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Holocene Climate and Environmental History of Laguna Saladilla, Dominican Republic

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I am submitting herewith a dissertation written by Maria Anne Caffrey entitled "Holocene Climate and Environmental History of Laguna Saladilla, 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, Major Professor

We have read this dissertation and recommend its acceptance:

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

Holocene Climate and Environmental History of
Laguna Saladilla, Dominican Republic

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

Maria Anne Caffrey
May 2011

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I am very grateful for the assistance of my colleagues at the University of Tennessee and other universities. I would like to thank my dissertation committee members, Henri Grissino-Mayer, Liem Tran, and David Finkelstein, for their guidance, help with statistics, and edits on the dissertation. I also thank David Finkelstein for his help in the analyses of water samples and the identification of manganese fragments. In addition to his role in obtaining funds for this project, Ken Orvis, together with Sally Horn and Duane Cozadd, retrieved the Laguna Saladilla sediment core in 2001, and

opened and described core sections. Ken later identified shell remains from the lower levels in the profile. Lawrence (Larry) Conyers at the University of Denver was instrumental in the collection and analyses of the ground penetrating radar data. Kurt Haberyan at Northwest Missouri State University assisted in the identification of diatoms.

To undertake a work of this magnitude over the past four years has required the help of many people, most notably my colleagues in the University of Tennessee's Laboratory of Paleoenvironmental Research, who have been a constant source of support and good humor. Their support has been invaluable, whether it be for bouncing ideas off of each other, commiserating when I have encountered setbacks, or celebrating an achievement. In particular, I thank Ian Slayton, Brian Watson, Joshua Albritton, Alisa Haas, Matthew Valente, and Alicia Smith. Alicia Smith assisted by counting manganese fragments from Laguna Saladilla on pollen slides. Grant Harley in the University of Tennessee's Laboratory of Tree-Ring Science provided help with graphics. I would especially like to thank Ian Slayton for his help in the lab and in the field in the Dominican Republic. His valor in the face of countless cold showers and mosquitoes while visiting Laguna Saladilla went beyond the call of duty for any field assistant. I would further like to thank Javier Hernandez from Carbonera, Dominican Republic for his assistance in the field.

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ABSTRACT

Stratigraphic analyses of lacustrine sediments provide powerful tools for reconstructing past environments. The records that result from these analyses are key to understanding present-day climate mechanisms and how the natural environment may respond to anthropogenic climate change in the future. This doctoral dissertation research investigates climate and environmental history at Laguna Saladilla (19° [degrees] 39' N, 71° [degrees] 42' W; ca. 2 masl), a large (220 ha) lake along the north coast of Hispaniola.

I reconstructed changes in vegetation and environmental conditions over the mid- to late Holocene based on pollen, microscopic charcoal, and diatoms in an 8.51 m sediment core recovered from the lake in 2001. Fieldwork in December 2009 included the use of ground penetrating radar to identify subaqueous deltas that indicate past positions of the Masacre river, which flows into the lake from the Cordillera Central.

Laguna Saladilla was deeper and more saline from the base of the sediment profile approximately 8030 cal yr BP to about 3500 cal yr BP. Mangrove (*Rhizophora*) pollen percentages were highest around 7650 cal yr BP, when mollusk shells in the core suggest marine conditions. The lake became progressively brackish ca. 3500 cal yr BP, followed by a transition ca. 2500 cal yr BP to its current freshwater state. This shift in water chemistry was likely due in part to a change in the position of the Masacre river. Diatoms show that lake levels decreased as evaporation/precipitation ratios increased. Amaranthaceae and other herbs dominated the pollen record under the drier conditions of

the last 2500 cal yr BP; pollen of fire-adapted taxa, particularly *Pinus*, increased in the last 800 years.

Patterns of microscopic charcoal influx at Laguna Saladilla over the Holocene are similar to patterns at Lake Miragoane, Haiti and Laguna Tortuguero, Puerto Rico. The changes in fire frequency or extent indicated by these Caribbean charcoal records may be driven by increased winter insolation at ca. 5000 cal yr BP that led to earlier winter drying. Comparing the charcoal record to archeological data and other paleoenvironmental records facilitated the disentangling of changes in climate from anthropogenic impacts.

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CHAPTER 1

INTRODUCTION AND OVERVIEW

1.1 Introduction

Islands are dynamic landscapes that present myriad opportunities and challenges to interpreting the drivers and impacts of climate change over time. The island of Hispaniola (19°N, 71°W) is positioned in a region where global ocean-atmospheric interactions dictate climate. However, relatively little is known of how these climate mechanisms in the Caribbean have operated in the past (Hodell et al. 1991; Hurrell et al. 2001; Bates et al. 2008). Reconstructions of changes in vegetation and other environmental factors based on materials preserved in lake sediments can provide valuable information about variations in synoptic climate patterns within the tropics in the past, and can potentially be used as analogs to determine how the natural environment could react to anthropogenic climate change in the future.

This research examines changes in Caribbean climate and environments over the past ca. 8000 years using a lacustrine sediment core from Laguna Saladilla (Figure 1.1), a large coastal lake located just inland of the north coast of Hispaniola, on the Dominican side of the border with Haiti. The 8.51 m Saladilla sediment core (Figure 1.2) was recovered with National Geographic Society funding by Drs. Sally Horn and Ken Orvis in 2001. The base of the core contains mostly marine shells and sandy silts layered with sand, indicating that the lake was more saline in the past, before becoming fresh. Accelerator mass spectrometry radiocarbon dates together with shell and diatom data indicate that conditions were marine to brackish from 8031 cal yr BP until around 2500 cal yr BP, and fresh thereafter. The Laguna Saladilla core is one of several cores that are the focus of NSF grant #0550382 awarded to Horn, Orvis, and Dr. Claudia

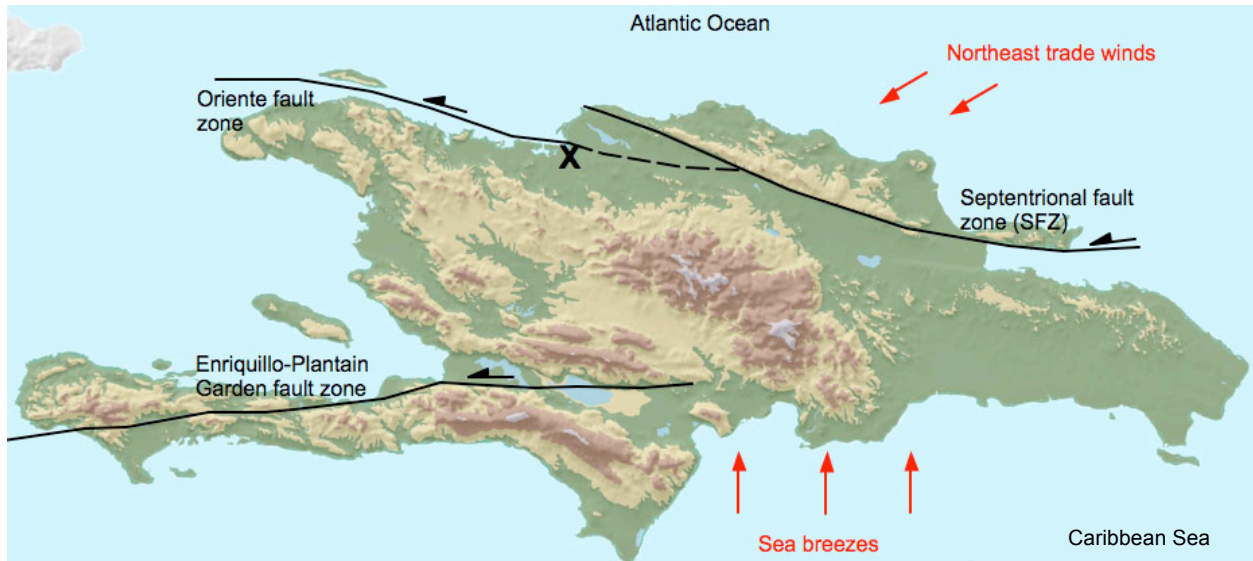


Figure 1.1: Major climatic and tectonic drivers of environmental change on the island of Hispaniola. “X” indicates the location of Laguna Saladilla. Dashed line shows the inferred western extension of the Septentrional fault zone (Mann et al. 1991, 1998).

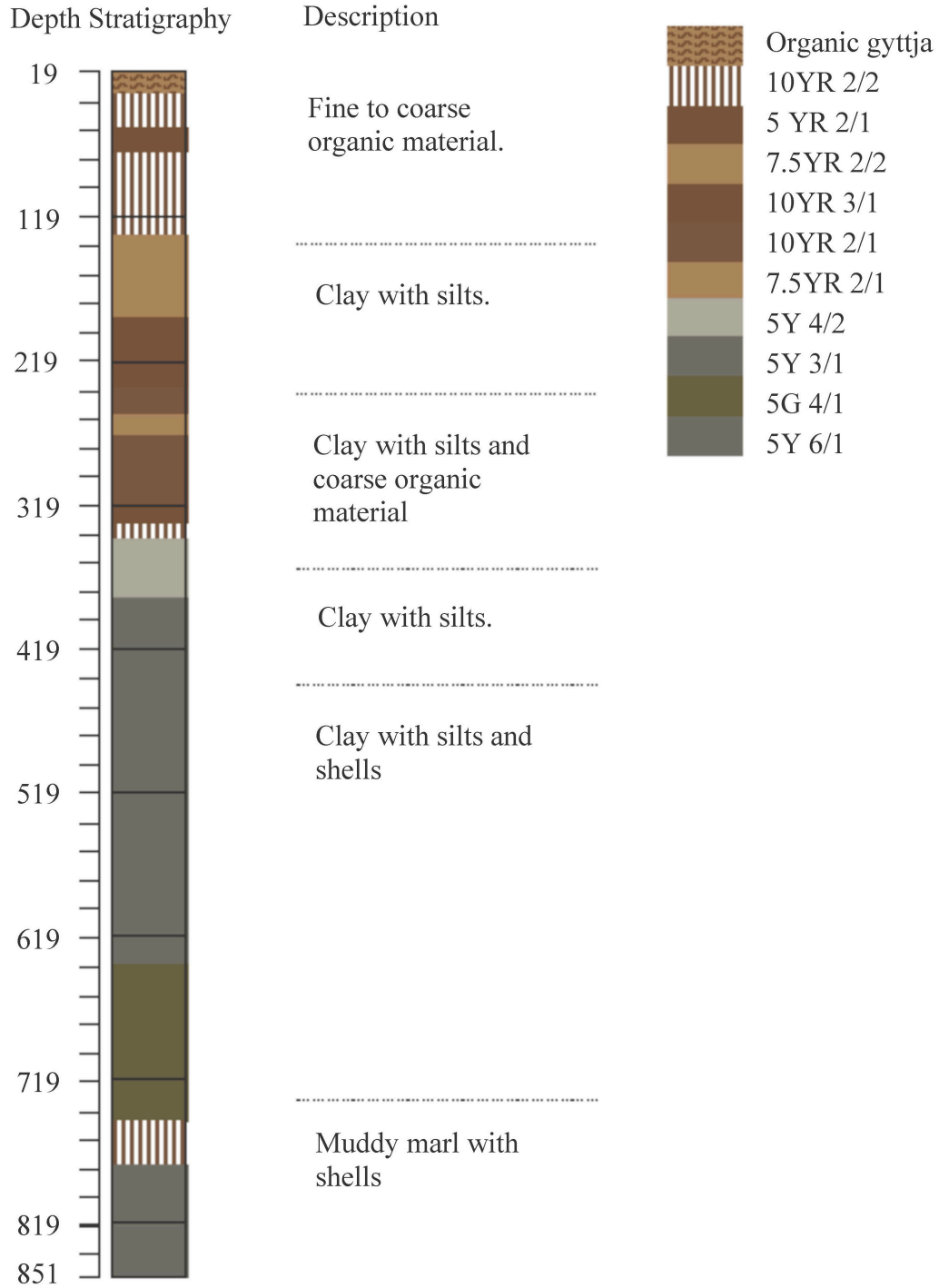


Figure 1.2: Stratigraphy of the Laguna Saladilla sediment core. The upper 19 cm of organic sediment collected in the mud-water interface core is not shown.

Mora for research on Dominican paleoclimates. A December 2009 visit to the site to conduct ground penetrating radar (GPR) analyses and collect water and surface sediment samples was funded by National Science Foundation grant #0927619, a doctoral dissertation research improvement grant awarded to Maria Caffrey and Sally Horn.

The original NSF grant for work on the Saladilla core included pollen and microscopic charcoal analysis at the University of Tennessee, and coarse-resolution diatom analysis by collaborator Kurt Haberyan of Northwest Missouri State University. Haberyan found diatoms to be well preserved in samples taken at 17 levels in the core, and identified 42 marine and freshwater types. Assemblages were characterized qualitatively, rather than by the numerical abundance of different diatom taxa. I performed additional, quantitative diatom analyses of core samples that allowed me to determine changes in the lacustrine environment caused by changing climate and/or depositional conditions (Hecky and Kilham 1973). Adding diatom analyses allowed a more detailed reconstruction of past climate and paleoenvironment than was possible from pollen and microscopic charcoal analysis alone. To improve my ability to interpret the diatom assemblages in the Saladilla profile, I collected modern surface samples along transects across Laguna Saladilla, together with water samples and limnological data (Table 1.1).

I also added GPR characterization of the sediments in the lake basin to the original project. GPR and diatom analyses in combination allowed me to determine how the depositional environment of the lake has changed. Characterization of sediments is a relatively new application of GPR that has been successfully used on a number of Colorado lakes by Drs. Donald Sullivan and Lawrence Conyers of the University of Denver, with whom I worked to collect GPR data at Laguna Saladilla. Bristow and Jol (2003) have discussed the various

Table 1.1: Data collected in the field (December 2009) and quantified in the laboratory from water and dredge samples returned to the University of Tennessee⁺ and University of Denver[‡] (*indicates tests performed by D. Finkelstein).

Data collected in the field	Data collected in the laboratory
GPS coordinates (UTM 19 latitude/longitude/elevation)	Particle size (% sand, silt, clay) using a Beckman Coulter LS 13 320 series laser diffraction particle size analyzer [‡]
Photographs (facing N,E,S,W) from the boat at each dredge sample	Fluoride (ppm) using a Dionex ICS-2000 Ion Chromatography System ^{+*}
Filtered and unfiltered pH using EMD [™] colorpHast [™] testing strips	Chloride (ppm) using a Dionex ICS-2000 Ion Chromatography System ^{+*}
Unfiltered pH using a Fisher Scientific [™] Accumet AP series handheld pH/mV/Ion meter	Nitrite (ppm) using a Dionex ICS-2000 Ion Chromatography System ^{+*}
pH, alkalinity (CaCO ₃), total hardness, free chlorine, and total chlorine using Hach [™] AquaChek [™] 5 test multiparameter, multirange testing strips	Bromide (ppm) using a Dionex ICS-2000 Ion Chromatography System ^{+*}
Nitrite (10–500ppm) using EM [™] Quant [™] strips	Nitrate (ppm) using a Dionex ICS-2000 Ion Chromatography System ^{+*}
Nitrate (range 2–80ppm) using EM [™] Quant [™] strips	Sulfate (ppm) using a Dionex ICS-2000 Ion Chromatography System ^{+*}
Unfiltered water temperature (°C)	Potassium (ppm) using a Dionex ICS-2000 Ion Chromatography System ^{+*}
Water depth (m)	Magnesium (ppm) using a Dionex ICS-2000 Ion Chromatography System ^{+*}
Dredge samples to be transported back to the University of Tennessee and University of Denver for surface diatoms and particle size analysis	Calcium (ppm) using a Dionex ICS-2000 Ion Chromatography System ^{+*}
Two separate filtered water samples from each GPS point (one with 2–4 drops nitric acid added) to be analyzed at the University of Tennessee	Alkalinity (ppm) using a Dionex ICS-2000 Ion Chromatography System ^{+*}

applications of GPR in paleoecological studies. For example, GPR has been used to determine lake sediment thicknesses (Hunter et al. 2003; Sullivan and Carter 2009) and to characterize lake deposits (Jol and Smith 1991; Shuman et al. 2005; Shuman and Donnelly 2005). However, my work at Laguna Saladilla marks the first use of GPR at a lake in the Caribbean.

1.2 Drivers of Caribbean Climate Change

The interplay between the topography of Hispaniola and the prevailing trade winds is responsible for a diverse number of microclimates (García 1976). The climate is generally warm throughout the year, with wet conditions from May to November (Higuera-Gundy et al. 1999; McSweeney et al. 2008). Precipitation is lowest during the winter, when the North Atlantic subtropical high (NAH) moves south. The NAH is the dominant driver of Caribbean climate, creating high sea level pressure that leads to stronger trade winds and cooler sea-surface temperatures from January to March (Giannini et al. 2000, 2001a). This pattern is negatively correlated to changes in the North Atlantic Oscillation (NAO) (Giannini et al. 2001b). During positive phases of the NAO, the NAH is enhanced, resulting in decreased Caribbean rainfall.

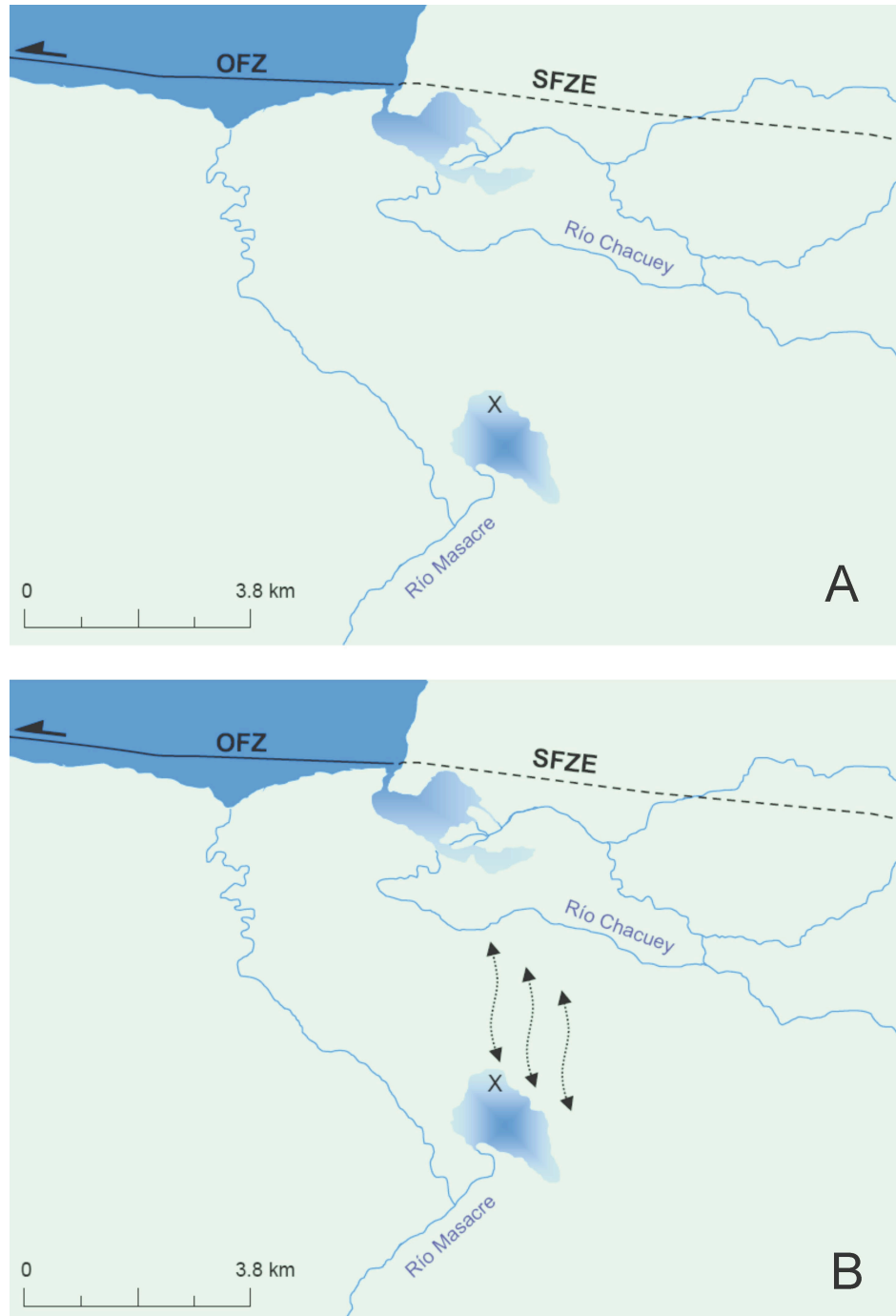
The NAH also shares important teleconnections with the El Niño-Southern Oscillation (ENSO), which creates anomalously high sea level pressure that produces stronger trade winds and drier than average conditions in the circum-Caribbean region during its mature phase (Giannini et al. 2000, 2001b). However, these dry ENSO conditions are preceded by wetter than average conditions during the spring and summer rainy season, especially in the Greater Antilles. Giannini et al. (2001b) observed that when ENSO events coincide with a positive phase of the NAO, Caribbean climatic conditions are at their driest and these conditions last longer. While the Caribbean climate of the last 100,000 yrs has been heavily influenced by changes in global

orbital position (McIntyre and Molino 1996), climate in the future is expected to change significantly due to anthropogenic alteration of the atmosphere that will alter the balance of climate drivers described above (Hurrell et al. 2001; IPCC 2007). Improved understanding of the drier phases that occurred in the past can contribute to preparations for drier conditions in the future, when anthropogenic warming could exacerbate natural occurrences of drought (Bates et al. 2008). Pollen grains, diatoms, charcoal fragments, and other proxy indicators in the sediments of Laguna Saladilla can provide key evidence of dry periods, and other aspects of past climate and environment at Laguna Saladilla.

