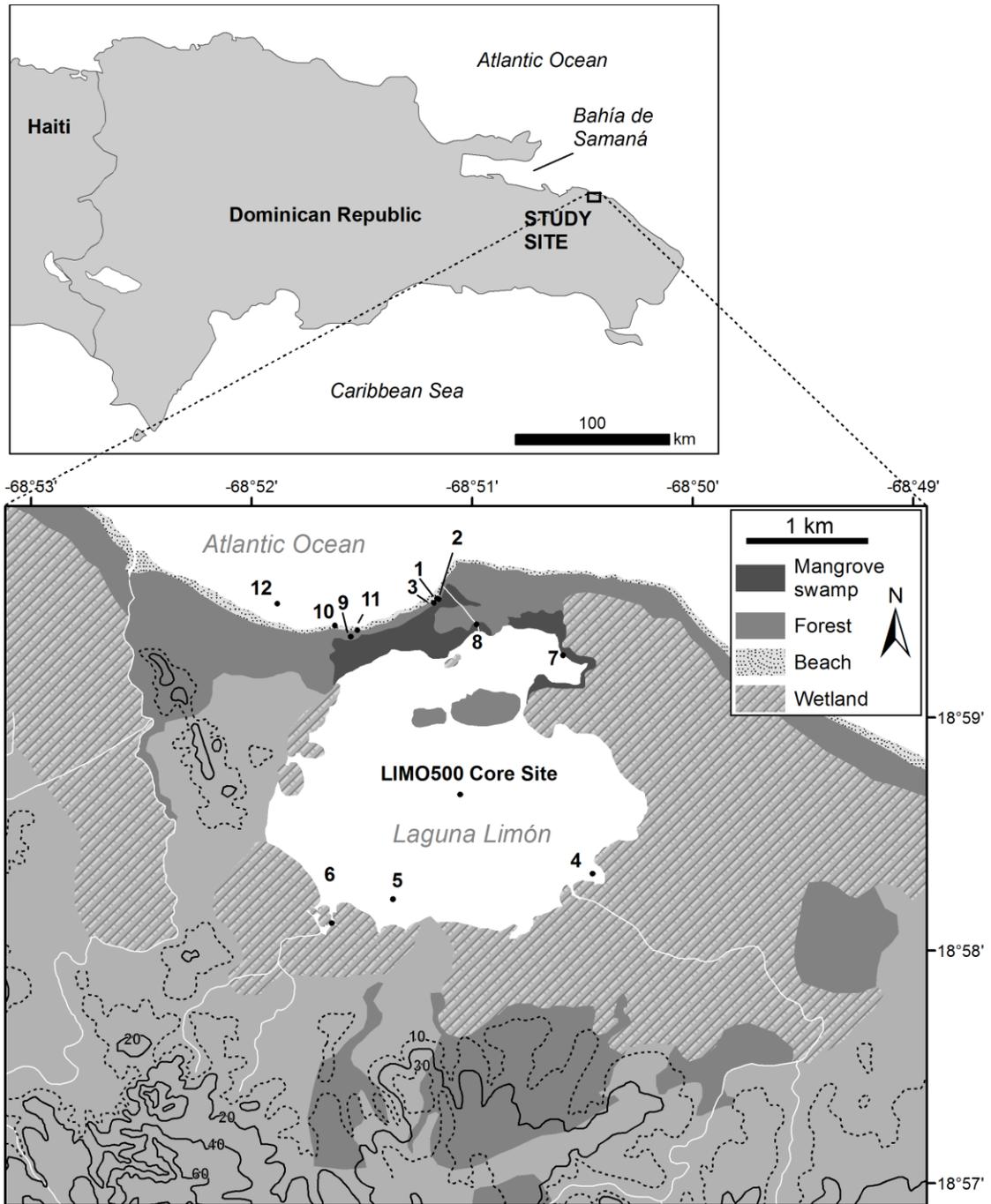


Figure 1. Map of the Laguna Limón area showing land covers and sediment core and surface sample locations. Elevations are in meters.

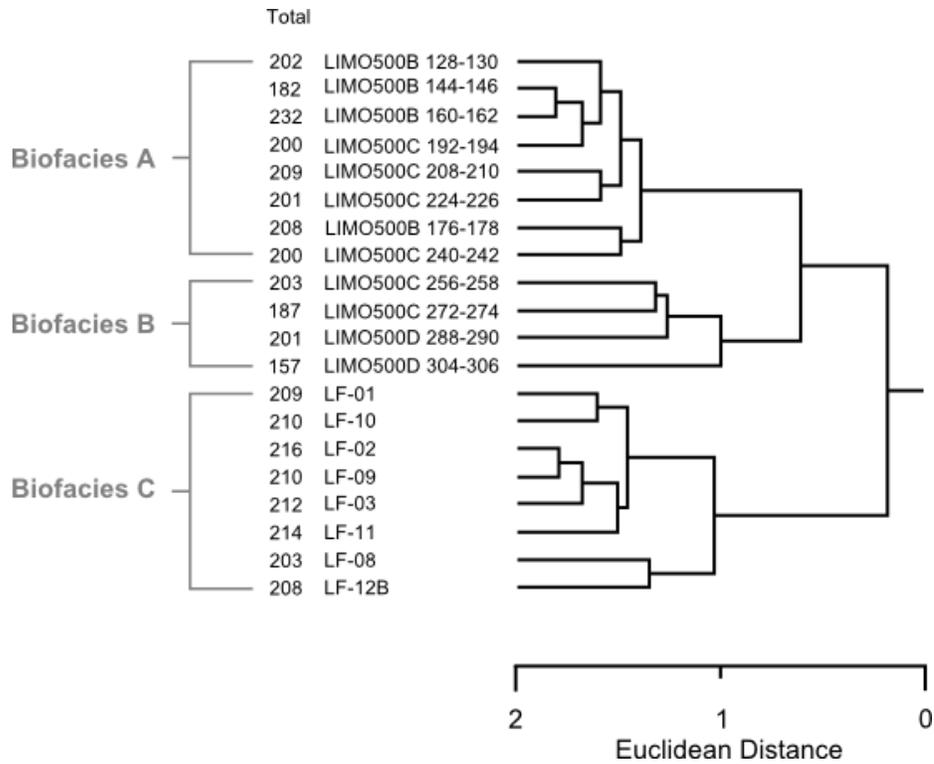


Figure 2. Dendrogram resulting from non-stratigraphically constrained cluster analysis of arcsine-square root transformed foraminiferal abundance data. The LIMO500 core encompasses biofacies A and B, while the surface samples cluster together as biofacies C.