1.3 Tectonic Drivers of Caribbean Environmental Change

While lacustrine sediments provide important evidence of past changes in climatic conditions, Carroll and Bohacs (1999) emphasized that any interpretation of stratigraphic data must take into account changes in the balance between tectonic and climatic controls. For example, changes in lake infill rates due to tectonic processes can alter the hydrologic environment and alter evaporation/precipitation (E/P) ratios as the depth of the lake decreases due to sediment accumulation (Carroll and Bohacs 1999).

Hispaniola is an agglomeration of 11 island arc terrains that range in age from the Late Cretaceous to the late Eocene (Mann et al. 1991). The Septentrional-Oriente and Enriquillo-Plantain Garden fault zones (Figure 1.1) are active faults roughly paralleling each other. They are responsible for a considerable amount of transpressional stress that has likely influenced rates of sediment infill to many of the lakes of Hispaniola as land has been uplifted, eroded, streams pirated, and the groundwater table altered (Figure 1.3; Dolan and Mann 1998).



Figures 1.3a, b: Examples of how movement of the Septentrional fault zone western extension (SFZE) could have altered the hydrology of Laguna Saladilla (coring location indicated by “X”). Dashed line represents the inferred western extension of the Septentrional; solid line represents the beginning of the Oriente Fault Zone (based on Mann et al. 1991, 1998). “A” shows the present-day position of the lake, the Río Masacre, and the Río Chacuey. “B” indicates how movement of the SFZE could have altered the groundwater (illustrated using dotted arrows) around the lake.

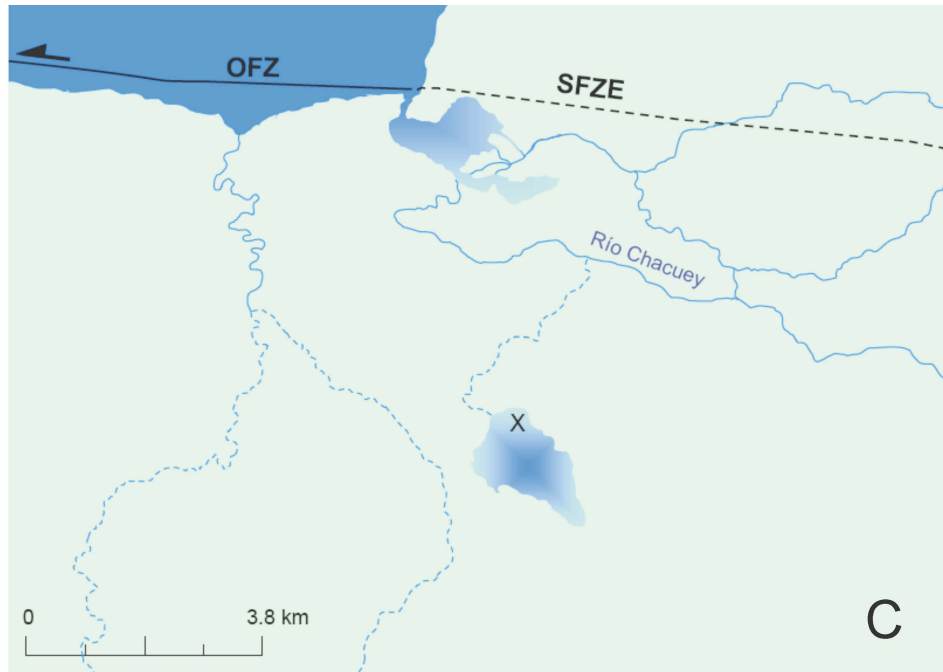


Figure 1.3c: The possible past positions of the Río Masacre and Río Chacuey (dashed blue lines) that could have been altered by movement of the SFZE (based on apparent extinct river channels interpreted from satellite images of the region).

Based on the geomorphology of the surrounding area, the Septentrional fault zone western extension (SFZE) could have altered the limnology of Laguna Saladilla in one or more ways. For example movement along the SFZE could have altered osmotic pressure within the aquifer resulting in transient flow between the lake and the Atlantic Ocean (ca. 5.3 km north of the site) or the surrounding Chacuey and Masacre Rivers. This could result in changes in lake water depth and salinity that would not be directly related to changes in climate (Figure 1.3b). In addition, displacement created by movement of the SFZE could have changed the position of the Chacuey River. Based on satellite images, it appears that various outlets may have existed in the past from Laguna Saladilla to the surrounding Chacuey and Masacre Rivers. If Laguna Saladilla was connected to the rivers at various times, then the limnology of the lake would have been significantly altered. However, these outlets have since been pirated by movement of the surrounding faults, changes in climate, or the build up of sediment (Figure 1.3c).

Other subaqueous features of the lake detectable using GPR may reveal evidence of changes in the lake and its outlets due to changes in tectonic balance (Carroll and Bohacs 1999). Changes in the position of the groundwater table are unlikely to be directly preserved in any turbidite features, but paleodeltas together with sedimentary diatom evidence can reveal changes in lake level and salinity in the past.

1.4 Research Questions and Objectives

The purpose of my research is to reconstruct changes in the climate of Hispaniola over the middle to late Holocene based on analyses of microfossils and other proxy indicators in a near-coastal sediment record. Other researchers have inferred paleoclimate from sediment records from Caribbean coastal regions, for example in Haiti (Higuera-Gundy et al. 1999),

Mexico (Islebe and Sanchez 2002), southern Florida (Liu and Fearn 2000), and Cuba (Peros 2007a, 2007b), but few have taken into account both the climatic and tectonic factors outlined above.

My study has several objectives. The main objectives are to (1) reconstruct how and when Laguna Saladilla changed from an estuarine water body to the freshwater lake that it is today; (2) examine evidence for climate and environmental change¹ during the lake's freshwater period by documenting pollen and diatom assemblages, microscopic charcoal concentrations, and the organic content of the sediments at close intervals; and (3) compare my results to other Caribbean records of Holocene climate and environmental change to reveal regional patterns. I take a regional approach in examining how changes in seasonality (driven by changes in insolation) affected the Caribbean fire record as documented in charcoal profiles from Laguna Saladilla and coastal lakes in Haiti and Puerto Rico. I hypothesize that changes in vegetation as well as fire at Laguna Saladilla are the result of changes in the intensity of seasonality during the Holocene.

Such changes in climate could have strongly influenced diatom assemblages in the Laguna Saladilla sediment core by changing local hydrological conditions. However, diatom composition also may have been affected by changes in the depositional environment caused by movement along the SFZE. Therefore, a fourth objective of this research is to examine whether evidence exists of variations in the physical properties of sediments across the lake. Such variations could point to buried features, such as sand deltas or axial mud fans (Figure 1.4) that can be used to reconstruct the previous position of inflowing waters. These lines of evidence

¹ For the purpose of this research evidence of "environmental change" will include evidence of changes in vegetation, fire occurrence, and hydrology at and around Laguna Saladilla.

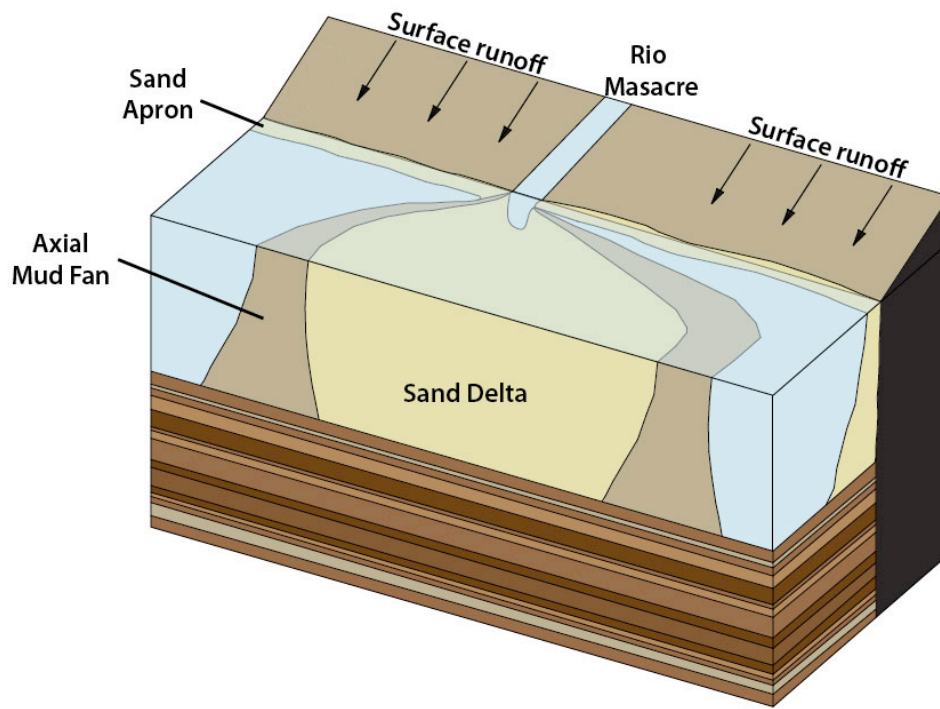


Figure 1.4: An illustration of some of the limnological features that may be present in Laguna Saladilla.

related to tectonic impacts on the lake can be assessed in combination with evidence of climatic influences to reconstruct the drivers of changes in lake salinity.

Based on the objectives above, eight research questions can be posed:

1. How has vegetation near the lake changed over the past ca. 8000 years?
2. What trends are apparent in fire occurrence based on sedimentary charcoal?
3. Does the Saladilla sediment profile preserve evidence of human influences on the environment (e.g. agricultural pollen, pollen indicators of clearing of the dry forest vegetation, charcoal evidence of increased burning)?
4. How does the microscopic charcoal record compare with records from Haiti and Puerto Rico, and what do these patterns suggest about the impact of changes in insolation on regional fire occurrence?
5. What is the timing and nature of the change from brackish to fresh conditions at Laguna Saladilla?
6. Does GPR show evidence of paleodeltas within the lake that could indicate shifts in positions of surrounding rivers?
7. How did diatom communities change over time at Laguna Saladilla?
8. How do modern-day diatom communities vary within Laguna Saladilla?

1.5 Dissertation Organization

This dissertation is organized into six chapters. Chapter 2 describes the study area and reviews relevant literature. Chapters 3, 4, and 5 are organized as research manuscripts that each address one or more of the aforementioned research questions.

Chapter 3 addresses questions related to the depositional environment of the lake. This

chapter introduces bathymetric data that will be used in later chapters as well as a new method of interpreting GPR data to determine boundary properties of underlying sediments (relating to particle size).

Chapter 4 focuses on charcoal evidence of fire history from Laguna Saladilla and compares the data to charcoal records from Lake Miragoane, Haiti and Laguna Tortuguero, Puerto Rico. I examine whether changes in fire activity occurred at similar times across the region, which could indicate a regional shift in climate. Archeological evidence from the region is discussed and compared to changes in charcoal values at each site.

Chapter 5 combines the sedimentary reconstructions from Chapter 3 and the regional charcoal analyses from Chapter 4 with pollen and diatom results to reconstruct changes in vegetation and lake salinity during the Holocene. Using these multiple lines of evidence, informed by the literature discussed in Chapter 2, allows me to describe and interpret the impacts of climate, eustasy, fluvial dynamics, and humans on the Laguna Saladilla record.

In Chapter 6, I conclude my dissertation by returning to my original research questions and objectives and summarizing my results from the preceding chapters. Five appendices follow the conclusion: Appendix I summarizes the pollen and microscopic charcoal preparation procedure; Appendix II lists diatom species identified in surface sediments and sediment core samples from Laguna Saladilla; Appendix III shows the GPR profiles collected across the lake in December 2009; and Appendix IV shows where samples were taken for pollen and diatom analyses along the Laguna Saladilla sediment core. Finally, Appendix V presents a table showing where marine shells were found in the core.

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CHAPTER 2

STUDY AREA AND RESEARCH CONTEXT

2.1 Laguna Saladilla and its Physical and Human Setting

Laguna Saladilla (19.6°N, 71.7°W, 2 masl¹) is a large (220 ha) freshwater lake located approximately 5.3 km south of the northwest coast of the Dominican Republic (Figure 2.1). The surrounding vegetation is mostly xerophytic shrubs, cacti, and grasses with abundant aquatic vegetation (particularly *Typha*) around the edges of the lake (Figure 2.2). Despite its large size, the lake is shallow (1.18 m mean depth²).

2.1.1 Geologic Setting

Hispaniola has undergone a number of transformations since its earliest island arc formation when the North American plate collided with the Caribbean plate during the Late Cretaceous–Eocene (Mann et al. 1991). Movement along the northern boundary of the Caribbean plate against the eastern margin of the North American plate created a number of left-lateral faults. Laguna Saladilla lies approximately 5.4 km south of the inferred western extension of the Septentrional fault zone (SFZE), in a region where the extension has been buried by alluvial deposits of the Río Yaque Del Norte (Figure 2.3) (Mann et al. 1998). Based on GPS data from nearby Capotillo, current-day movement along the SFZE is at a rate of 11.7 ± 1.3 mm/yr (Dixon et al. 1998; Mann et al. 1998).

¹ Based on interpreted elevation from 1:50,000-scale topographic map, relative to local sea level. GPS elevation recorded in the field was 14 m.

² Based on two-way travel time of GPR energy across 26 transects across the lake.

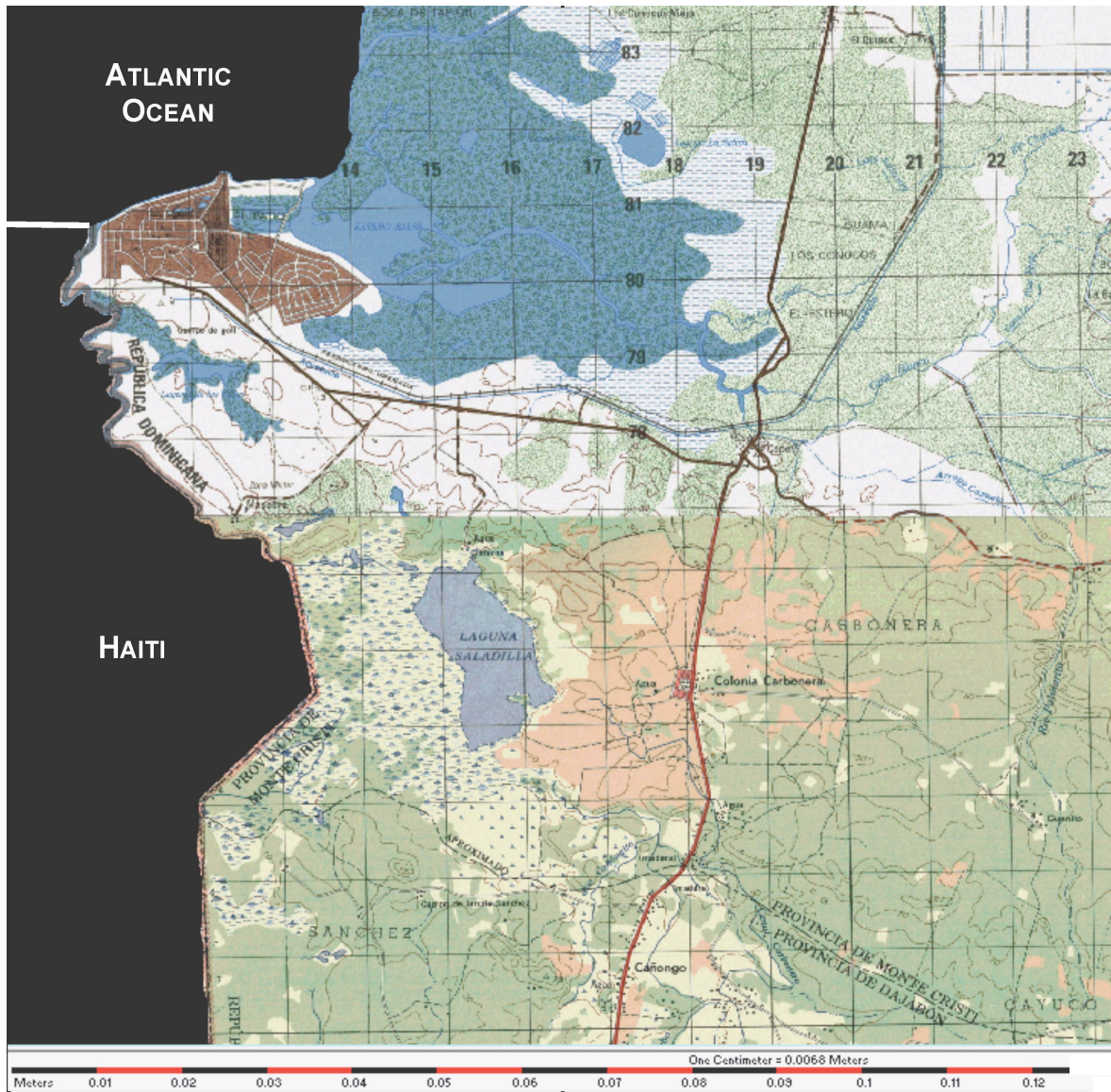


Figure 2.1: Portion of a topographic map of the Dominican Republic showing Laguna Saladilla and surroundings. Squares are 1 km x 1 km. Black shading indicates Haiti to the west, and the Atlantic Ocean to the north. The coastline of Haiti runs approximately E-W from the mouth of the Río Masacre (upper left of map, west of the community of Pepillo Salcedo, shaded brown) to the left margin of the map (shown by white line). Source: Instituto Geográfico Nacional de la República Dominicana (2002).