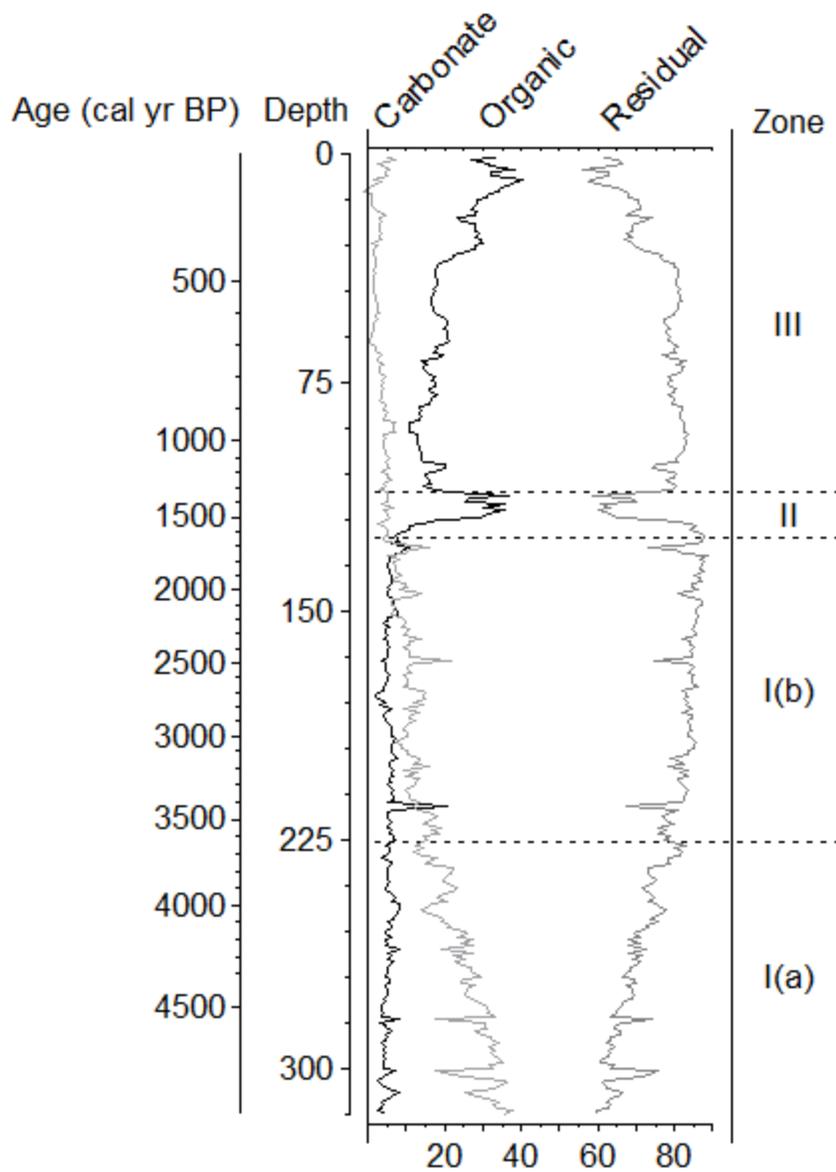


Figure 3. Loss on ignition results for the LIMO500 sediment core (1 cm resolution) compared to foraminiferal species associations. Estimated ages (left column) are based on the age-depth curve constructed from the calibrated radiocarbon dates (Table 1; and McVay 2013)

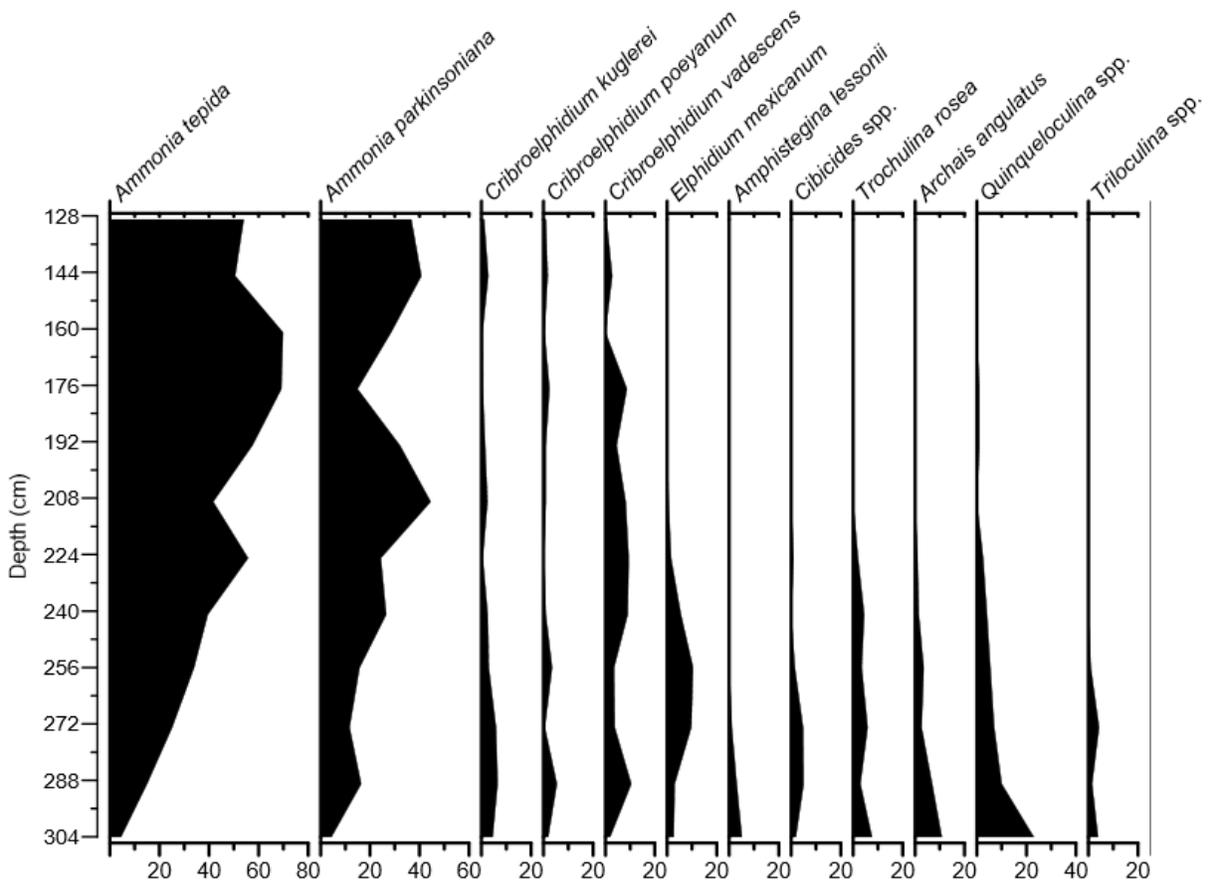


Figure 4. Species abundance diagrams for the most common foraminifera (>5%) encountered in the LIM050 sediment samples. Abundance values (x axis) are percentages of the total number of foraminifera per sample.

Chapter 2 Tables

Table 1. Calibrated ^{14}C ages for organic samples collected from the LIMO500 core, dated by Woods Hole Oceanographic Institute National Ocean Sciences Mass Spectrometry Facility and calibrated using the Calib 6. .1 program (Stuvier and Reimer 1993). BP = Before Present (where present is 1950 by convention).

Depth (cm)	Type	^{14}C yr BP	Cal yr BP $\pm 2\sigma$	Cal yr BP $\pm 2\sigma$ (mean)	Cal yr AD/BC $\pm 2\sigma$ (mean)
54	Charcoal	580 ± 35	580–652	616	1334 AD
96	Charcoal	1130 ± 20	969–1070	1020	930 AD
196	Charcoal	2940 ± 30	2995–3212	3104	1154 BC
272	Charcoal	3970 ± 35	4382–4525	4453	2503 BC
313	Wood	4150 ± 40	4569–4828	4697	2747 BC

Table 2. Mean, minimum, and maximum values for organic, carbonate, and silicate content (in percent) by zone, derived from loss-on-ignition analysis of the LIMO500 core.

Zone	Depth (cm)		% Organic	% Carbonate	% Silicate
III	111–surface	Max	40	7	43
		Min	11		56
		Mean	21	3	76
II	126–111	Max	37	6	88
		Min	2	2	58
		Mean	22	5	73
I(b)	226–126	Max	21	22	89
		Min	2	4	68
		Mean	6	11	83
I(a)	315–226	Max	8	38	83
		Min	2	12	60
		Mean	5	25	69

Table 3. Foraminiferal species present in each cluster as determined by non-stratigraphically constrained cluster analysis (Figure 2), listed in order of averaged relative abundance.