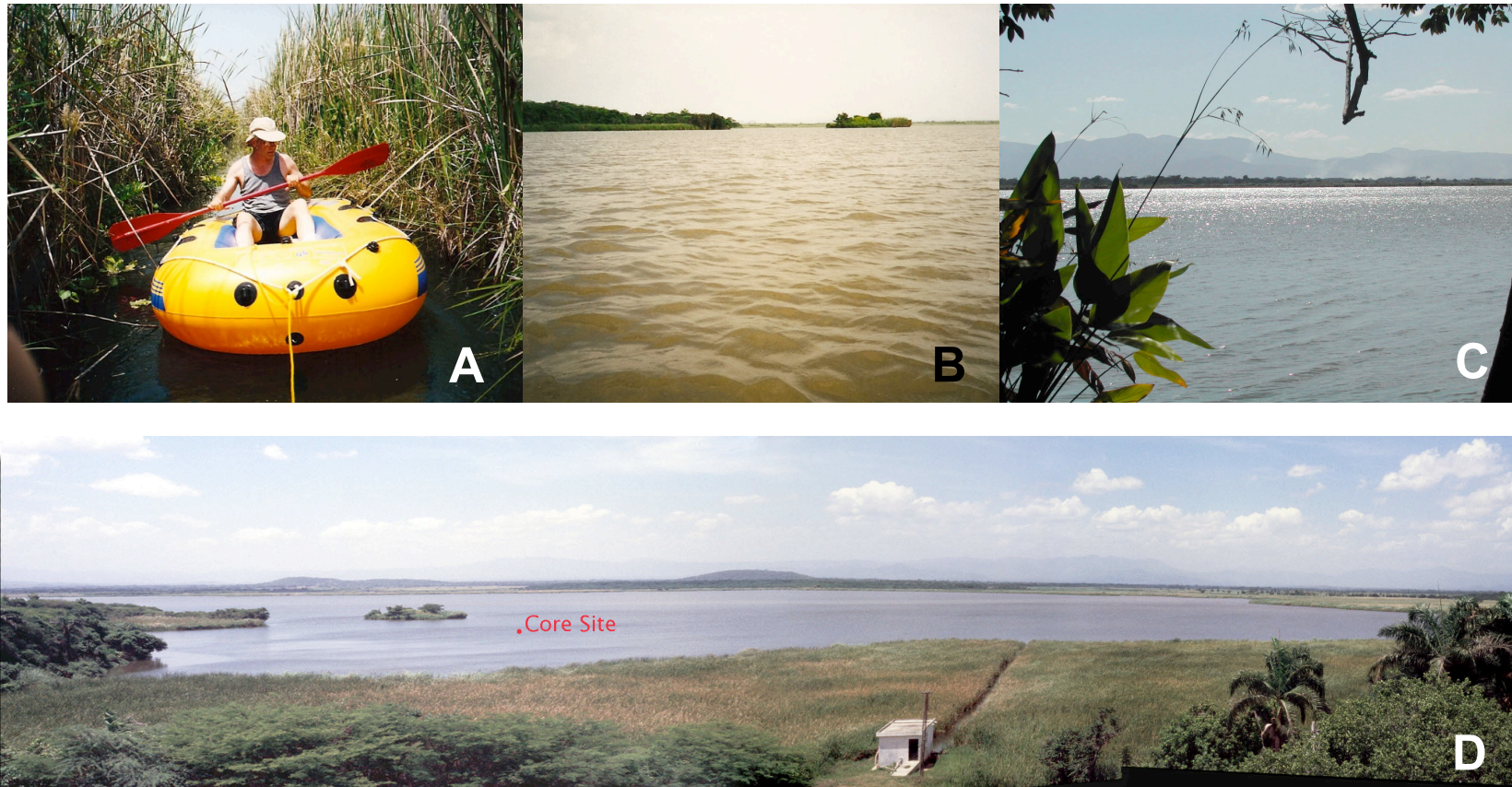


Figure 2.2a: K. Orvis maneuvering a raft through a floating *Typha* mat to access the lake in 2001 (photograph taken by S.P. Horn). Figure 2.2b: A view of the lake from the core site in 2001 (photograph taken by S.P. Horn). Figure 2.2c: Anthropogenic burning observed from Laguna Saladilla during fieldwork in December 2009. Picture is taken facing the Dominican Republic-Haiti border (photograph taken by D. Sullivan). Figure 2.2d: Panoramic montage showing Laguna Saladilla and approximate location of core site in 2001 (mosaic image created by K. Orvis from photographs taken by S. Horn). Foreground vegetation is largely *Typha*. Channel of open water is associated with the former use of Laguna Saladilla as a water source for nearby towns. The pump house and associated structures shown above were abandoned when I visited the site in December 2009.

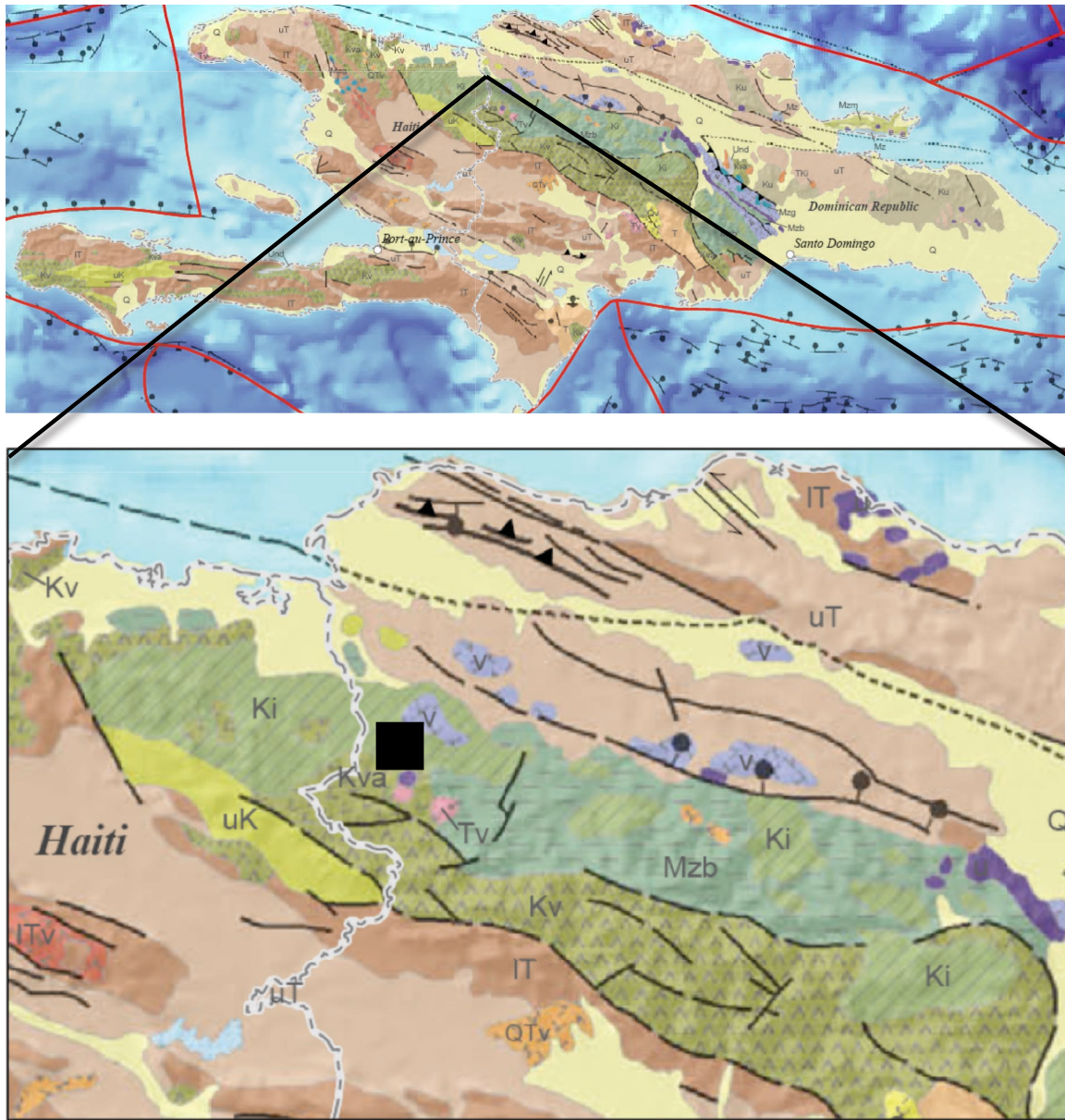


Figure 2.3: Geologic map of the region, modified from French and Schenk (1997). The approximate location of Laguna Saladilla is indicated by ■. Black dotted line indicates the Septentrional Fault Zone (SFZ) and the SFZE Western Extension. Q = Quaternary alluvium; QTv = Quaternary and Tertiary volcanic edifices, flows, tuff, silicic pyroclastic and volcanic epiclastic rocks; uT = Post-Eocene marine strata; ITv = Eocene and Paleocene volcanic flows and associated pyroclastic and volcanic sedimentary rocks; Tv = Tertiary volcanic rocks; IT = Eocene and (or) Paleocene marine strata; Kv = Cretaceous volcanic rocks; Kva = Cretaceous andesitic to silicic volcanic rocks; Ki = Cretaceous plutons (mostly intermediate to silicic); uK = Upper Cretaceous marine strata, Mzb = Mesozoic amphibolites and associated metasedimentary rocks; v = volcanic rocks.

2.1.2 Climate

The Saladilla site is uniquely positioned between the northwest to southeast trending Cordillera Septentrional and Cordillera Central, which shelter the site from Atlantic northeasterlies and sea breezes from the northeast and south, respectively (Figure 1.1). Atlantic northeast trade winds are the dominant source of precipitation for Hispaniola as a whole, but Laguna Saladilla receives most of its precipitation during the winter, when occasional cold fronts (Atlantic *nortes*) move in from the north (Bolay 1997; Hodell et al. 2008). Because of its relatively sheltered position, the site receives less than 700 mm/yr precipitation, while some regions of Hispaniola receive more than 2400 mm/yr (Bolay 1997). Mean annual maximum temperatures in nearby Monticristi are around 31.5 °C and mean annual minimum temperatures are around 21.5 °C. Temperatures are highest in August, when mean daily maxima reach 33.8 °C, and lowest in January (28.9 °C) (WMO 2011, data for 1961–1990).

2.1.3 Vegetation and Fire

Laguna Saladilla is located within the broad dry forest zone of Hispaniola as mapped by Holdridge (1945) (Figure 2.4, Table 2.1). Dry forest vegetation has been subject to extensive alteration and exploitation, especially during the post-Columbian era (Roth 1999). This is particularly the case in neighboring Haiti, where extensive deforestation for fuel and land-clearing has taken place. Roth (1999) broadly described the tropical dry forest as "a low, shrubby, and thorny xerophytic woodland of variable density composed mainly of Leguminous and Cactaceous species." She inventoried a number of dry forest stands around Jaiqui Picado, Santiago Province, Dominican Republic. She used cluster analyses of her observations of plant and soil characteristics, coupled with interviews of local residents, to distinguish between forest

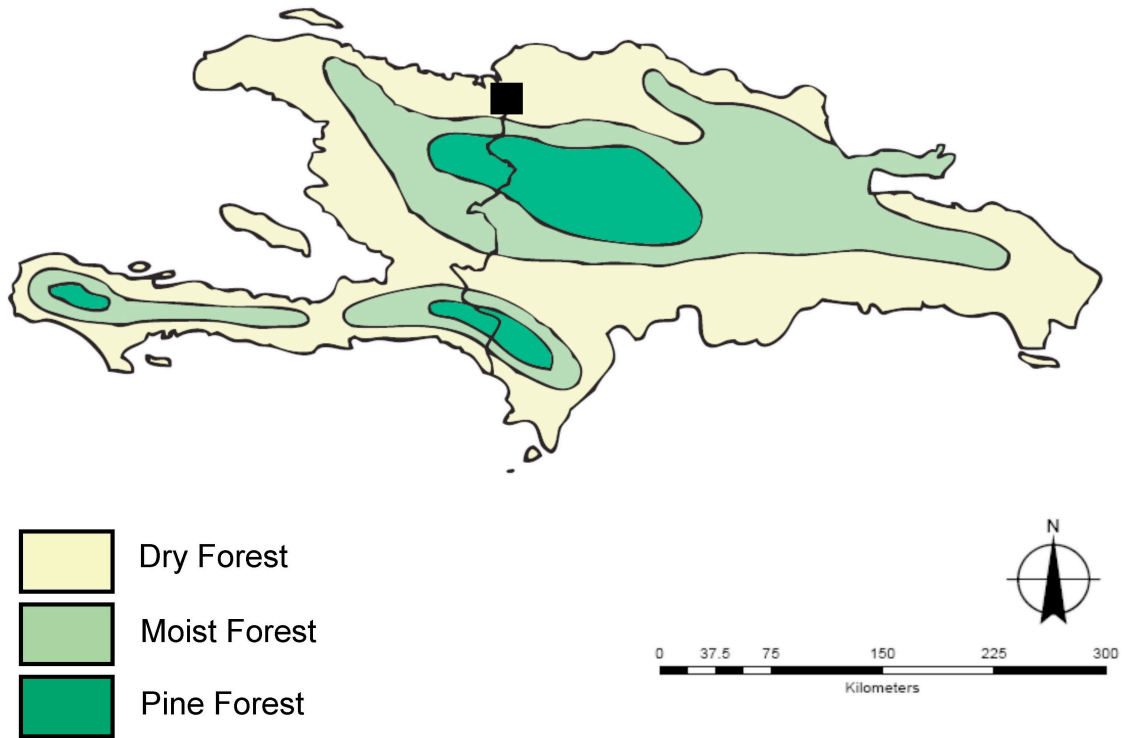


Figure 2.4: Broad forest types of Hispaniola, redrawn from Holdridge (1945). Location of Laguna Saladilla is indicated by ■.

Table 2.1: Species listed by Holdridge (1945) for the dry vegetation type that occurs near Laguna Saladilla.

Acacia scleroxyla
Anacardium occidentale
Bombax ellipticum
Brya buxifolia
Byrsonima spp.
Casearia ilicifolia
Cassia spectabilis
Ceiba pentandra
Cephalocereus spp.
Colubrina ferruginea
Cordia alliodora
Curatella americana
Elaphrium (Bursera) simaruba
Guaiacum officinale
Guaiacum sanctum
Guaiacum spp.
Haematoxylon campechianum
Krugiodendrum ferreum
Leguminosae spp.
Lemaireocereus hystrix
Lysiloma
Lysiloma latisiliqua
Metopium brownei
Opuntia moniliformis
Peireskia spp.
Petitia domingensis
Phyllostylon brasiliensis
Phyllostylon spp.
Pictetia spp.
Prosopis julifolia
Pseudobombax ellipticum
Pseudophoenix vinifera
Stenocereus fimbriatus
Swietenia mahogani

that had been relatively undisturbed over the past centuries (old-growth forest) and land that been disturbed (scrub cover sites). The expansion of scrub forest was caused by human activities, such as swidden agriculture and the harvesting of wood for charcoal. She found that scrub cover occupied four times more land than old-growth. In many cases, the old-growth forest occupied land that was difficult for humans to access (such as steep slopes) and that was marginal habitat for forest species. Roth (1999) identified three post-contact invasive species (*Acacia macracantha*, *Haematoxylon campechianum*, *Prosopis juliflora*, all legumes) that have begun to dominate the scrub cover in Santiago province. Bolay (1997) noted that the latter species dominates the scrubby dry forest vegetation of Montecristi National Park, located just north of Laguna Saladilla, where land is not under cultivation.

Extensive mangroves occur north of the lake, surrounding Estero Blanco (Figure 2.1) and extending to the delta of the Río Yaque del Norte (Bolay 1997). The principal species is *Rhizophora mangle* (red mangrove) (Bolay 1997), but white mangroves (*Laguncularia racemosa*), black mangroves (*Avicennia germinans*), and button mangroves (*Conocarpus erecta*) are also present (Montecristi National Park 2011). Saline and alkaline savannas and marshes occur inland of the mangroves, dominated by halophytes (especially *Sesuvium portulacastrum*) (Bolay 1997) and species of Amaranthaceae (formerly Chenopodiaceae) along with grasses and other herbs (Costa and Davy 1992).

Pine forests and highland moist forests of tropical broadleaf species occupy the slopes of the Cordillera Central to the south of Laguna Saladilla. The single pine species is the endemic Hispaniolan pine, *Pinus occidentalis* Swartz. High elevation moist forest species are *Brunellia comocladifolia* (West Indian sumac), *Dendropanax arboreus* (angelica tree), *Sloanea illicifolia* (bullwood), *Weinmannia pinnata* (bastard braziletto), *Maytenus domingensis* (Hispaniolan

mayten), *Laplacea alpestris* (laplacea) and *Lauraceae* spp. (laurel) (Holdridge 1945). Lower elevation moist forest species include *Cecropia peltata* (pumpwood), *Manilkara nitida* (bulletwood), *Tetragastris balsamifera* (masa), *Didymopanax morototoni* (matchwood), *Gnarea trichiloides* (muskwood), *Genipa americana* (jagua), and *Inga* spp. (inga), as well as understory species of vines, shrubs, and ferns (Holdridge 1945).

Fire affects forests throughout the Dominican Republic and wider Caribbean region. Robbins et al. (2008) used reports from fire managers and MODIS (Moderate Resolution Imaging Spectroradiometer) data to analyze patterns of fire occurrence. They found that most fires occur in regions with dry forest types (500–1000 mm rainfall/year) and near heavily populated regions, and concluded that dry forest ecosystems should be considered "fire sensitive," while pine forest systems are maintained by fire. They further concluded that increased logging, population growth, and other forms of human expansion have increased forest fire occurrences over the past century. They interpreted the increased fire occurrences over the last few decades as principally due to human negligence, although fire has also been intentionally used for other reasons, such as land clearance and management of invasive species. For the period 2000–2007, Robbins et al. (2008) found that Cuba averaged the largest number of fires (3786 per year), followed by the Dominican Republic with an average 850 fires per year. Neighboring Haiti averaged 122 fires per year, while Puerto Rico averaged considerably fewer (30 per year).

In her study of dry forest vegetation in the Dominican Republic, Roth (1999) mentioned fires set by humans to burn slash from clearing scrub forest for agriculture. She did not, however, specifically investigate the impacts of fire on forest composition, or local fire history, and I have found no other published studies that address these themes. In contrast, several researchers have carried out ecological and dendroecological studies in highland moist and pine forests of the

Cordillera Central. These studies of fire impacts and recent fire history complement long-term, sediment-based records of fire history described later in this chapter.

May (2000) analyzed changes in species composition and growth rates of plants in a 10 × 30 m plot in moist (cloud) forest in the Cordillera Central over a five year period following a crown fire. The aim of his research was to determine which species were most fire tolerant and to examine post-fire succession. He found that plants that regenerate by root sprouting were better adapted to recolonizing after fire, although he pointed out that this may not be the case with ground fires that burn into the O/A soil horizon.

May found that herbs and small shrubs (such as *Cyperus sphaelatus* and *Phytolacca icosandra*) were early colonizers that were replaced within three years by a more diverse array of species, including trees and shrubs, such as *Trema micrantha*. He noted that, in many ways, the vegetation followed a pattern of "competitive hierarchy" (Swaine and Hall 1983), except that later colonization of the plot was not by shade-tolerant species that currently occupy the understory of mature forest, but by species that prefer open canopy conditions. His five-year study was not long enough for his plot to reach full maturity, but he documented a secondary forest stage dominated by *Brunellia comocladifolia* and *Myrsine coriaceae*.

May (2000) reported that fern thickets dominated by *Dicranopteris pectinata* and *Gleichenia bifida* were particularly vulnerable to burning and that these species were poor recolonizers in the five years after the fire. However, later work by Kennedy and Horn (2008) found that bracken fern (*Pteridium aquilinum*) was quick to reestablish after fire in pines forests at higher elevations. May interpreted his observations as evidence that fern thickets are not communities that were created by fire, as was suggested by other Caribbean researchers (Ciferri 1936, Dalling 1994, Garcia et al. 1994). However, his results may simply reflect a difference

between the dominant species of fern in the cloud forest versus ferns found in the pine forest studied by Kennedy and Horn (2008). According to May, while root-sprouting species may be better at reestablishing after fire, they are vulnerable to being uprooted by hurricanes. He suggested that species with sprouting aerial buds are poorly adapted to fire, but are better at reestablishing after a hurricane.

Martin and Fahey (2006) examined fire frequencies and fire return intervals in the Cordillera Central based on analyses of fire-scarred specimens of *Pinus occidentalis* on the leeward and windward slopes. Their work overlapped in time with dendrochronological research by Speer et al. (2004) that showed this species produces reliably annual rings in some habitats. Martin and Fahey were interested in how fire regimes might vary across highland mesoclimates (e.g. leeward and windward, and above and below the trade wind inversion as discussed by Orvis et al. 1997). They tied their dendrochronological records to existing meteorological data for the Dominican Republic and to data they collected over a three-year period at seven sites where they deployed temperature, relative humidity, and rainfall loggers.

Based on the lack of archeological sites in the Cordillera Central, Martin and Fahey (2006) inferred that the highlands were not extensively impacted by human activities until the early twentieth century, and thus that their tree-ring records were principally records of climatically-driven environmental change, rather than human impact. By looking at the fire scars of individual trees, they estimated an average mean fire return interval per tree of 31.5 yrs (\pm 24.9 yrs) and a composite mean fire interval of the entire landscape to be 5.6 years (\pm 4.1 years).