Biofacies A (128–242 cm)		Biofacies B (256–306 cm)		Biofacies C (Surface samples*)	
<i>Ammonia tepida</i>	56%	<i>Ammonia tepida</i>	21%	<i>Trochulina rosea</i>	40%
<i>Ammonia parkinsoniana</i>	31%	<i>Ammonia parkinsoniana</i>	12%	<i>Archais angulatus</i>	14%
<i>Criboelphidium vadeszens</i>	5%	<i>Quinqueloculina</i> spp.	11%	Rotaliina (indeterminate)	10%
<i>Criboelphidium kugleri</i>	1%	<i>Elphidium mexicanum</i>	6%	<i>Quinqueloculina</i> spp.	8%
<i>Quinqueloculina</i> spp.	1%	<i>Archais angulatus</i>	6%	Miliolidae (indeterminate)	6%
<i>Criboelphidium poeyanum</i>	1%	<i>Trochulina rosea</i>	5%	<i>Articulina</i> spp.	4%
<i>Elphidium mexicanum</i>	1%	<i>Criboelphidium kugleri</i>	5%	<i>Amphistegina lessonii</i>	4%
<i>Trochulina rosea</i>	1%	<i>Criboelphidium vadeszens</i>	5%	<i>Asterigerina carinata</i>	2%
<i>Bolivina lowmani</i>	<1%	<i>Cibicides</i> spp.	3%	<i>Cibicides</i> spp.	2%
<i>Archais angulatus</i>	<1%	<i>Asterigerina carinata</i>	3%	<i>Triloculina</i> spp.	2%
<i>Nonionella atlantica</i>	<1%	<i>Criboelphidium poeyanum</i>	3%	<i>Borelis pulchra</i>	1%
<i>Eponides antillarum</i>	<1%	<i>Triloculina</i> spp.	3%	<i>Peneropolis</i> spp.	1%
<i>Bolivina striatula</i>	<1%	<i>Amphistegina lessonii</i>	2%	Soritiidae (indeterminate)	1%
Rotaliina (indeterminate)	<1%	Soritiidae (indeterminate)	2%	<i>Reusella</i> spp.	1%
Soritiidae (indeterminate)	<1%	<i>Rosalina subarucana</i>	1%	<i>Elphidium sagrum</i>	1%
<i>Valvulina</i> spp.	<1%	<i>Articulina</i> spp.	1%	<i>Spiroculina</i> spp.	<1%
<i>Asterigerina carinata</i>	<1%	<i>Eponides antillarum</i>	1%	<i>Elphidium discoidale</i>	<1%
<i>Cibicides</i> spp.	<1%	<i>Nonion grateloupi</i>	1%	<i>Rosalina</i> spp.	<1%
<i>Articulina</i> spp.	<1%	<i>Elphidium discoidale</i>	1%	<i>Rosalina floridana</i>	<1%
<i>Elphidium discoidale</i>	<1%	<i>Elphidium sagrum</i>	1%	<i>Textularia</i> spp.	<1%
<i>Elphidium sagrum</i>	<1%	<i>Siphonina pulchra</i>	1%	<i>Eponides antillarum</i>	<1%
<i>Planorbulina</i> spp.	<1%	Rotaliina (indeterminate)	1%	<i>Neoconorbina orbicularis</i>	<1%
Miliolidae (indeterminate)	<1%	<i>Planorbulina</i> spp.	1%	<i>Nonionella atlantica</i>	<1%
<i>Nonion grateloupi</i>	<1%	<i>Rosalina</i> spp.	1%	<i>Rosalina subarucana</i>	<1%
<i>Buliminella</i> spp.	<1%	<i>Valvulina</i> spp.	1%	<i>Siphonina reticulata</i>	<1%
<i>Nonion</i> spp.	<1%	<i>Nonionella atlantica</i>	<1%	<i>Siphonina</i> spp.	<1%
		<i>Reusella</i>	<1%	<i>Planorbulina</i> spp.	<1%

<i>Buliminella</i> spp.	<1%	<i>Bolivina</i> spp.	<1%
<i>Astrononion</i> spp.	<1%	<i>Siphonina pulchra</i>	<1%
<i>Bolivina lowmanii</i>	<1%	<i>Uvigerina</i> spp.	<1%
<i>Bolivina striatula</i>	<1%		
<i>Siphonina</i> spp.	<1%		
<i>Uvigerina</i> spp.	<1%		
Textulariina (indeterminate)	<1%		
<i>Haynesina</i> spp.	<1%		
<i>Milliolinella</i> spp.	<1%		
<i>Spiroculina</i> spp.	<1%		
<i>Nonion</i> spp.	<1%		
Miliolidae (indeterminate)	<1%		

Appendix A

Species reference list. Taxa in this study which have been identified to the species level.

- Ammonia parkinsoniana* (d'Orbigny) = *Rosalina parkinsoniana*, d'Orbigny, 1839.
Ammonia tepida (Cushman) = *Rotalia beccari* (Linne) var. *tepida*. Cushman, 1926.
Amphistegina lessonii d'Orbigny, 1826.
Archais angulatus = *Nautilus angulatus* Fichtel and Moll, 1803.
Asterigerina carinata d'Orbigny, 1839.
Bolivina lowmani Phleger and Parker, 1951.
Bolivina striatula Cushman, 1922.
Borelis pulchra (d'Orbigny, 1839) = *Alveolina pulchra* d'Orbigny, 1839.
Trochulina rosea (Guérin-Méneville, 1832).
Elphidium discoidale (d'Orbigny, 1839) = *Polystomella discoidale* d'Orbigny, 1839.
Criboelphidium kuglerei Cushman & Bronnimann, 1948.
Elphidium mexicanum Kornfeld, 1931.
Criboelphidium poeyanum (d'Orbigny, 1826) = *Polystomella poeyana* (d'Orbigny, 1826).
Elphidium sagram (d'Orbigny, 1826) = *Polystomella sagra* d'Orbigny, 1826.
Criboelphidium vadescens Cushman and Bronniman, 1948.
Eponides antillarum (d'Orbigny, 1839) = *Rotallina antillarum* d'Orbigny, 1839.
Neoconorbina orbicularis (Terquem, 1876) = *Rosalina orbicularis* Terquem, 1876.
Nonionella atlantica Cushman, 1936.
Nonionoides grateloupi (d'Orbigny, 1839) = *Nononina grateloupi* d'Orbigny, 1839.
Rosalina floridana (Cushman, 1922) = *Discorbis floridana* Cushman, 1922.
Rosalina subarucana (Cushman, 1922) = *Discorbis subarucana* Cushman, 1922.
Siphonina pulchra Cushman, 1919
Siphonina reticulata Czjzek, 1884.

Appendix B

Foraminiferal census data from the LIMO500 core and Laguna Limón surface samples.

Taxon	LIMO500 Core Samples												Surface Samples							
	128	144	160	176	192	208	224	240	256	272	288	304	01	02	03	08	09	10	11	12
<i>Ammonia</i> (ind. juveniles)	14	1			1					6										
<i>Ammonia parkinsoniana</i>	74	74	66	31	64	93	49	53	32	22	33	7								
<i>Ammonia tepida</i>	109	92	162	144	115	87	112	79	69	47	30	7								
<i>Amphistegina lessonii</i>										2	6	8	6	11	14	4	8	8	7	6
<i>Archais angulatus</i>							2	3	7	5	14	17	31	37	35	27	45	42	17	15
<i>Articulina</i> spp.								1		5	3	1	12	16	11	3	5	10	9	5
<i>Asterigerina carinata</i>							1	1	5	6	4	7	3	2	7	5	1	3	6	9
<i>Astrononion</i> spp.									1	1										
<i>Bolivina lowmani</i>		2	2	2	2				1		1									
<i>Bolivina</i> spp.																1				
<i>Bolivina striatula</i>				1	1			1				1								
<i>Borelis pulchra</i>													3	2	1	1	4	2	2	1
<i>Buliminella</i> sp.				1					1	1										
<i>Cibicides</i> spp.							2		3	9	10	3	3	2	1	9	2		1	15
<i>Criboelphidium kuglerei</i>	2	5	1	1	3	5	1	5	6	11	13	7								
<i>Criboelphidium poeyanum</i>	2	3	1	5	2	2		2	7	1	11	3								
<i>Criboelphidium vadescens</i>	1	5		18	9	17	19	18	7	7	21	3								
<i>Elphidium discoidale</i>								1	3		5				2					3
<i>Elphidium mexicanum</i>					1	3	11	21	18	6	4									
<i>Elphidium sagrum</i>								1	3	1	1	2	1		4			4	1	
<i>Eponides antillarum</i>						2	1	2	1		5			1	2	1				
<i>Haynesina</i> spp.										1										
Miliolidae-indeterminate								1					7	16	18	16	12	15	10	13
Miliolinella spp.											1									
<i>Neoconorbina orbicularis</i>													1		2					
<i>Nonion</i> spp.					1			1												
<i>Nonionella atlantica</i>				3				1	2		2		1		1					1
<i>Nonionoides grateloupi</i>						1				1		6								
<i>Peneropolis</i> spp.														1		5	1		3	3
<i>Planorbulina</i> spp.								1	3	1		2		1						1
<i>Quinqueloculina</i> spp.			2	2		5	8	11	13	20	36	18	13	11	38	6	12	15	15	16
<i>Reussella</i> spp.								1	1		1	2	2		4	1			1	1
<i>Rosalina floridana</i>															4					
<i>Rosalina</i> spp.											4									5
<i>Rosalina subarucana</i>								4			5				2					

Rotaliina- indeterminate					3				3		4		27	14	11	20	16	27	36	22		
<i>Siphonina pulchra</i>									1		4	2	1									
<i>Siphonina reticulata</i>																2						
<i>Siphonina</i> spp.												1							1	1		
Soritii dae- indeterminate									2		7	1	3	7				6				
<i>Spiroculina</i> spp.												1					2			6		
<i>Textularia</i> spp.																	3			1		
Textulariina- indeterminate													1									
<i>Triloculina</i> spp.											2	8	3	6	7	3	1	7	3	2	3	4
<i>Trochulina rosea</i>									4	9	7	11	6	12	79	95	102	39	105	79	101	80
<i>Uvigerina</i> spp.														1							1	
<i>Valvulina</i> spp.										1		1	1	2								
Total Count	202	182	232	208	200	209	201	200	203	187	201	157	209	216	212	203	210	210	214	208		