More fire scars were found on the drier leeward slopes. Martin and Fahey cited anecdotal reports that most fires occur in the region during the end of the dry season in late February and March. Their climate data showed a bimodal pattern in which the dry season lasts from January

to March, with windward slopes receiving a mean monthly average of 80 mm rainfall, more than twice the average monthly rainfall of the leeward slopes (31 mm) during the three month dry period. This difference had a significant impact on fire frequency, particularly on the lower slopes where humidity rarely dropped below 65%, the threshold established by Uhl et al. (1988) as critical for prolonged fires.

Martin and Fahey (2006) also found the dry season to be exacerbated during El Niño years, based on the Mann et al. (2000) Niño3 index. Dry season precipitation was lower in 80% of El Niño years, and fire frequency incidence increased markedly during those years. Also, six out of eight large fires³ occurred during those years. Large increases in fire activity that could signal human ignition sources were not seen until ca. 1900 CE. In recent decades, fire suppression has been the policy, but has been difficult to implement in hard to reach higher elevations.

Martin and Fahey discussed the possible interactions of hurricanes and fires. They stated that hurricanes tend to displace and create a great amount of organic debris that is deposited on the forest floor. In the dry season, this debris dries out and can turn into a source of kindling if ignited by lightning or (more recently) by people.

Following an initial study by Horn et al. (2001), Kennedy and Horn (2008) examined post-fire vegetation recovery in five sites in the Cordillera Central that had burned up to seven years prior to their study. Their research showed that shrubs were the primary post-fire colonizers. They also found that pines had a relatively high mortality (>50%) even in what appeared to be relatively low intensity fires. However, pine mortality was greatly reduced once

³ Large fires were defined as fires recorded in at least half of the six zones studied by Martin and Fahey (2006). Their total study area covered 2050 ha.

individuals of pine reached diameters greater than 13 cm (approximately 19–26 years old; Sachtler 1974). Once the pines had grown thicker bark to protect the cambium, they were more resistant to fire.

Kennedy and Horn (2008) also found that *Baccharis myrsinites* (a member of the Asteraceae family) was present as a colonizer in large quantities even though it had a relatively low percentage of resprouts (56.3%). While Sherman et al. (2005) stated that the occurrence of *Pinus occidentalis* should be indicative of a strong link with fire, Kennedy and Horn showed that shrubs of the pine forest are also well adapted to fire, and that fire at close intervals can destroy pine seedlings and saplings and favor shrubs over pines.

2.1.4 Modern Human Settlement Within the Laguna Saladilla Watershed

The town of Carbonera to the east of Laguna Saladilla (Figure 2.1) was established in 1959 as part of a government initiative that involved 68 other agricultural communities (Augelli 1962). The aim of the initiative was to relieve some of the growing population pressure on the cities, increase the education and standard of living levels of their citizens, and—most importantly—create "frontier colonies" along the border with Haiti that the Dominican government could use to establish a strong presence in sparsely populated areas that were vulnerable to "infiltration" by Haitians (Augelli 1962).

According to Augelli (1962), the initial settlers in Carbonera consisted of 202 families originally from Ciudad Trujillo (now Santo Domingo) who were given a number of moving incentives, including ca. 9 acres of land per family, and a government-built home, that was theirs for nine years, after which time they could purchase the land to obtain title that could be passed to their heirs or divided and sold as separate parcels. Farming on the land around Carbonera

(including land that abuts the north and east shorelines of Laguna Saladilla) included supervision by a government agronomist who provided seed and prescribed what types of crops and/or animals had to be kept on up to 90% of the land. Settlers were required to plant corn, yucca, and plantains during the initial establishment of the cropland under government control. Today, in addition to the above crops, farmers also keep a variety of animals (mostly goats, but also sheep and cattle) and use Laguna Saladilla for limited fishing, harvesting crayfish and catfish among other species.

During fieldwork in December 2009, a local Carbonera resident, Javier Hernandez, explained that he was a member of the local fishing cooperative that provides access to Laguna Saladilla and monitors stocks of fish and crayfish to prevent overharvesting. He told us that there were not enough fish or crayfish in the lake to make fishing profitable or support families, making fishing a supplemental income source. When asked about farming, Javier reported that the farmers do not use any pesticides or artificial fertilizers on the surrounding farmland, as their government agronomist had instructed them that it would lead to problems with the runoff into Laguna Saladilla. My observations of fields surrounding Laguna Saladilla showed that farming techniques were not particularly technologically advanced (i.e., no apparent sprinkler systems or extensive forms of mechanization), but that farmers were using modern soil conservation techniques (contour farming and conservation tillage).

2.2 Background and Literature Review

2.2.1 Previous Paleoenvironmental Studies

Laguna Saladilla is one of seven lakes in the Dominican Republic for which investigators have developed environmental reconstructions based on sediment profiles. Lane and colleagues

carried out multi-proxy analyses (pollen, charcoal, pine stomata, stable isotopes) of sediment cores from two lakes located at mid-elevation (ca. 1000 m) on the southern slope of the Cordillera Central (Lane 2007; Remus 2008; Lane et al. 2008a, 2008b, 2009). They found evidence of human impacts including forest clearance and maize agriculture, and of marked drought intervals between 1200 and 1000 cal yr BP and at ca. 450 and 150 cal yr BP. Lane et al. (in press) later analyzed oxygen isotopes in biogenic carbonates in a nearby third lake, and found evidence of dry conditions during the Little Ice Age of the 15th to 19th centuries.

In the highlands of the Cordillera Central, Horn et al. (2003) analyzed pollen, charcoal, and mineral sediments in cores from Laguna Grande de Macutico (2048 m elevation). The Macutico sediments and other geomorphic evidence suggest wetter conditions in the highlands after ca. 4500 cal yr BP (Orvis et al. 2005, and in preparation). Kennedy et al. (2006) analyzed pollen and charcoal in a ca. 4000-year sediment record from a bog in the Valle de Bao (ca. 1800 m elevation). They found evidence of long-term dominance of pine forests and repeated natural or human-set fires, along with some indications of shifts in climate.

Desjardins (2007), working with Kennedy, investigated the sediments of Laguna Alejandro along the southwestern coast of the Dominican Republic. Their paleotempestological and paleoenvironmental reconstructions for the past ca. 1100 cal yr BP revealed evidence of at least three hurricanes, at around 1022, 1097, and 1131 cal yr BP, and a drought that occurred ca. 660 cal yr BP. Laguna Saladilla provides a significantly longer chronology of environmental change from a coastal region that is a valuable addition to the coastal work of Kennedy and Desjardins, and to the work of University of Tennessee researchers at mid- and high elevations in the Cordillera Central.

The Dominican Republic records complement earlier work by Higuera-Gundy et al. (1999) at Lake Miragoane, Haiti. In a study of pollen and other proxies in a ca. 10,300 yr sediment record, the researchers found a mid-Holocene expansion of moist forest and subsequent decline in the last 1000 years in response to human deforestation and late-Holocene changes in climate. However, the chronology of their results was subject to a hardwater lake error that required a correction factor that could only be estimated. Laguna Saladilla potentially offers a stronger chronology of past changes in regional climate.

2.2.2 Charcoal Records

In the mid-1980s, Patterson et al. (1987) comprehensively reviewed the state of the science of microscopic charcoal analysis. While some of their questions have been answered by research since their publication, Patterson et al. (1987) addressed a number of topics (including limitations) to microscopic charcoal analysis that are still subjects of research today. They discussed charcoal production and taphonomic processes (dispersal and deposition), and how these may affect data collection and interpretation. They stated that the intensity, duration, and temperature of a fire event will play critical roles in the particle size distribution of charcoal fragments dispersed from the fire.

Patterson et al. (1987) also discussed water deposition of charcoal. They cited Griffin and Goldberg (1975) as evidence of greater fluxes of charcoal in coastal marine sediments compared to deeper ocean deposits. This may be due to the distance-decay principle of charcoal deposition (more charcoal will be deposited closer to the fire event), or due to the weight of charcoal in water. This is based on the research of Davis (1967), who showed that once charcoal is wet, it sinks rapidly unless it has a high porosity that increases buoyancy.

Patterson et al. (1987) pointed out that dispersal time from the initial fire event to when the charcoal is incorporated into lake sediments or peat is also a function of "fire-rainfall events," because without rain, charcoal (particularly larger fragments) may lie on the surface of a soil for days to months before it is redeposited. Fredskild (1973) used surface charcoal traps in Greenland to illustrate the role of "fire-rainfall events". His charcoal traps worked in a manner similar to pollen traps that are designed to capture pollen that is deposited on the trap either by wind or rain. Fredskild (1973) found that the "charcoal rain" around his sites increased in the spring and summer—despite the lack of any local to regional fire events. He attributed the increase in seasonal charcoal deposition to the position of seasonal wind currents and rainfall.

Patterson et al. (1987) designed simplified models that illustrate the distance-decay principle of charcoal deposition and a selected number of associated factors that can alter deposition patterns and, therefore, interpretations (Figure 2.5). Their models assume that small- to large-sized charcoal particles can be quantified microscopically and that deposition is principally by wind. However, they also pointed out that deposition by water may result in the damage and disintegration of larger-sized charcoal that could render quantification of microscopic charcoal useless (or at least very difficult to interpret results). Whitlock and Millspaugh (1996) found differences in the sizes of macroscopic charcoal fragments quantified by sieving in lakes in Yellowstone National Park were useful in determining whether charcoal remains were from a more local versus regional point source. Patterson et al. (1987) acknowledged that differences in microscopic charcoal sizes could be caused by the proximity of the point source (with larger pieces indicative of closer fires), but were poorly understood at the time of writing.

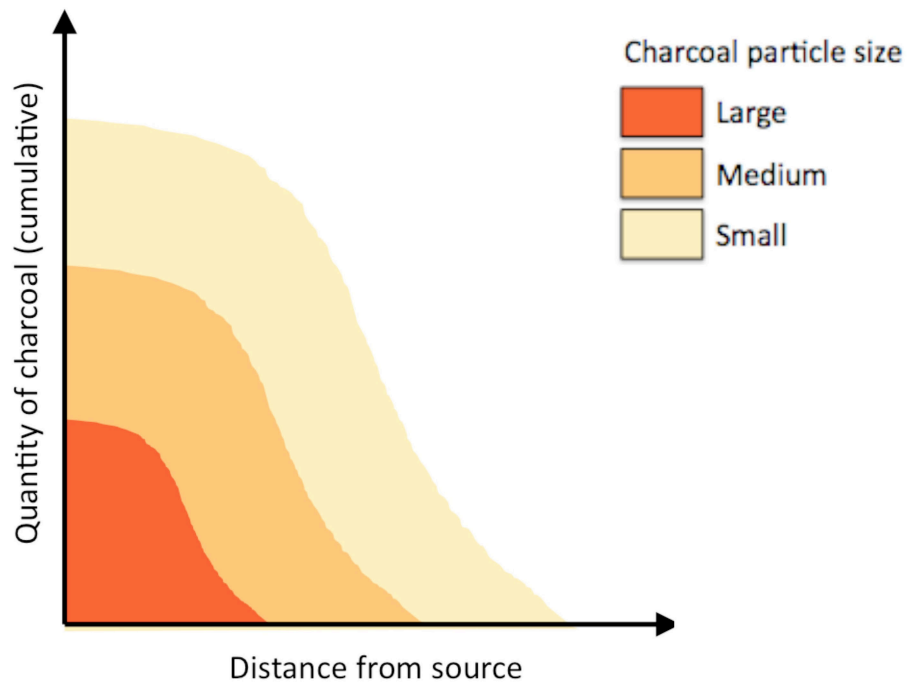


Figure 2.5a: A simplified chart showing charcoal accumulation versus distance from source for large- to small-sized charcoal fragments. This assumes equal proportions of each charcoal size fraction, and is based entirely on dispersal and deposition by wind. Redrawn from Patterson et al. (1987).

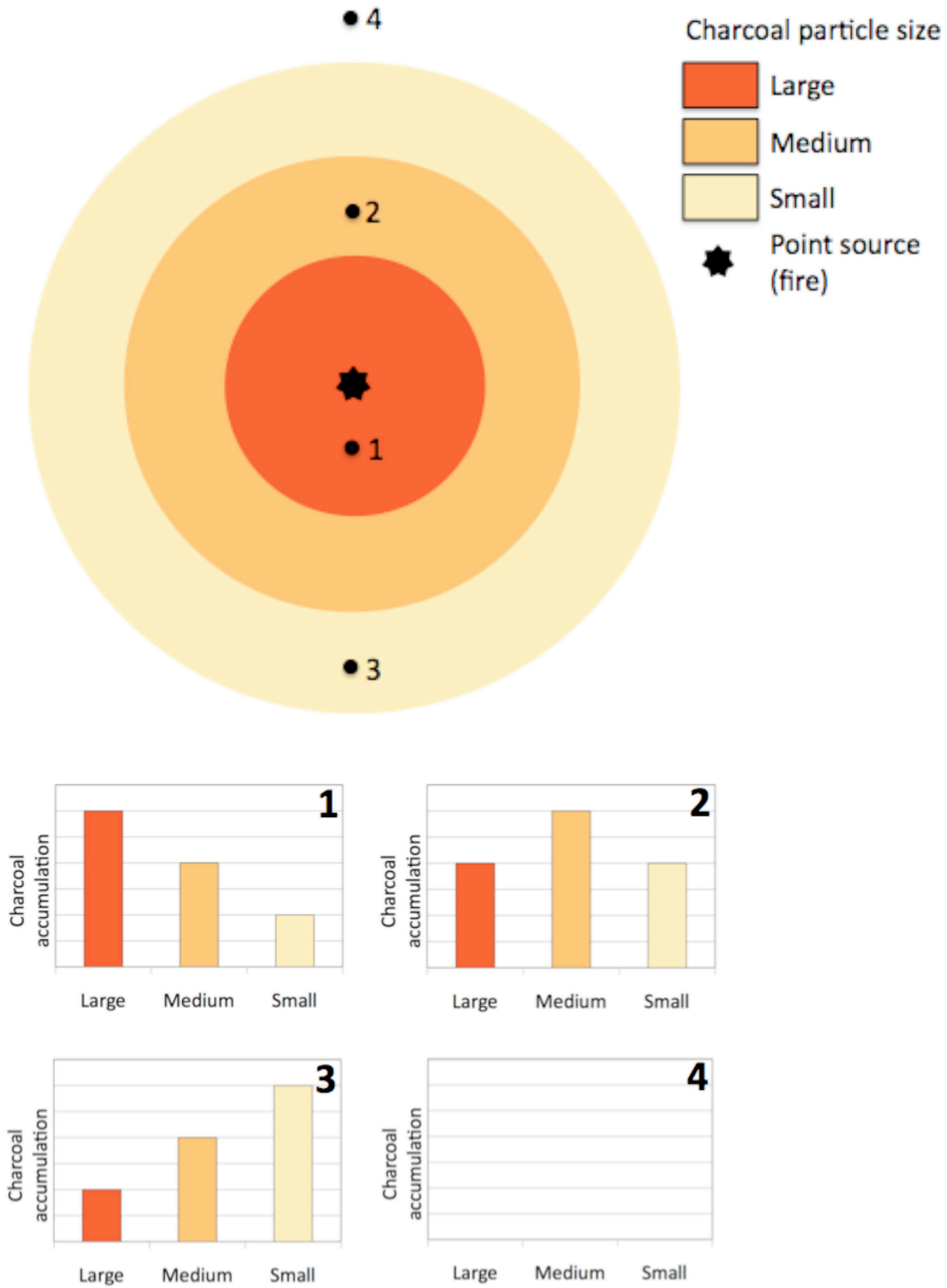


Figure 2.5b: The distribution of small- to large-sized charcoal particles in four hypothetical surface sediment samples after a fire. This assumes that wind direction plays little to no role in the deposition of charcoal sizes. Redrawn from Patterson et al. (1987).

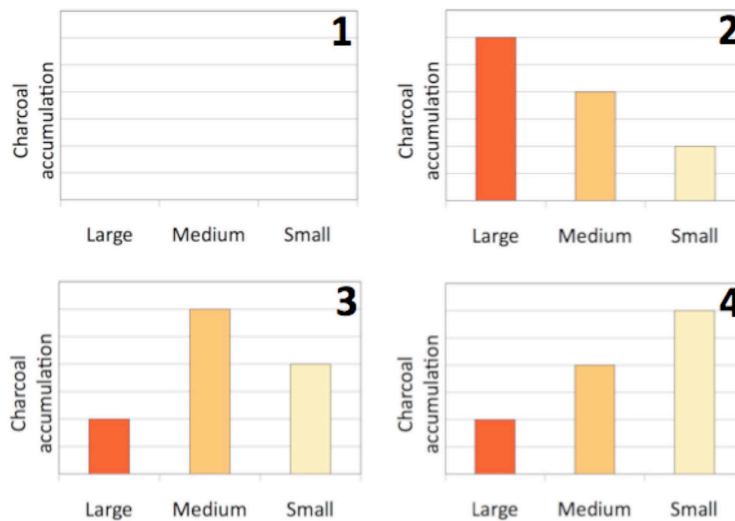
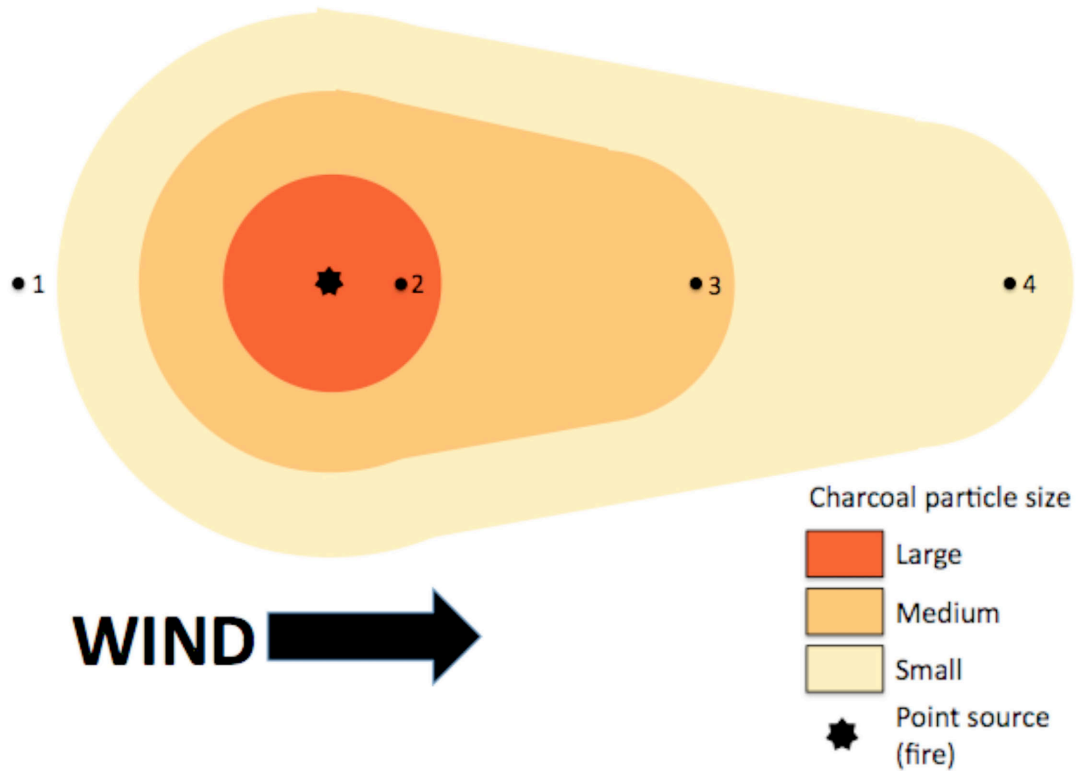
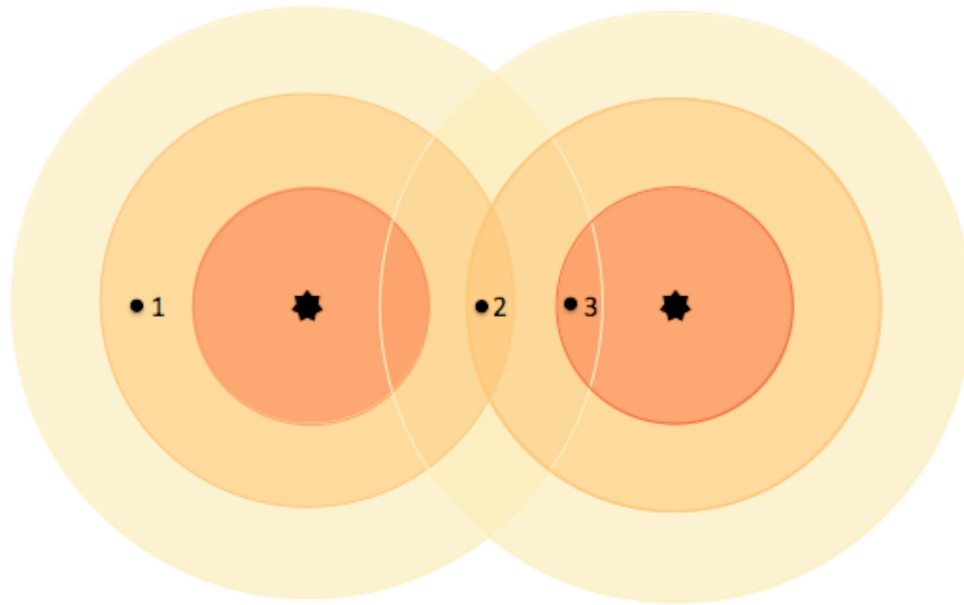


Figure 2.5c: The distribution of small- to large-sized charcoal particles in four hypothetical sediment surface samples after a fire, taking into account wind direction. This assumes wind direction was unidirectional during burning and particle deposition. Redrawn from Patterson et al. (1987).



Charcoal particle size

Large

Medium

Small

Point source
(fire)

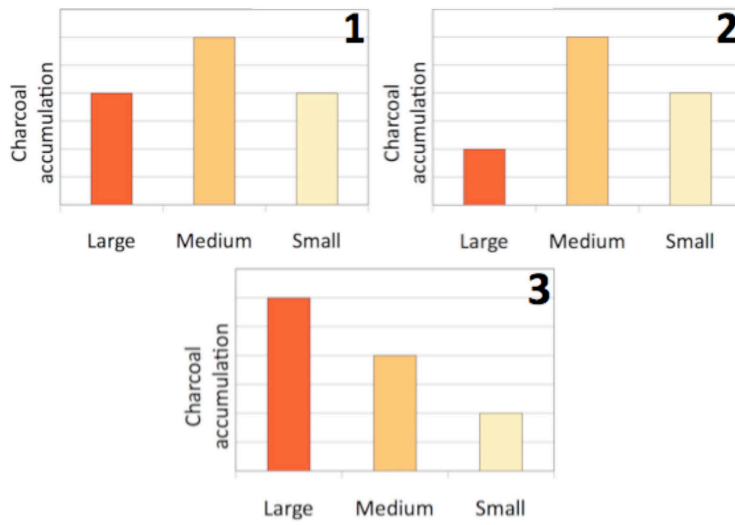


Figure 2.5d: The distribution of small- to large-sized charcoal particles in three hypothetical sediment surface samples during two fires that occurred simultaneously. Redrawn from Patterson et al. (1987).

Patterson et al. (1987) also emphasized that determining fire frequency based on microscopic charcoal is nearly impossible. Some researchers have attempted to match microscopic charcoal deposits to particular events based on remains in annually laminated sediments (e.g. Swain 1973, O'Sullivan 1983). However, Patterson et al. (1987) enumerated a number of factors that make tracing a singular event using microscopic charcoal practically impossible, such as bioturbation and variability in deposition rates. For example, a large (widespread, stand-replacing) event may be represented as a narrow band of charcoal that may be missed or underrepresented because microscopic charcoal samples are typically prepared using samples that each span several years to decades and are separated from other samples in the profile by decades to centuries. If no other fires took place preceding or superseding the large event in the above example, it may appear that charcoal concentrations are low when averaged over the time span of the sample. Conversely, there may be many small fires over a similar period that would result in higher charcoal concentrations. Therefore, Patterson et al. warn that the appearance of a concentration of charcoal should be interpreted carefully and not assumed to be the result of a single, large event.

Finally, Patterson et al. (1987) discussed various techniques for quantifying charcoal fragments on pollen slides. They found Clark's (1982) point counting technique to be relatively easy to execute, but stressed that it does not yield data on individual particle size. Clark's (1982) technique provides data on charcoal surface area per unit volume of sediment, meaning that it determines the two-dimensional surface of pollen on a volumetrically standardized pollen slide. Data can be expressed as concentration ($\text{mm}^2 \text{ charcoal} / \text{cm}^3$) or influx ($\text{mm}^2 \text{ charcoal} / \text{cm}^2 / \text{yr}$). Patterson et al. (1987) cited tests performed by Backman (1984) that compared results from point counting to microscopic charcoal counts performed by random sampling within a grid. Backman

found that both methods produced similar results, with a Pearson's product moment correlation coefficient of 0.76. Clark's (1982) method was considered to slightly underestimate charcoal values as null when charcoal concentrations were low, but overall the two approaches were in good agreement. These are potentially important results to consider when comparing Laguna Saladilla's charcoal record from Laguna Saladilla to that of Lake Miragoane and Laguna Tortuguero, where microscopic charcoal was quantified in a different manner (this will be discussed further in Chapter 4).

Many researchers have examined microscopic or macroscopic charcoal in soils of the tropical Americas to reconstruct past fires and their interactions with climate and human activities. Here, I summarize a few studies that provide context for my charcoal analysis of the Saladilla sediments. Horn and Sanford (1992) compared sedimentary and soil charcoal records from two sites in Costa Rica (La Selva Biological Reserve and Cerro Chirripó). They found evidence of fires at both sites at 2430 cal yr BP and 1110–1180 cal yr BP that could have been ignited by humans. They could not determine whether the presence of charcoal at those times at both sites indicated immense regional fires (that would have had to span at least 120 km between each site), or co-eval smaller fires, but conjectured that the fires were likely favored by drier conditions. Horn and Sanford (1992) stated that, even if the fires were human-set, they could still provide evidence of more severe drought conditions.

Layers of charcoal in sediments from Lago Chirripó may have been created when lake levels were lower, resulting in charcoal being eroded from the nearshore sediments and being preserved as a concentrated charcoal layer at the site. A layer formed in this manner would, therefore, represent drier conditions because the lake was at a low stand. Horn and Sanford also pointed out that changes in climate could change lightning ignition frequencies.

Horn (1993) looked at pollen in a ca. 10,000 year sediment profile from Lago de Las Morrenas 1, in the Chirripó páramo, to determine the extent of páramo conditions in the highlands over time. As part of her analyses, she also examined microscopic charcoal and compared it to the charcoal record from nearby Lago Chirripó to evaluate whether fire was a natural part of the páramo landscape or whether humans had introduced it. She found distinct peaks in the charcoal record that could possibly be tied to humans, but she also found evidence of burning during the early Holocene when her pollen data suggested that the climate was gradually warming (based on increased inputs of forest taxa that implied forest species were moving up slope in response to warmer conditions). The early Holocene evidence of charcoal suggested that fire was indeed a natural part of the páramo ecosystem, although fire frequencies did change in response to changing climate.

The loss of biomass by fire is highly dependent on (1) the type of landcover, and (2) the intensity of the fire. Kaufman et al. (2003) conducted a number of experiments by burning dry tropical forest in Jalisco, Mexico. They measured the amount of biomass lost to the initial fire and monitored rates of post-fire decomposition, erosion, and vegetation reestablishment on three blocks of land. To measure the effects of different fire severities, one block of vegetated land was slashed and left to dry for 95 days prior to burning, one block was slashed and dried for 65 days before burning, and the third block was left as pasture and burned. They found that the block of land that had been slashed and dried the longest lost the most biomass by initial combustion (80%), while the block dried for 65 days lost 63% of its biomass. The pasture lost 63–75% biomass by combustion.

Research by Kaufman et al. (1995) and Guild et al. (1998) showed that tropical evergreen forests (such as the moist forest found on the lower slopes of the Cordillera Central) lose from

21–57% biomass by combustion. Kaufman et al. (2003) also showed that the length of time vegetation dried before ignition had a significant impact on the amount of biomass lost. This may be important in interpreting the Laguna Saladilla record, in which increases in charcoal may be the result of increased pre-drying. However, these interpretations would be tentative because an increase in charcoal can also signal numerous small, low intensity fires (Patterson et al. 1987).

Clark et al. (2002) examined nine "dambos" (streamless, low relief, grass-covered hollows) in the highlands of the Cordillera Central of the Dominican Republic to investigate origins. Charcoal in soil cores and an excavation in one dambo dated to 11,060 cal yr BP (Horn et al. 2000; Clark 2002). They found charcoal deposits in the majority of their core sections, suggesting that fire has played a role in the highlands from the Pleistocene-Holocene transition to the present. Clark et al. (2002) hypothesized that the ignition source of most of the fires was likely natural given the remoteness of the locations. Histic (peaty) horizons also suggested that the dambos may be relict features from earlier wetter conditions. Charcoal was found in horizons that also contained soil morphological evidence indicating drier climate phases.

One objective of the study by Kennedy et al. (2006) of a 4000-year wetland sediment record from Valle de Bao in the Cordillera Central was to determine whether changes in pollen and charcoal frequencies indicated changes in climate over the mid- to late-Holocene. Their reconstructions were from an area that was unlikely to have been impacted by past indigenous cultures, although commercial logging had been performed in the wider region over the last century. Kennedy et al. counted charcoal on pollen slides, although they only recorded the occurrence of fragments $>50 \mu\text{m}$. They noted that smaller fragments were also present through the core. Their results showed that fire was an important and consistent part of the Valle de Bao ecosystem. Sedimentary charcoal concentrations were relatively steady from level to level,

implying that fire frequencies were relatively consistent from 4280 cal yr BP–present. Lightning was presumed to be the ignition source.

Based on pollen preservation, Kennedy et al. (2006) inferred that periods of drying (and possibly desiccation) occurred between ca. 3700–1200 cal yr BP, a time of dry climate in circum-Caribbean lowlands. An increase in mistletoe (*Arceuthobium* sp.) pollen around 1000 cal yr BP coupled with a change in charcoal/pollen ratios was interpreted to signal a change in the fire regime from a period that included more high-intensity crown fires to a period with more low-intensity surface fires. This was hypothesized because mistletoe is a parasitic plant that grows in the crowns of pine trees that would not have been able to persist if crown fires were common. Finally, three radiocarbon dates obtained by Kennedy et al. (2006) from 126.5–103 cm depth in the core appeared to be out of sync with the rest of their chronology, which they interpreted as evidence that the charcoal had been redeposited. Based on observed slope failures around the site during fieldwork that were driven by intense storm activity (typically hurricanes), they suggested that the redeposited charcoal in the core was from similar tropical storm-driven slope failures.

Nevle and Bird (2008) used fifteen charcoal records from Central America and the Caribbean to examine the impact of humans on biomass burning. They hypothesized that burning from ca. 3500–500 ¹⁴C BP was primarily the result of humans in the region. They observed a large decrease in burning ca. 500 ¹⁴C BP that they hypothesized resulted from a widespread decrease in human population (ca. 90%) due to pandemic disease. With population decline, field abandonment, and decreased burning, the forest began to regrow, leading to regionally significant forest regeneration after 500 ¹⁴C BP.

Increases in charcoal are typically found when humans enter a new region for the first time (e.g. the Maori into New Zealand, Lowe et al. 2000; the Polynesians on Easter Island, Fenley et al. 1991; the Norse in Greenland, Fredskild and Humle 1991); however, Nevle and Bird (2008) also stated that a decrease in burning ca. 500 ¹⁴C BP could be due to cooler temperatures during the Little Ice Age (LIA; Joos et al. 1999). Nevle and Bird (2008) sided with human population decline as the cause, but described their evidence as "circumstantial."

2.2.3 Humans and the Archeological Record of the Caribbean Region

The peopling of the Caribbean region has been the subject of archeological research for decades. However, relatively little is known about the first inhabitants of the region (Rouse 1992; Keegan 1994), and different hypotheses exist about routes of migration (Rouse 1951; Wilson et al. 1988). A limited number of archeological sites as well as other forms of reconstruction, such as glottochronology (Rouse 1986) and mtDNA (Lalueza-Fox et al. 2001), have been used to characterize five cultural periods: the Lithic age (ca. 6000–4000 yrs BP), Archaic age (ca. 4000–2200 yrs BP), Ceramic age (ca. 2200–800 yrs BP), Formative age (ca. 800–500 yrs BP), and Historic age (ca. 500 yrs BP–present) (Rouse 1992; Keegan 1994).

Keegan (1994) discussed the distribution of a series of indigenous ethnic groups across the Caribbean over time. The Casimiroids were early inhabitants (ca. 6000–2400 cal yr BP) in the region whose archeological remains (mostly flaked stone artifacts) show they were present on the islands of Cuba, Hispaniola, and possibly Puerto Rico. The Ortoiroid were present in the Lesser Antilles at roughly the same time as the Casimiroids, from ca. 4000–2400 cal yr BP. The Saladoid peoples moved in waves of colonization through the region from 4000–1400 cal yr BP, leaving small settlements with pottery remains (Keegan 1994, 2000). Finally, the Ostionoid (ca.

1400–500 cal yr BP) entered into the region from South America and were present when Columbus arrived in 1492 CE. Today, indigenous groups are integrated with European and South American settlers to varying degrees across the Caribbean (Keegan 2000).

Burney (1997) discussed the importance of paleoenvironmental records for establishing a chronology of human movement onto and around the Caribbean islands, as well as other islands such as Madagascar. He outlined some of the benefits of paleoenvironmental records over archeological evidence, but also cautioned that interpretations of sediment archives can be complicated by natural changes in climate or abrupt natural events, such as volcanic eruptions. He listed four stages of human-environment interaction that can be traced using sedimentary records. These four stages are (1) human discovery and settlement of the island, (2) modification of the environment with fire, forest clearance, pastoralism, and cultivation, (3) introduction of exotic organisms, and (4) decline and extinction (or extirpation) of indigenous species (Burney 1997).

Steadman et al. (2005) assessed the extinction of large mammals during the Holocene, particularly various species of sloth. Following the human overkill "blitzkrieg" hypothesis by Martin (1984), they dated individual bone fragments from sloths (*Neocnus comes*) to around 5000–4500 cal yr BP in Hispaniola, an interval that coincides approximately with apparent sloth decline in Cuba. They cited the work of Burney et al. (1994) as evidence that these declines were the result of humans, although none of the remains in Hispaniola were found in proximity to archeological sites, and no sloth bones at all have been found in Puerto Rico.

Burney (1997) stated that the actual date of human arrival on an island may be difficult to pinpoint within ± 100 years using radiocarbon dating. He also discussed the archeological record of the Caribbean and cited a date for human establishment of around 5580 ± 80 ^{14}C BP for

Hispaniola and 3010 ± 70 ^{14}C BP for Puerto Rico (Moore 1991, Rouse 1992). However, he pointed out that his own investigations of Laguna Tortuguero, Puerto Rico (Burney et al. 1994) showed an increase in burning around 5300 cal yr BP that he interpreted as resulting from human ignition sources because Hodell et al. (1991) indicated that pollen and ^{18}O isotope data from Hispaniola indicated that the climate was wetter at that time. If Burney et al. (1994) are correct in this interpretation, it would mean that Rouse's (1992) earliest estimate for human arrival in Puerto Rico would be incorrect by 2000 years.

Burney (1997) also discussed how a pattern of drying that started around 3200 years BP and culminated in maximum drying at 2400–1500 yrs BP was observed in both the Caribbean and in Madagascar (Burney 1993). Kjellmark (1996) examined sediments from Church's Blue Hole, Andros Island, Bahamas to reconstruct changes in environment over the past 3200 cal yr BP. He found an increase in charcoal concentrations after the arrival of humans around 1200–1100 cal yr BP (based on the archeological record of Berman and Gnivecki 1994). However, he noted that the climate within the region was also drier than present from the base of his sediment core (3260 cal yr BP) to 1500 cal yr BP. This interpretation is in keeping with other records from the region (Higuera-Gundy et al. 1999, Lane et al. 2009, Burney et al. 1994), and no evidence of human activities is apparent during that time at Church's Blue Hole. Kjellmark hypothesized that the period of aridity could explain why humans did not colonize the island earlier than 1200–1100 cal yr BP.

One possible way to determine whether a charcoal record reflects human activity or natural climate variability is to interpret peaks in charcoal as the result of increased fire intensity (Burney 1997). Burney (1997) suggested that human-ignited fires tend to be set when conditions will create a low intensity fire that will not burn out of control (typically during wetter periods in

the year), whereas natural fires are typically ignited on drier days when maximum pre-drying has occurred. This assumes that a natural fire is not ignited during a wetter phase when more lightning is present (Higuera-Gundy et al. 1999; Kennedy et al. 2006). However, Patterson et al. (1987) discussed the difficulties of determining fire intensity from microscopic charcoal remains.

A better approach for determining whether humans played a role in changing fire frequencies is to examine the archeological record for evidence of human establishment at the time of peaks in charcoal values. Evidence exists of regional indigenous cultures travelling between islands and creating temporary fishing outposts or camps on islands before they were permanently settled (Keegan 1994, 2000). However, extensive burning likely would not have taken place until groups began to settle and attempted to use the land for agriculture (Keegan 2000).

Lane and colleagues shed light on the establishment of humans in the interior of Hispaniola by examining changes in pollen, charcoal and isotope records preserved in the sediments of Laguna Castilla and Laguna Salvador on the southern slope of the Cordillera Central (Lane 2007; Lane et al. 2008a, 2008b, 2009). Their records spanned the last 2000–3000 years and revealed how shifts in the position of the mean annual position of the Intertropical Convergence Zone (ITCZ) affected precipitation in the region and how human occupation of the lake watersheds was linked to aridity.

Increased microscopic charcoal coupled with pollen evidence of maize (*Zea mays* subsp. *mays*) and a decrease in forest types signaled the first evidence of humans in the region around 890–700 cal yr BP (Lane et al. 2009). Based on changes in $\delta^{18}\text{O}$ ratios from ostracods (*Cypridella boldii*), Lane et al. concluded that settlement within the watersheds appeared to coincide with a period of severe drought.

Changes in carbon isotope ratios in the Laguna Castilla, sediment profile led Lane et al. (2008a) to conclude that initial settlement took place around 900 cal yr BP, although maize pollen concentrations did not peak until 765–730 cal yr BP. Human impacts appear to have decreased after that time until the site appears to have been abandoned after 550 cal yr BP.

The abandonment of the watersheds of both lakes ca. 700–350 cal yr BP initiated a period of ecosystem recovery (recolonization by pine, declining herbaceous pollen types). Lane et al. (2009) and Lane et al. (in press) found conditions to be drier in the region around the time of the LIA period (ca. 450–150 cal yr BP), although less severe than the severe drought events identified by Hodell et al. (2008). Human occupation appeared to decrease over time and the watersheds appear to have been abandoned by humans for 350 years before a second occupation period around 95 cal yr BP.

The maize evidence found by Lane et al. (2008b) is particularly significant as relatively little evidence of maize cultivation has been found (to date) in the Caribbean (Newsom and Deagon 1994; Newsom and Wing 2004; Newsom 2006). In addition to using marine resources for food, early inhabitants also grew root vegetables (Keegan 2000; Lane et al. 2008b). The Ostionoid archaeological period was described by Wilson (1997) as one of a culture of pottery making horticulturalists that had a strong cultural presence across the Caribbean from 500–1000 CE following the decline of the Salanoids.

Other pollen evidence of maize in Hispaniola was found at El Jobito, Dominican Republic (believed to date to ca. 930 cal yr BP; Garcia Arevalo and Tavares 1978), and Lake Miragoane, Haiti (ca. 450 cal yr BP; Higuera-Gundy et al. 1999). A report of much earlier maize pollen from El Curro, Dominican Republic appears unreliable (Ortega and Guerrero 1981; Lane et al., 2008b). The maize remains from Lake Miragoane were initially reported by Higuera-

Gundy (1991) to date to ca. 1100 cal yr BP, but later radiocarbon dating by Higuera-Gundy et al. (1999) placed them at ca. 450 cal yr BP. Macroscopic remains (cobs, capules, and kernels) dating to ca. 700 cal yr BP were recovered from the archeological site En Bas Saline, Haiti (Newsom and Deagan 1994) located approximately 50 km west of Laguna Saladilla.

In addition to the records of maize in Hispaniola, evidence of maize in the form of starch grains was found at the Maruca and Puerto Ferro archeological sites in Puerto Rico (Bonzani and Oyuela-Caycedo 2006). Pagan et al. (2005) suggested that the maize dated from the Archaic period, which would correspond to ca. 4000–2200 yr BP, while macroremains of maize at the Tutu site on nearby St. Thomas were dated to much later, ca. 810–610 cal yr BP (Newsom and Pearsall 2003).

2.2.4 Tropical Pollen

On a global scale, islands represent a small area, but can contain a number of habitats that are sensitive to changes in environmental conditions (MacArthur and Wilson 1967; Bates et al. 2008). Hispaniola is the second largest island of the Greater Antilles and includes 20 different vegetation zones (Chandler and Chandler 2005) from its coastal mangrove swamps to the pine forests and savannas (grasslands) that surround its highest point, Pico Duarte in the Cordillera Central (3098 m; Orvis 2003). Changes in the extent of these environments are highly dependent on temperature and precipitation, and these variables have changed considerably during the Holocene. Pollen preserved in lake sediments is used to reconstruct changes in forest composition resulting from changes in climate.

Snedaker (1995) hypothesized that changes in the extent of mangrove forests over time are directly related to rainfall and runoff. Reconstructions of changes in vegetation from pollen

analysis from Lake Miragoane near the south coast of Hispaniola in Haiti documented a change from mid-Holocene moist forest taxa to dry forest in the later Holocene (Higuera-Gundy et al. 1999). Results also indicated that fire had a significant impact on forest composition based on associations between pollen and microscopic charcoal concentrations.

Other pollen records of Holocene (and earlier) environmental change in the Caribbean and Central America are summarized in recent reviews by Horn (2007) and Graham (2010). Marchant et al. (2002) and Gajewski (2008) addressed issues of pollen taxa interpretation in the Latin American tropics. Identification of pollen types is facilitated by Colinvaux et al. (1999), and by online resources such as the Latin American Pollen Database (Marchant et al. 2002) and Neotropical Pollen Database (Bush and Weng 2006).

2.2.5 Reconstructions of Lacustrine Environments Using Diatoms

Diatoms (Bacillariophyceae) have been used as paleohydrological proxies for decades by researchers in Europe and North America. Smol et al. (2010) estimated that at least 10^4 modern diatom species can be found globally. However, relatively little is known about the ecology of tropical diatoms (Metcalf 1988; Haberyan et al. 1997). This is unfortunate as changes in tropical assemblages can potentially indicate important shifts in physical and chemical conditions, such as lake level, salinity, concentrations of dissolved solids, water temperature, or water clarity. In my analysis of diatoms in the Laguna Saladilla sediment core, I found changes in assemblages that reflected changes in salinity, caused by changes in relative sea level (RSL) and/or saltwater intrusion through the aquifer (Figure 1.3).

Takano (1960) was one of the earliest to study diatoms within the Caribbean. He collected samples from 29 locations across the Caribbean Sea over a one year period to map

variations in marine species across the region. He found a total of 83 pelagic species, within which species of *Chaetoceros*, *Rhizosolenia*, and *Coscinodiscus* were the most abundant. Diatom concentrations were highest near the coasts of Colombia and Venezuela and where the Gulf Stream flows from the Atlantic Ocean between Mexico and Cuba.

Bradbury (1971) conducted one of the most extensive diatom studies in Central America when he looked at diatoms in a 46 m sediment core from Mexico City to reconstruct changes in salinity and high stands of ancient Lake Texcoco. Bradbury (1971) took samples at 20-cm intervals from which he identified 204 different taxa. Lake Texcoco was drained in 1900 during the building of Mexico City, but prior to that the lake had undergone changes in salinity resulting from changing flows of a freshwater spring, and periods of high and low lake stands.

Bradbury (1971) identified 15 diatom zones in the Texcoco core based on changes in dominant types. He reported only three radiocarbon dates from the sediment core, but attempted to date periods of change by matching the stratigraphy to other records. He estimated the age of the base of the core to be ca. 100,000 ¹⁴C yrs based on downcore extrapolation from a radiocarbon date taken from higher in the core. Bradbury (1971) found the lake to be fresh from zone VI to the present day. Prior to that zone, the lake was brackish. Based on the erratic appearance of *Cyclotella* cf. *stylorum*, Bradbury (1971) suggested that the sediments were reworked and that non-contemporaneous taxa were redeposited as lake level fluctuated. The lake appeared to be shallow prior to zone VI. He interpreted lower lake levels as a signal of drier conditions from 10,000–6000 ¹⁴C yrs BP. In the upper 6 m of the sediment core, after 6000 ¹⁴C yrs BP, he noted a change to non-arboreal pollen types (principally Poaceae, Amaranthaceae, and *Zea mays*) that indicated that humans were modifying the environment.

Overall, Bradbury (1971) identified a transition in diatom types as climate became drier over the early to middle Holocene. He found his record to be dominated by planktonic freshwater diatoms (such as *Denticula elegans*) during the cooler and also wetter periods, with transitions to planktonic brackish diatoms (such as *Cyclotella striata* and *Cyclotella quillensis*) when climate started to become drier. When the climate was dry enough to significantly lower lake levels, the record was dominated by brackish benthic diatoms (*Anomoensis costata*, *Campylodiscus clypeus*, and *Nitzschia frustulum*). Finally, when the lake was at its lowest stand, the brackish waters had receded to where the sediment core was taken, and so only freshwater benthic diatoms were found due to the freshwater spring nearby.

Watts and Bradbury (1982) expanded on the work of Bradbury (1971) in the Cuenca de Mexico region by examining two sediment cores from Lake Patzcuaro and the Chalco Basin. The core from the Chalco Basin was a relatively short core (ca. 5 m, compared to the 15.2 m Lake Patzcuaro core), with a basal date of 14,450 ¹⁴C yrs BP. Diatoms were analyzed through the core and grouped by habitat preference: slightly acidic marshes (*Eunotia* spp., *Pinnularia*, spp. and *Tabellaria flocculosa*), shallow freshwater (*Fragilaria construens*, *F. bevestriata*, *F. pinnata*), saline water marshes (*Anomoensis costata*, *Amphora veneta*, *Navicula el-kab*), and shallow alkaline marshes (*Cocconeis placentula*, *Nitzschia amphibia*, *Denticula elegans*, *Navicula fragilarioides*).

They found acidic marshes to be most abundant during the Pleistocene and early Holocene, after which time saline marsh types expanded. They found minor fluxes between fresh and saline diatoms types after 6000 ¹⁴C yr BP that they considered resulted from minor climatic fluctuations. However, diatom assemblages in the last 3500 ¹⁴C years of the record showed evidence of damming of the lake and water diversions by early agriculturalists.

To expand their understanding of regional environmental changes, Watts and Bradbury (1982) also examined changes in pollen frequencies in Lake Patzcuaro and compared their results to the Chalco Basin diatom record. This approach allowed them to look at environmental changes that affected the entire watershed, rather than solely at changes in the Chalco sediment core that were susceptible to alteration by tectonic processes in addition to climate and people.

Lake Patzcuaro pollen assemblages indicated a relatively cool, dry period dominated by *Juniperus* and *Artemisia* from the base of the sediment core ca. 44,000 ¹⁴C yrs BP to the latest Pleistocene ca. 11,000 ¹⁴C yr BP. While percentages of *Pinus*, *Alnus*, and *Quercus* were high throughout the sediment core, they found a further increase in percentages in the early Holocene. Weedy herbaceous pollen types increased around 5000 ¹⁴C yrs BP and *Alnus* percentages dropped. This roughly corresponded to the time when the flooding of the Chalco site appears to have decreased, and shallow freshwater ponds became more established. Agricultural pollen types (abundant Poaceae, Amaranthaceae and *Zea mays*) were found in Lake Patzcuaro until ca. 3500 ¹⁴C yrs BP; however, Watts and Bradbury (1982) attributed the changes in pollen and diatoms ca. 5000 ¹⁴C yrs BP to early human activities.

Gasse and Takeia (1983) developed transfer functions for tropical East African diatoms to estimate pH. They used percentages of diatoms from 245 taxa in 156 samples between 12°N and 12°S and 26–43°E. Based on initial regression results and component analyses, they formulated the following transfer function:

$$y_{(j)} = \sum_i^s a_i p_{ij} + \bar{y} + e_j \quad \text{Equation 2.1}$$

Where;

s = number of species

$y_{(j)}$ = estimated value of parameter y (pH) in sample j

p_{ij} = percentage of species i in sample j

\bar{y} = mean of parameter y for all the samples

e_j = the difference between the estimated value and the measured value of parameter y in sample j

a_i = the coefficient for species i

Gasse and Takeia (1983) grouped pH indicator species into six pH groups. However, they stated that their results should only be used for modern diatom paleoecology. They did not test whether their results were applicable to fossil diatom assemblages.

Metcalf (1988, 1995) pointed out that, compared to other regions such as the United States and Canada, relatively little research involving diatoms has been carried out in Mexico and Central America. As a result, the ecological profiles of individual species of diatoms were lacking. In earlier diatom analyses, a single sediment core or lake was commonly studied. The meaning of changes in diatom frequencies was often unclear because a change in hydrologic conditions could result from a number of chemical and physical factors, and diatom species populations could respond to single or multiple factors.

To determine the environmental factors to which modern tropical diatom species respond, Metcalf (1988) sampled diatom populations from plants, rocks, and sediments from 47 sites across Central Mexico (Oriental Basin–Zacapu Basin). Her aim was to measure water chemistry and compare it to diatom assemblages at each site. She ran each dataset in statistical packages

TWINSPAN (two-way indicator species analysis; Hill 1979a) and DECORANA (detrended correspondence analysis; Hill 1979b) to determine whether her diatom samples shared a relationship with any of the water chemistry data and with other diatom species. Metcalfe (1988) found that the distribution of diatom types depended on water chemistry. For example, species of *Nitzschia* spp. were found to be most abundant in chemically concentrated waters, particularly those with high concentrations of Na⁺ and K⁺ with higher alkalinities and more Cl⁻. Results from the detrended correspondence analysis indicated that diatoms are sensitive to variations in microhabitat across even single lakes, which Metcalfe (1988) stated could be missed if only a single sediment sample is taken from the center of a lake. Results from the indicator species analysis indicated that diatoms from lake margins and that grew on plants were important in making modern analogs that could be compared to sediment profiles. Metcalfe found that surface sediment samples were the best method for sampling modern diatoms because they provide an "average" picture for the particular water body, particularly when samples cannot be collected several times during the year to compensate for seasonal changes in diatom frequencies.

However, Metcalfe (1988) cautioned that while water chemistry appeared to play a significant role in the distribution of many diatom species, humans also have had a pervasive and significant impact on diatom frequencies throughout the region. She recommended that her results are most applicable to modern diatom interpretations and should be used with caution when analyzing diatom assemblages from the Pleistocene or earlier Holocene.

Fritz et al. (1991) later modified Gasse and Tekaiia's (1983) methods to infer changes in salinity from sedimentary diatoms at Devils Lake, North Dakota. Although conducted in the temperate zone, the study is relevant to tropical diatom work. Fritz et al. (1991) first collected water chemistry and diatoms from thirty-nine lakes in North and South Dakota and twenty-seven

lakes in Saskatchewan, Canada to identify the range of salinities to which modern diatom taxa respond. They used principal component analysis (PCA), DECORANA, and canonical correspondence analysis to identify a strong first order relationship between water chemistry and diatom taxa abundance to estimate salinity optima and tolerances for all diatom types that were present in >2% of the assemblages.

Once the modern diatom salinity functions were identified, Fritz et al. (1991) used their results to infer changes in salinity over the Holocene in Devils Lake. Based on the diatoms found in a 24 m sediment core from the lake, they inferred that the lake was freshwater in the early Holocene until ca. 8000 ¹⁴C yrs BP, when saline diatom types appeared. They interpreted saline conditions as reflecting lower lake levels until ca. 7000 ¹⁴C yrs BP, when water chemistry began to oscillate between fresh and saline. Statistical analyses revealed that the lake salinity varied from 1–40‰ throughout the Holocene. The Fritz et al. (1991) study is a model for diatom studies but required a large number of closed-basin diatom samples and water chemistry data in order to construct transfer functions. No one has been able to attempt this approach in the Caribbean due to the lack of modern diatom data, especially diatom data that has not been significantly impacted by human alteration of lake hydrology and chemistry.

Metcalf (1995) examined changes in diatom frequencies in the Zacapu Basin, Mexico using four sediment cores that covered the period from 8000–3000 ¹⁴C yrs BP. Unlike her previously discussed research, Metcalf (1995) aimed to use sediment cores from sites that share similar water chemistry, from which she interpreted changes in diatom percentages resulting from changes in habitat. In her first site, CEMCA 1, she found the profile to be dominated by *Cocconeis placentula*, which she interpreted to indicate alkaline marsh conditions. Peaks in *Fragilaria* spp., particularly *F. pinnata*, were considered to reflect more open water conditions

(this was partly based on a large number of other planktonic types also found with *Fragilaria* spp.), although she noted that *Fragilaria* spp. commonly occurred after volcanic ash layers that suggested that the genera could also be responding to increases in silica.

Metcalf (1995) also found periods similar to those reported by Bradbury (1971) and Watts and Bradbury (1982) during which diatoms that were indicative of slightly acidic conditions were mixed with diatoms commonly found in high pH, alkaline conditions. She offered two possible explanations for these results, (1) reworking of sediments, or (2) rapidly fluctuating environmental conditions. Her second sediment core, CEMCA 4, showed relatively poor diatom preservation, but was dominated overall by *Fragilaria* spp., particularly *F. pinnata* var. *lancettula*, as well as *Aulacoseira* spp. Below peaty layers, diatoms indicated circumneutral conditions. After the lake became hydrologically isolated between 7000 and 6500 ¹⁴C yrs BP, a change to warmer conditions was noted ca. 5000 ¹⁴C yr BP.

Her third and fourth cores, Zacapu and Zacapu section 1, also showed fluctuations in lake levels over the past 4000 ¹⁴C yrs BP. Lake pH appeared to have been relatively stable over time with the exception of the most recent period, when humans began to alter hydrologic conditions. High percentages of *Stephanodiscus* spp. were discussed as a possible indicator of human alterations because they occurred where a peak in phosphorous was recorded. The lake was also somewhat deeper for a period ca. 2200 ¹⁴C yrs BP.

Metcalf (1995) noted that the four records together showed shallow, slightly acidic to circumneutral conditions prior to 7000 ¹⁴C yrs BP. After a period of disturbance (most likely when the lakes became hydrologically isolated) around 6900–5800 ¹⁴C yrs BP, the climate appeared to become drier with increased lake alkalinity and shallow lake levels by ca. 4500 ¹⁴C yrs BP. A return to wetter conditions was shown by 2800 ¹⁴C yrs BP, before humans caused a

rapid fall in lake level at 1100 ¹⁴C yrs BP. Metcalfe (1995) concluded that her records seemed to agree with other research from the region that signaled drier conditions in Central America around 5000 ¹⁴C yrs BP. She contrasted this with the Caribbean data that showed a change in climate towards wetter conditions at this time. She attributed this difference to the complexity of climate in the region but did not speculate on the driving mechanisms for the differences.

The role of disturbance in determining Caribbean diatom species richness was studied by Agard et al. (1996). As part of their test of the dynamic equilibrium model (Huston 1979, 1994), Agard et al. (1996) examined diatom species richness within the uppermost meter of water from 46 sampling stations across the Caribbean Sea. Their aim was to test Huston's model by analyzing species richness as it related to disturbance from outflow from the Amazon/Orinoco basin. The authors pointed out that, between the months of June–January, ca. 60% of outflow from the Amazon and Orinoco Rivers was carried by ocean currents into the Caribbean Sea, which can temporarily lower salinities, creating a disturbance for marine diatoms and altering productivity.

Agard et al. (1996) recognized 43 different diatom taxa. They found that Caribbean marine diatom species richness was significantly correlated ($r = 0.667$) with primary productivity. They also found that species richness increased with disturbance, although they could not specify why primary productivity and disturbance affected species richness. However, they hypothesized that factors such as deforestation of the Amazon basin, increased pollution, and El Niño could impact freshwater discharges into the Caribbean, which in turn would impact Caribbean marine diatom richness.

Early research into the distribution of diatoms (as well as other phytoplankton and zooplankton) in Costa Rica by Haberyan et al. (1995) revealed that species richness partly

depended on sampling methods. At 30 lakes across the country ranging in elevation from 8–3520 m, water clarity (based on secchi disk measurements) was inversely correlated with phytoplankton species richness as determined from water samples. Diatoms dominated two of the lakes and were ranked second and fifth in abundance in two other lakes. Haberyan et al. (1995) stated that high diatom abundance may have been due to higher silica (>30 ppm) in the lakes, although they also noted that diatoms were not present in other high silica lakes (31–40 ppm). Overall, they found only weak relationships between planktonic species patterns and abiotic and biotic characteristics of the lakes. However, they stressed the need for further research and for an examination of the role of seasonality on zooplankton.

Later work by Haberyan et al. (1997) examined diatoms in the surface sediments of twenty-five lakes. They used canonical correspondence analysis and principal components analysis to compare the distribution of 59 Costa Rican diatom species to 21 chemical and physical variables. They found that diatom diversity shared a strong inverse relationship with magnesium ($r = -0.99$). However, they also found that magnesium shared a positive relationship with silicon dioxide and temperature, and was weakly correlated with sulfate and lake depth. They found a strong positive relationship between diatom diversity and lake area ($r = 0.96$), although they noted that this variable is likely to be related to lake depth, mixing, and shoreline development, which means that lake chemistry may be more important than lake size (Haberyan et al. 1997).

Haberyan et al. (1997) identified five diatom types as potential indicator species, most of which were related to dilute water conditions. *Brachysira serians* and *Frustulia rhomboides* var. *rhomboides* were identified as potential indicators of low to very low calcium, magnesium, hardness, alkalinity, and silica. *Cynbella minuata* var. *silesiaca* responded to the same variables,

except silica. *Nitzschia* cf. *amphibia* was found in lakes with moderate to high concentrations of magnesium. Finally, *Pinnularia braunii* var. *amphicephala* was associated with low values of calcium, magnesium, and silica. However, the authors also noted that many of the 59 taxa identified were only found in one lake and so they could not determine whether species were responding in a linear or unimodal manner.

Haberyan et al. (1997) compared their results to East African diatom analyses performed by Gasse et al. (1983) and Gasse (1986). While Gasse et al. (1983) found the genus *Achnanthes* spp. to have no clear chemical environmental preference, Haberyan et al. (1997) found it to be widespread in Costa Rica and noted it to be alkaphilious in the United States (Patrick and Reimer 1966). Haberyan et al. (1997) also pointed out that numerous studies of *Aulacoseira* spp. characterized the genus as preferring high silica, turbidity, and at least moderate productive conditions (Richardson 1968; Gasse 1986), but that specimens of the same genus were found in glacial lakes in Costa Rica that are characterized by cool, clear, low silica (6–8 ppm) waters.

Haberyan et al. (1997) hypothesized that their contrasting results might be caused by two separate species and cautioned that ecological knowledge of diatoms needs to be developed in each region because reports from distant sites may not be relevant. They emphasized the need for further diatom analyses in Costa Rica and pointed out that their results would be particularly useful in closed basins where changes in diatom species in response to the changing chemical properties of the lake would be more likely to reflect changing E/P ratios.

Haberyan and Horn (1999) followed up Haberyan et al.'s (1997) observations of *Aulacoseira* spp. from Lago de Las Morrenas 1, Costa Rica by analyzing changes in diatom frequencies preserved in the same ca. 10,000 ¹⁴C yr BP sediment core that Horn (1993) had analyzed for pollen and microscopic charcoal. Diatom slides were counted at 21 levels in the

core, although a total of 52 sample levels were prepared to verify initial results. Percentages of *Aulacoseira* spp. were high throughout the core with $\geq 95\%$ *Aulacoseira* spp. at all levels counted. Twenty-six other diatom types were identified (comprising 12 species of *Navicula*, 5 of *Pinnularia*, 2 of *Brachysira*, and 1 each of *Caloneis*, *Gomphonema*, *Cymbella*, *Cocconeis*, *Nitzschia*, *Cyclotella* and *Eunotia*), although *Aulacoseira* spp. percentages remained relatively consistent except for a broad, modest rise at 90 cm in the profile when other Central American and Caribbean records suggest the climate may have been drier.

The Lago de Las Morrenas 1 diatom record suggested that lake conditions were relatively stable during the postglacial period. This would be in agreement with the pollen record of the region, although Horn (1993) found variations in the charcoal record that should have altered the lake chemistry to some degree. However, Haberyan and Horn (1999) suggested that sampling closer to the charcoal peaks may have revealed more variability in the percentages of *Aulacoseira*. Riedinger (1993) also found high percentages of *Aulacoseira* in her 900-year highland record from Huarimicocha, Ecuador that may derive from the same species or a close relative to the species found in Lago de Las Morrenas 1. Haberyan and Horn (1999) hypothesized that lower lake levels could also favor *Aulacoseira* when a lowered level would create shallower, clearer water for photosynthesis and when the waters would be well mixed, as this would favor dense *Aulacoseira* valves that require turbulence to remain suspended in the water column.

Haberyan and Horn (2005) also used diatoms to look at the paleoecology of Laguna Zoncho in southern Pacific Costa Rica. Their analyses showed the presence of five species of *Aulacoseira* in a 290 cm section of sediment core spanning ca. 3240 cal yr BP to 1997 CE. Results were zoned A–C and showed that lake paleoecology was very similar in zone A (ca.

3240–1020 cal yr BP) and zone C (ca. 420 cal yr BP–1997 CE). *Aulacoseira* spp. dominated both zones, although zone C also showed progressive changes in acidophilous and/or benthic diatom species, such as *Pinnularia braunii*, *Eunotia* spp. and *Encyonema* spp. The authors cited the earlier research by Haberyan et al. (1997) that showed that *P. braunii* is indicative of low concentrations of calcium, magnesium and silica.

In zone B, *Aulacoseira* spp. were notably absent and *Staurosira* spp. were replaced by *Eunotia* spp. and *Pinnularia* spp., which Haberyan and Horn (2005) interpreted as a transition from dilute, circumneutral water conditions to shallower, more acidic conditions from ca. 1020–420 cal yr BP. This period coincides with pollen evidence of indigenous agriculture in the lake basin. The diatom assemblage becomes more diverse at that time, although Haberyan and Horn noted that these changes may not exclusively result from human activities, as Bush and Colinvaux (1994) interpreted diatom shifts at Lake Wodehouse, Panama to also indicate drier conditions at that time.

The Barú tephra layer marks a transition in Laguna Zoncho to zone A, which also marks the return of *Aulacoseira*-dominant, wetter, and circumneutral conditions. Zone A corresponds to the arrival of Europeans, decreased agricultural activities within the basin, and the return of forest conditions. It is unclear whether *Aulacoseira* spp. re-established because of a decrease in human disturbance or because of a change in lake chemistry resulting from the deposition of the tephra.

Romero et al. (2009) studied changes in the composition of modern diatom assemblages at 275 m and 455 m water depth in the Cariaco Basin, Venezuela. They submerged traps that collected sediment (of which diatoms were the dominant constituent) at two-week intervals. The traps were emptied every six months from 1996–1999. *Cyclotella litoralis* was the most

frequently identified species (average 11–68%) out of the ca. 160 diatom taxa. They found diatom fluxes to be highest during the boreal winters when the ITCZ moves south and increases the upwelling of nutrients in the water. When the ITCZ moves northward in the boreal summer, the N–NE tradewinds are weakened, resulting in less input of nutrients and primary productivity, and diatoms frequencies decrease. During an El Niño-Southern Oscillation (ENSO) year, Romero et al. (2009) noted that diatom assemblages were significantly different and contained a mixture of coastal and pelagic species. *C. litoralis* was identified as a secondary species during the ENSO year as the assemblage was dominated by *Thalassionema nitzschoides* var. *inflata* and *Nitzschia bicapitata*. The composition of the diatom assemblage during ENSO included a greater variety of temperature- and nutrient-dependent species that reflected changes in ocean currents over a very short period of time.

2.2.6 Caribbean Records Relating to Salinity and Sea Level

Bard et al. (1990) used coral (*Acropora palmata*) from Barbados to date and estimate changes in Caribbean sea level over the past 130,000 yrs BP. They used both radiocarbon (^{14}C) and uranium/thorium (U-Th) age determination methods. Their data showed that sea level was 85 m lower during marine isotope stage 3 (ca. 30,000 yrs BP) and that sea level had risen at rates of ca. 2.5–3.7 m per century after the meltwater pulses of ca. 13,500 and 11,000 yrs BP. They did not go into further detail about the Holocene sea level changes; however, their work was later cited by Peltier and Fairbanks (2006), who showed sea level gradually increasing throughout the Holocene.

Holmes et al. (1995) analyzed a 9.23 m sediment core extracted from a coastal lake in Jamaica, Wallywash Great Pond, to reconstruct changes in water chemistry over the past ca.

125,000 yrs BP. They used geochemical and isotopic data (Sr/Ca, Mg/Ca, $\delta^{18}\text{O}$, $\delta^{13}\text{C}$) to reconstruct changes in salinity, P/E ratios, and productivity, from which they estimated relative lake levels. High stands of the lake were also indicated by the deposition of marls. Reconstructed Sr/Ca ratios were found to indicate changes in evaporative water concentrations, as well as input from the brackish coastal aquifer to the west of the pond. Mg/Ca ratios were interpreted as reflecting changes in biogenic decalcification of the water and in temperature. $\delta^{18}\text{O}$ values resulted from changes in P/E ratios (decreasing $\delta^{18}\text{O}$ values = increased precipitation) and $\delta^{13}\text{C}$ showed changes in productivity of the submerged aquatic macrophytes in the pond (increased $\delta^{13}\text{C}$ values = increased productivity).

In the marl units during the Holocene (10,000–8300 cal yr BP), Holmes et al. (1995) found moderately high Sr/Ca values, low Mg/Ca, and slightly negative $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, which they interpreted as indicating moderate P/E ratios, slightly elevated salinity, and moderate aquatic productivity. A later marl unit deposited from 4400–3500 cal yr BP showed decreasing Sr/Ca and Mg/Ca values and negative $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values that together signaled moderately high P/E ratios, decreasing salinity, and moderate aquatic productivity. Based on similar conditions from 1200 cal yr BP–present, Holmes et al. (1995) interpreted the most recent interval to represent a high stand of the pond that was initiated by a flooding event (based on a large decrease in $\delta^{18}\text{O}$ values). They concluded that periods when marls were not deposited likely represented drier periods in the Caribbean (ca. 8000–5000 and ca. 3300–1200 cal yr BP).

While the 1995 study of Wallywash Great Pond was based on isotopic analysis on a single species of ostracod, Holmes (1998) later expanded the previous research by examining changes in ostracod assemblages through the sediment core as an indicator of changing environmental conditions. He discussed nine ostracod taxa deposited throughout 103 levels in

the core. Only his Holocene data are directly relevant to understanding the Laguna Saladilla record; however, it is worth noting that Holmes found evidence of fluctuations in salinity prior to the Holocene that he attributed to changes in groundwater saltwater intrusion.

From ca. 10,000–8300 cal yr BP, Holmes (1998) found the sediment to contain *Cypretta brevisaepta*, a nektonic species associated with high lake levels. Shallow water ostracod species began to increase after 8300 yrs BP, suggesting gradually lowering lake levels until ca. 6600–4600 cal yr BP, when the environment became very dry based on the dominance of the ostracod assemblages by *Candonopsis* spp. coupled with $\delta^{18}\text{O}$ values and the disappearance of marls. The reappearance of marls from ca. 4400–3500 cal yr BP marked a lake transgression that indicated wetter conditions. Water levels appeared to decrease from ca. 3500–2400 cal yr BP, when *Candonopsis* spp. began to flourish again.

In the upper part of the sediment core (the current wet period initially discussed by Holmes et al. 1995), *C. brevisaepta* once again increased along with species of *Darwinula* spp., although analyses of modern conditions are complicated by a flooding event of the nearby Black River that deposited several species of ostracod in the pond. According to Holmes (1998), the P/E ratios of the last 1000 cal yr BP that seem to suggest slightly drier conditions, but no significant changes in the ostracod assemblages seem to parallel this change.

Peros et al. (2007a) examined changes in salinity relating to relative sea level (RSL) using isotopes ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, $^{87}\text{Sr}/^{86}\text{Sr}$) in coastal lake Laguna de la Leche, Cuba. They used changes in the ratios of $^{87}\text{Sr}/^{86}\text{Sr}$ in ostracods as a paleosalinity indicator. The resolution of their record is somewhat coarse because their sediment core was only 2.27 m long and covered 6350 calibrated years. Their deepest radiocarbon date shows the base of the sediment core to date to 7950 ^{14}C yrs BP. However, their radiocarbon dates were from bulk sediment that appeared to

have been affected by the "carbon reservoir effect," which made their dates appear to be older than they actually were. Based on dates taken near the top of the sediment core and dates from nearby locations, they interpreted their chronology as having a 1600 year age overestimate, and so they subtracted 1600 years from all of the ^{14}C results before calibrating the dates. Higuera-Gundy et al. (1999) had a similar problem with radiocarbon dates from ostracods from Lake Miragoane. They used a date from a piece of wood taken at the same level as an ostracod radiocarbon date to determine that their chronology needed to be corrected by subtracting 1000 years from each ostracod date.

Based on their corrected chronology coupled with other isotope data, Peros et al. (2007a) found the base of their core from ca. 6200–4800 cal yr BP to have high $\delta^{18}\text{O}$ values and to indicate saline conditions. They interpreted this period as one when the lake was a closed system with increased evaporative (drier) conditions. From the isotope data that showed more saline conditions, they inferred that drier conditions reduced lake levels and that storm surges or short-term increases in RSL may have periodically input marine water into the lake.

Isotope $\delta^{18}\text{O}$ values decreased after ca. 4800 cal yr BP until ca. 4200 cal yr BP. Peros et al. (2007a) characterized the period as having deeper, freshwater conditions, although they could not determine whether a freshening of the water was due to a regional climatic change or a more local change in drainage that could have led to increased surface runoff. A mesohaline lagoon appears to have replaced the lake after a severe 100-year drought ca. 4200 cal yr BP. Peros et al. (2007a) stated that rising RSL may have played a role in the system becoming open to marine waters at that time. Those conditions continued until ca. 1700 cal yr BP, cutting the basin off from the marine influence. Salinity does not appear to have been significantly affected by the expansion of mangroves, although $\delta^{13}\text{C}$ values signaled a change in local vegetation. Slightly

elevated $\delta^{18}\text{O}$ values also suggested greater evaporation at that time. The lake remained oligohaline until the present.

Peros et al. (2007b) further discussed the role of RSL on fluctuations in salinity in Laguna de la Leche and introduced data from nine other sediment cores taken from mangrove swamps near the lake. They compared changes in stratigraphy across all sediment cores and examined changes in loss-on-ignition, pollen, and foraminifera assemblages in the three longest cores (Laguna de la Leche, E6, and LR). All cores revealed the same changes from a closed basin, to a lagoon, to a mangrove-impounded lake. The foraminifera and pollen data allow further inference of changes in RSL over the last ca. 6200 cal yr BP. Peros et al. (2007b) attributed the establishment of the oligohaline lake from ca. 6200–4800 cal yr BP to higher RSL, which increased the elevation of the phreatic aquifer. The freshening of the lake from ca. 4800–4200 cal yr BP was again hypothesized to result from either regional climatic changes or a local change in drainage.

However, at ca. 4200 cal yr BP, RSL was found to have a more direct impact on the lake when the Bahia de Perros exceeded the elevation of the sill separating the lake from the ocean waters. Laguna de la Leche was saline from ca. 4200–2000 cal yr BP, which Peros et al. (2007b) hypothesized was caused by a connection with marine waters that was frequent and possibly permanent. The expansion of mangroves ca. 1700 cal yr BP may have been facilitated by a decrease in the rate of RSL rise. Marsh plants also took hold around the lake at that time, although they were somewhat hampered by the brackish nature of the waters.

Gonzalez et al. (2010) examined a 175 cm-long sediment core from Bahia Honda, on the Caribbean island of San Andres. A date of ca. 2780 cal yr BP was obtained at the bottom of the sediment core; however, other radiocarbon dates and a layer of coarse calcareous and terrigenous

debris indicated that approximately 2000 years of sediment accumulation was missing. The authors suggested this was evidence of a hurricane event, possibly dating to 1605 CE when a strong hurricane destroyed several ships in the region. Their sediment core was estimated to reflect changes in environment that only covered from ca. 400 calibrated years, from the time of the LIA to the present. Gonzalez et al. (2010) raised the sediment core from a mangrove swamp and hypothesized that pollen analyses of the sediments would reflect changes in RSL, as such changes can significantly impact on mangrove dynamics. Other factors that can also impact mangroves include tidal amplitude, frequency of storm surges, and intrusion of seawater into surface waters. Mangroves are also highly dependent on the structure of the underlying sediments (typically peats), which Gonzalez et al. (2010) stated would also change with changes in RSL.

After the hurricane ca. 400 cal yr BP, they found pollen assemblages to be dominated by herbaceous taxa (Poaceae, Cyperaceae, Asteraceae, *Acrostichum* ferns) for ca. 100 years before *Rhizophora* (mangrove) recovered and became dominant. They cited the work of Urquhart (2009) as evidence that mangroves can take 10–200 years to reestablish after a hurricane. From ca. 300–150 cal yr BP, mangrove pollen percentages increased, which the author interpreted as a signal that, during the LIA, climate changed from drier to more humid. After ca. 150 cal yr BP, humans altered the environment. After comparing their data to other historical records, they concluded that two phases of fluctuating mangrove pollen percentages (ca. 1580–1600 CE and ca. 1770–1800 CE) reflected greater hurricane and storm frequencies.

2.2.7 Ground Penetrating Radar (GPR) and Its Applications to Paleolimnology

GPR makes use of high-frequency radar pulses transmitted from an antenna (transmitter). An image of the sediment layers can be created based on the amount of time it takes the radar pulses to be reflected back to the antenna (receiver; Conyers 2004). GPR is a relatively new technique that has only recently been used in lacustrine environments. Early users of GPR were principally prospectors using GPR to detect ground water tables and other geological features that could be used by people in the field of natural resource exploration (Davis and Annan 1989). Later users included academics from the fields of geology and archaeology that used GPR to discover buried deposits and subsurface features (Conyers 2004; Neal 2004; Jol 2009).

One of the earliest users of GPR technology for lake sediments and peats was Lowe (1985). In his work, he used a GPR system to map alternating tephra and peat layers in Lake Maratoto and Rukuhia peat bog, New Zealand. His results showed he was able to penetrate around 8 m depth by towing antennae in a boat at a speed of ca. 5 km/hr. While he was not able to discern discrete reflections from each peat layer, he was able to map the underlying basin. He attributed this inability to determine peats to the fibrous nature of the materials, which could increase the signal-to-noise ratio of the GPR signals.

Some GPR studies on land are relevant to issues of radar penetration and sediment characterization in lakes. An example is the work of Doolittle et al. (1990), who used a GPR system to examine the depth of permafrost in two sedge tundra sites near Bethel, Alaska. They dragged their GPR system across a number of transects to map the depth of the active (perennially frozen) upper layer of the soil and determine the distance to the permafrost boundary. The mean depth of the active layer was measured to be between 1.0–1.03 m, although Doolittle et al. (1990) were able to achieve a little over 1.5 m total radar penetration. They stated

that the results of their research also showed that GPR was incapable of determining the composition (texture, bulk density, organic carbon, soil moisture) of the underlying active soil layer, which they interpreted as being due to variations in these properties being "too diffuse" for detection. Instead, soil auger samples were collected to record depth of radar penetration in sandy vs. silty sites.

Jol and Smith (1991) carried out some of the earliest GPR deltaic studies by looking at six river deltas in Canada to identify changes in subsurface facies orientation and depth to characterize the depositional environment. Radar penetration between the six sites ranged from 3–32 m. Shallowest radar penetration was in a peatland deposit that was underlain by electrically conductive clays. Jol and Smith (1991) were able to discern changes in profiles attributable to water table position changes, changes in particle sizes (gravel beds), and deltaic facies (described as bottomsets, topsets, and foresets), based on changes in the incline of gravel beds. Overall, they found optimal conditions to be in quartz-rich, dry, sand and gravel that was lacking any clay traces. However, they still found GPR to be a very effective technique of achieving high resolution subsurface images, although depth of penetration was limited in locations with large amounts of clay or saline waters that are more electrically conductive.

Mellett (1995) evaluated GPR profiles from three lakes in the United States and one bog in Finland. The aim of his research was to determine the effectiveness of GPR for measuring the sediment packet in basins to find optimum locations for extracting cores for pollen analysis. His paper discussed finding sand layers in peats and ponds that he "ground truthed" using sediment cores. However, he did not make any attempt to determine whether changes in energy wave velocity were the result of changes in the layering of sand vs. ground water boundaries using GPR alone. His technique is somewhat limited in that, to determine optimum coring locations, a

sediment core must be taken first so that the nature of the underlying sediments can be characterized. In one of his study sites, Ball Pond, Connecticut, Mellett (1995) used a sediment core to determine the position of intertonguing beds of sands and silts where a sand delta terminated and merged with finer lacustrine sediments. While the presence of the delta was visible by GPR that showed a change in the subsurface bedding plane, distinct layering between sand and silts was not apparent. Deltas in Laguna Saladilla also did not show any changes in sand-silt boundaries at the terminus of deltas. However, the sand-silt boundary could be identified using changes in signal amplitude (see Appendix III and Chapter 3).

Moorman and Michel (1997) carried out GPR analyses at three lakes (Bulb Lake, Kettle Lake, and Kame Lake) in a glacial valley on Bylot Island, Canada. They performed a number of surveys across the lakes, which were 10–19 m deep. Their surveys revealed that the lakes were surrounded by an apron of boulders and that lacustrine sediments were deepest in the center of the lakes. The lakes showed no evidence of submerged deltas, a finding that Moorman and Michel (1997) interpreted as evidence that sediment accumulation was derived principally from aeolian sources, with the lake never having received glacial outwash. They also noted a lack of clearly discernable submerged shorelines that indicated the lakes do not have a history of strong wave action that could have cut a distinct shoreline boundary.

While Moorman and Michel (1997) were able to use GPR to penetrate to depths up to 25 m (5 m short of the authors' expected signal penetration depth), the depth resolution (the resolution at which sedimentary layers could be observed) was calculated to be around 0.25 m. The authors used a 100 MHz antenna that Davis and Annan (1992) stated could be used to penetrate up to 40 m deep. The research by Moorman and Michel (1997) revealed the important

role that depth resolution plays in analyses of this nature. Radar penetration is irrelevant if the resolution for interpretations is lacking.

Moorman and Michel (1997) also used sediment samples obtained with a box grab sampler and gravity corer. They used the samples to estimate the relative dielectric permittivity (RDP) of the sediment, which can be used to tell how fast reflected waves travel through the sediment. However, they only used their samples to estimate GPR depth penetration based on two-way travel time. They did not use the samples to examine what changes in RDP indicate about changes in depositional environment.

Grant et al. (1998) used GPR to map changes in sediment boundary layers in four lakes in South Carolina. They used 500 MHz and 100 MHz antennae to examine the sediment to a depth of around 20 m. GPR results revealed a clear relict soil B/C horizon, as well as a number of sand sheets and wedges. They noted that sand was identified where it became hard to delineate GPR reflections. They attributed this to what they termed minimal variations in grain size, but did not verify their hypothesis. They did recover sediment cores from a small number of locations, but in many instances they determined the stratigraphy was too deep to be cored, preventing the ground truthing of their interpretations of their GPR profiles. Nevertheless, they used their results to model the evolution of Carolina bays.

Pipan et al. (2000) used a combined GPR and acoustic profiling technique to analyze subaqueous features of Cheko Lake, Russia. Their aim was to examine how the 1908 Tunguska meteor impact affected basin morphology. The lake contains a great amount of suspended sediment and iron oxides that prevented the use of GPR in deeper parts of the lake (areas up to 54 m water deep). However, GPR was used to image to a depth of 10 m (sediment plus the water layer). Based on their GPR profiles, they characterized four types of sedimentary environment:

deep sub-horizontal reflectors, zones of chaotic deposition, dipping reflectors, and shallow parallel reflectors. From this information, they were able to identify areas of the lake that should be cored to examine the impact of the Tunguska meteor event. The method for identification of coring locations used by Pipan et al. (2000) did not first require collection of exploratory sediment cores to characterize sediment composition, as did the technique of Mellett (1995).

In another land-based study relevant to my work at Laguna Saladilla, Carreon-Freyre et al. (2003) used 300 MHz and 900 MHz antennae to assess spatial variation in the water content of former volcanic soils in the Chalco Basin, Mexico. They did not expect to penetrate the soil very deeply because the profile contained large amounts of clay with high electrical conductivity, but the contrasting nature of the sediments nevertheless allowed them to detect at least three distinct soil boundaries. Based on their mainly qualitative assessment of the GPR profiles, Carreon-Freyre et al. (2003) concluded that GPR was very effective in profiles where sedimentary sequences may not show any visual differences, but have different physical and/or chemical properties that are enhanced in a GPR profile image, such as differing water content. Overall, Carreon-Freyre et al. (2003) found the 300 MHz antenna to be best suited to detecting broad changes in soil physical characteristics (stratigraphy), while the 900 MHz antenna was better at revealing fine details, such as changes in particle size.

Havholm et al. (2003) used GPR to map sedimentary sequences that they attributed to Holocene aeolian-fluvial-lacustrine succession in the Souris River, Canada. GPR was used to examine the sediments because it was expected that the sedimentary sequence contained many physical and chemical contrasts that would be easily detectable with GPR. In particular, Havholm et al. (2003) expected that their B horizon, identified as an aeolian sand dune unit rich in iron and manganese, would provide a contrast to the underlying sand and silt fluvial sheet unit.

However, they were only able to achieve around 5 m radar penetration because of iron-rich B horizons and silt-rich C horizons that significantly attenuated the signal of their 100 MHz antenna.

Tary et al. (2007) examined seventeen GPR profiles covering almost 5 km of land in eastern coastal Maine to map relict marine deltas of the East and West Pineo Ridge. The former deltas were studied using GPR because they are currently used for blueberry production, prohibiting coring or the digging of pits to examine the stratigraphy. Instead, Tary et al. (2007) used the less invasive method of GPR with a 120 MHz system with a 300 nanosecond recording window to penetrate as deep as 16 m (estimated depth) into the dry sediments. Tary et al. (2007) recorded changes in dip, as well as buried channels, to map two separate lobes of the delta.

Jol (2009) compiled an edited volume on GPR that covered the underlying principles of the techniques and assessed the relatively new role of GPR in the environmental and earth sciences. A chapter by Bristow (2009) discussed the use of GPR in sand dunes, for which the technique is well suited due to the low conductivity and low magnetic permeability of dry sand. However, he suggested that GPR measurements can be very poor under saturated conditions. For saturated sandy conditions with a 400 MHz antenna, Bristow (2009) calculated a theoretical resolution of any propagating waves of around 0.0375 m (0.15 m for a 100 MHz antenna), compared to 0.09375 m (0.375 m at 100 MHz) for a dry sand. These projections appear to agree with the work of van Dam (2001) who stated that water content is the most important factor in measuring sediment conductivity, which directly impacts relative dielectric permittivity.

2.2.8 Sedimentary Properties and GPR

While a great deal of research has been carried out into the electrical properties of soils, a paper by Saarenketo (1998) is one of the most frequently cited papers in the GPR literature. Saarenketo (1998) conducted a number of laboratory experiments using four different types of clay from the United States (kaolinite, Eddy Clay, Houston Black Clay, and Beaumont Clay) to determine how changes in clay physical and chemical properties altered relative dielectric permittivity. He examined how changes in saturation (and by extension, cation exchange capacity) affected relative dielectric permittivity values. He found that, depending on the clay type, relative dielectric permittivity values did not increase in a linear manner with the addition of water. Although Saarenketo (1998) did not specifically mention the difference between the octrahedral and tetrahedral structure of the different clay types, he discussed how changes in the outer adsorption films of clays alter semi-saturated clay soils. He also found that relative dielectric permittivity values stabilize once they reach 100% saturation and that "free water" plays more of a role than inner and outer adsorption and capillary zones. He suggested that other physical factors, such as compaction, play a greater role in determining relative dielectric permittivity values at 100% saturation, although his published findings only show models ranging up to 60% moisture (by volume).

Overall, Saarenketo (1998) summarized his conclusions as showing that the RDP and electrical conductivity of a soil are very closely related and that properties such as optimum compaction, moisture content, plastic limit, water sensitivity, and frost susceptibility can all impact RDP values. He suggested that relative dielectric permittivity values of clays in free water could be affected by a number of factors, and suggested that these values could exceed those of water, particularly in soils with high amounts of calcium and/or manganese. While

Laguna Saladilla does not show any large excursions in calcium values, manganese has been found from 1.29–8.49 m in the sediment core. Large concentrations of manganese could possibly increase RDP values, thereby reducing signal velocity. Although this variable was not actively investigated by Saarenketo (1998), he suggested further examination.

Earlier research into the electrical properties of soils includes work by Lyon et al. (1988), who used a 120 MHz antenna to map five different soil profiles in Ohio. Their goals were to see how well they were able to determine individual soil features, such as clay boundaries (including fragipans) and to test the accuracy of GPR-derived depths calculated based on two-way travel time of the propagating signals. They were able to detect soil boundaries due to changes in moisture content, differences in texture, and changes from coarser to finer sediments in the over- and underlying sediments. They did not attempt to measure these variables, but instead took a more qualitative approach by defining the broader A to C soil horizons. Depths were compared to field measurements from soil pits. GPR-estimated soil depths were ± 4 cm from actual depths, which they considered satisfactory.

In 1989, Davis and Annan published their seminal paper discussing the application of GPR in high-resolution mapping of soil and rock stratigraphy. They included a table listing calculated values for relative dielectric permittivity, electrical conductivity, velocity, and attenuation of common geological materials (Table 2.2). The values published in their table are still used today in most environmental applications of GPR (e.g. Conyers 2004, Mumpy et al. 2007, Jol 2009).

Starr et al. (2000) investigated the effect of soil particle concentrations and size on relative dielectric permittivity by studying changes in refractive index (the square root of the dielectric constant) in suspended sediment. Specifically, they measured how refractive index

Table 2.2: Average values for the relative dielectric permittivity (formerly known as K), electrical conductivity (σ), velocity (v), and attenuation (α) of common geological materials, adapted from Davis and Annan (1989).

Material	K	σ (mS/m)	v (m/ns)	α (dB/m)
Air	1	0	0.30	0
Distilled water	80	0.01	0.033	2×10^{-3}
Fresh water	80	0.5	0.033	0.01
Sea water	80	3×10^4	0.01	10^3
Dry sand	3–5	0.01	0.15	0.01
Saturated sand	20–30	0.1–1.0	0.06	0.03–0.3
Limestone	4–8	0.5–2	0.12	0.4–1
Shales	5–15	1–100	0.09	1–100
Silts	5–30	1–100	0.07	1–100
Clays	5–40	2–1000	0.06	1–300
Granite	4–6	0.01–1	0.13	0.01–1
Dry salt	5–6	0.01–1	0.13	0.01–1
Ice	3–4	0.01	0.16	0.01

values changed as suspended sediment settled out. This was based on the hypothesis that changes in refractive index can be used to determine changes in the concentration of particles settling out in solution. They found refractive index values to show a general curve as particles of different sizes gradually settle out. However, they also found that, once clay begins to settle, it will carry bound water, and that as a result, clay may have a greater impact on measured refractive index values than would silt. Their initial tests showed that clays were taking longer than expected to settle in solution (based on Stokes Law), which led them to consider their observations of clays to be somewhat unreliable. Their results were complicated by their use of swelling clay types. Based on their observations it would appear that refractive index (and therefore, relative dielectric permittivity) is lower when large amounts of sand are present. It is unclear whether the transition from predominantly silts to clay results in a further decrease in refractive index.

Martinez and Byrnes (2001) tested a number of models that examined how RDP varied based on the ratio of electric-field storage capacity of any medium in comparison to free space (air). Their results corroborated findings by Saarenketo (1998), that water saturation was the primary factor controlling RDP values. Based on their models, they determined that subsurface permeability could be predicted if good correlations could be established between the hydraulic permeability and porosity of individual sediments.

Klein and Santamarina (2003) conducted a number of laboratory experiments using commercially available clay samples (Wilkey RP-2 Kaolin) to examine how various soil characteristics affected electrical conductance. While their tests focused mainly on fine-grained samples, they were able to project what role soil properties had on electrical conductance in sands also. Soil characteristics examined were the role of ionic concentration, porosity, specific surface and particle orientation, and (to a lesser degree ion) mobility surface conduction, and

isotropy (directional dependence). Their results broadly agreed with those of Saarenketo (1998), although they went further by examining the role of particle orientation. They found that, under laboratory conditions, effective conductivity was greatest when pore spaces within the material mixture are oriented parallel to the electrical signal field. However, while this variable was significant in artificial sediment mixtures in the laboratory, it was regarded as less likely to affect soil conductivity in the field, where soil pore space orientation can exhibit a larger degree of variability. Overall, they found that electrical conductance in saturated soils is largely a function of conductivity within particles, bulk fluid conductivity (the conductivity of the free water), and surface conduction.

Lebron et al. (2004) carried out further laboratory experiments on the effects of calcium carbonates in four soils on permittivity values. They compared how permittivity values varied in calcium-enriched soils from arid (California and Spain) versus temperate (Illinois) locations in both liquid (saturated) and solid (dry) states. Their tests revealed that calcium in soils could increase dielectric permittivity, which they interpreted as due to changes in crystal density. This research highlights how many tropical GPR records could be compromised by the presence of calcium carbonate, either in solid form or in solution. Lebron et al. (2004) suggested that using dielectric permittivity values of 6.6 instead of 5 for calcium-enriched soils could partially compensate for this effect. In a saturated state, this may lead to a mild relative dielectric permittivity overestimate because calcium carbonate has a lower dielectric permittivity than water. The authors also stated that their research does not take into account differences in particle size and mineral solubility.

2.2.9 Other Geophysical Techniques of Relevance

A number of geophysical techniques that work on the same principles as GPR have been used to investigate the paleolimnology and underlying geology of selected regions. Edgar (1991) used high-resolution seismic reflection data to map the northern extension of the Septentrional fault zone to the north of Laguna Saladilla. Based on unconformities in sediment layers, Edgar (1991) was able to plot the offshore margins of the fault. However, this technique has not yet been applied to the terrestrial portion of the fault described by Mann et al. (1998).

Nelson et al. (1999) analyzed changes in sediment supply to Lake Baikal, Russia caused by tectonics by taking a series of seismic reflection profiles of the lakes turbidites. They characterized margins of the lake that received greater inputs of sediments from the fault boundary as interbedded with sand-rich aprons. Extensive mud- and sand-rich fans typically accumulate in axial channels and where rivers discharge into Lake Baikal. Based on models by Scholz et al. (1990) of tropical lakes, progradational facies or fluvial channels could be evidence of lower lake-levels in the past. However, if sand-rich aprons are interbedded with hemipelagic muds, then the sands are more likely to be tectonically-induced deposits (Nelson et al. 1999; Scholz et al. 1990).

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CHAPTER 3

USING GROUND-PENETRATING RADAR TO PROFILE LAKE SEDIMENTS AT LAGUNA SALADILLA, DOMINICAN REPUBLIC

This chapter is in preparation for submission to the journal *Archaeological Prospection* by Maria A. Caffrey, Lawrence B. Conyers, Sally P. Horn, and Donald G. Sullivan.

Abstract

Lacustrine basins contain sediment types with unique physical and chemical properties that are unknown until sediment cores can be extracted and examined. Variations in sediment properties and other constituents over time and space within lake basins provide researchers with important clues as to how climatic and/or tectonic conditions have changed over time. While some researchers have extracted multiple sediment cores from single lakes to examine the spatial variability of submerged sediments, this large-scale approach is costly in time and resources. Here, we report an alternative approach to determine the physical properties (particle size) of lake sediments using ground-penetrating radar (GPR). We used a 400 MHz antenna to collect reflection data along 26 transects covering much of the extent of Laguna Saladilla, a large (220 ha) lake on the north coast of Hispaniola, in the far northwest of the Dominican Republic. Our objective was to identify subaqueous depositional facies and deltas deposited by the Río Masacre. A change in the amplitude of radar reflections, which is a function of variations in electrical conductivity and magnetic permeability in sediment and water-sediment boundaries, was found to be indicative of changes in sediment type across the basin. The

coefficient of reflectivity was calculated for 13 sediment dredge samples. For these samples collected at the sediment-water interface, the coefficient was lowest where underlying sediment had large percentages of sand. The coefficient of reflectivity was higher where underlying sediment was mostly silt and clay. The differences in the coefficients of reflectivity are due to differences in water content of the sediments. These results show how the coefficient of reflectivity can be used to detect a change in underlying sediment texture. This research demonstrates how GPR can be used in lacustrine research to determine changes in the physical properties of subaqueous sediments by non-invasively measuring changes in wave velocity across lake basins.

Keywords: GPR, Relative dielectric permittivity, porosity, paleodelta, Hispaniola.

3.1 Introduction

All lacustrine environments are composed of various heterogeneous sediment facies with unique physical and chemical properties that are unknown until physically sampled. Typically, determination of sediment mineral properties (such as particle size) is accomplished by the extraction of sediment samples from the lake and their examination in the laboratory (Cant and Walker 1978; Woodward et al. 2003; Johnston et al. 2007). However, this approach is limited by the number of individual samples that can be taken from a site, and results need to be interpolated between sampling points to approximate conditions over the larger area.

Ground-penetrating radar (GPR) is a geophysical technique that analyzes buried features and lithofacies by measuring the behavior of high frequency radar pulses

generated from a surface antenna through a material (Conyers 2004; Jol 2009). An image of the sediment layers can be created based on the amount of time it takes the radar pulses to be reflected back to a receiving antenna, and on the amplitude changes of the reflected waves, which reveal differences in sediment types. This technique provides continuous measurement of sediment properties using reflected electromagnetic waves to characterize and image boundaries between sediment units. Reflections are generated when a propagating electromagnetic wave encounters any sediment boundary. These discontinuities (which can be physical or chemical) reflect a wavelet that is recorded by the receiving antenna. The velocity (m/ns) at which energy can travel through any medium depends on its electromagnetic properties: electrical conductivity (σ), electrical permittivity (ϵ), and magnetic permeability (μ) (Moorman 2001; Cassidy 2009). A change in radar propagation velocity indicates a change in material, such as the boundary between two geologic units or a change in sediment water content. The ability for energy to travel through any medium depends on its relative dielectric permeability (RDP), or dielectric constant, ϵ_r .

The method we present in this paper was used to determine sediment conditions, specifically particle size and sediment porosity, for water-saturated sediments from Laguna Saladilla, Dominican Republic. The aim of this research was to examine subaqueous depositional features (principally deltas) to determine how the depositional environment of Laguna Saladilla has changed over the past quarter century.

3.2 Literature Review

The application of GPR as a technique to measure spatial variation in submerged sediments is still relatively new (Moorman 2001; Neal 2004). One of the earliest users was Lowe (1985), who used GPR to analyze alternating tephra and peat layers in the sediments of a lake in New Zealand by towing GPR equipment behind a boat. Freshwater often presents a problem when using GPR because it is poor conductor and results in a very slow propagation velocity (0.033 m/ns) relative to other geologic materials, such as limestone (0.12 m/ns), granite (0.13 m/ns) or ice (0.16 m/ns) (Davis and Annan 1989). Energy from GPR can be markedly slowed down, resulting in a lengthy two-way travel time in very deep water. To address this issue, Pipan et al. (2000) used an acoustic profiling technique in addition to GPR to characterize sediment profiles in Cheko Lake, Russia.

Despite these possible limitations, a number of other researchers have cited an ability to achieve depth penetrations of up to 19 m through water (Moorman and Michel 1997) and 30 m including sediment (Moorman 2001) using a 100 MHz antenna. However, Bristow (2009) calculated the maximum GPR penetration for a saturated sand to be only around 0.0375 m using a 400 MHz antenna, which provides higher resolution data, compared to 0.15 m for a 100 MHz antenna, for which resolution is lower. A few researchers have attempted to resolve this trade-off between depth penetration and resolution of sedimentary beds by employing both high- and low-frequency antennae along GPR transects (e.g. Grant et al. 1998; Carreon-Freyre et al. 2003). Based on a mainly qualitative assessment of GPR profiles, Carreon-Freyre (2003) found that GPR was very effective where sedimentary sequences may not be visible to the human eye, but

may have physical and/or chemical properties that can be resolved by studying properties of GPR reflected waves (e.g. changes in water content or fine-scale differences in texture). Overall, Carreon-Freyre et al. (2003) found a lower frequency antenna (300 MHz) to be best suited to detecting broad changes in soil physical characteristics (stratigraphy), while a higher frequency antenna (900 MHz) was better for looking at finer details, such as changes in particle size. We were unable to test this in the Dominican Republic due to time and logistical constraints.

Jol and Smith (1991) emphasized the need for high-resolution subsurface analyses when examining the depositional environment of six deltas. As deltas were our primary focus, we chose to use a 400 MHz antenna to obtain higher resolution imagery. Bristow (2009) discussed how the transition boundary from water to sand makes GPR a particularly effective technique because large differences in the RDP across boundaries produce sharp contrasts in reflectivity of the over- and underlying materials (Neal 2004).

The RDP (ϵ_r) is a dimensionless measure of a particular material's permittivity relative to the permittivity constant (based on the permittivity of a vacuum = 8.8542×10^{-12} farads per meter). The velocity (v) that a wave can travel through a material greatly depends on RDP, with which it shares an inverse relationship with ϵ_r . Conyers (2004) stated that the relationship between ϵ_r (formerly κ , Cassidy 2009) and v can be expressed as:

$$\kappa = \left(\frac{C}{v}\right)^2 \quad \text{(Equation 3.1)}$$

Where;

κ = RDP (ϵ_r) of the material radar energy is passing through

C = The speed of light (0.2998 m/ns)

v = The radar wave velocity through the material (m/ns)

The conductivity (and therefore, RDP) of the geological material is most influenced by its water content (Saarenketo 1998). Saarenketo conducted a number of laboratory experiments using four different types of clay from the United States (kaolinite, Eddy Clay, Houston Black Clay, and Beaumont Clay) to determine how changes in clay physical and chemical properties altered relative dielectric permittivity. He examined how changes in saturation (and by extension, cation exchange capacity) affected relative dielectric permittivity values. He found that, depending on the clay type, relative dielectric permittivity values did not increase in a linear manner with the addition of water. He also found that relative dielectric permittivity values stabilize once they reach 100% saturation and that "free water" plays more of a role than inner and outer adsorption and capillary zones. However, he also suggested that other physical factors, such as compaction, have a greater effect on relative dielectric permittivity values at 100% saturation.

Starr et al. (2000) investigated changes in refractive index (the square root of the RDP) in suspended sediment. Specifically, they measured how refractive index values changed as suspended sediment settled out. Based on their observations it would appear that refractive index, and therefore, RDP, is lower when large amounts of sand are present.

Neal (2004) summarized the work of Collinson and Thompson (1989), noting that sedimentary beds can be characterized based on sediment composition, particle size, shape, orientation, and sorting. These affect pore water space, which in turn affects the RDP of the material because pore water space can limit the amount of free water within the sediment.

3.3 Site Description

Laguna Saladilla (19°36' N, 71°42' W; ca. 2 masl) is a large (ca. 220 ha) lake located in northwest Dominican Republic approximately 5.3 km inland from the Atlantic coastline (Figure 3.1). The lake is freshwater and fed by the Río Masacre, which flows into the lake from the southern Cordillera Central; it lacks surface outflow. Chemical analysis of nine water samples collected across the lake in December 2009 revealed near neutral pH (mean pH 7.7) and alkalinity (CaCO₃) values ranging from 157–209 ppm. Loss-on-ignition estimates of carbonate content in a sediment core taken from the lake in 2001 showed less than 1% carbonate in the upper meter of sediment.

The low carbonate content of the Laguna Saladilla sediments facilitates the use of GPR. One reason for the relative paucity of examples of GPR use in tropical lakes is that many tropical lakes are underlain by carbonate bedrock that can create higher than average alkalinities. Sites with waters that are rich in charged elemental species of minerals (such as carbonates) are highly conductive and can attenuate radar energy, even at shallow depths, that can reduce penetration to less than a meter (van Dam et al. 2002; Conyers 2004).

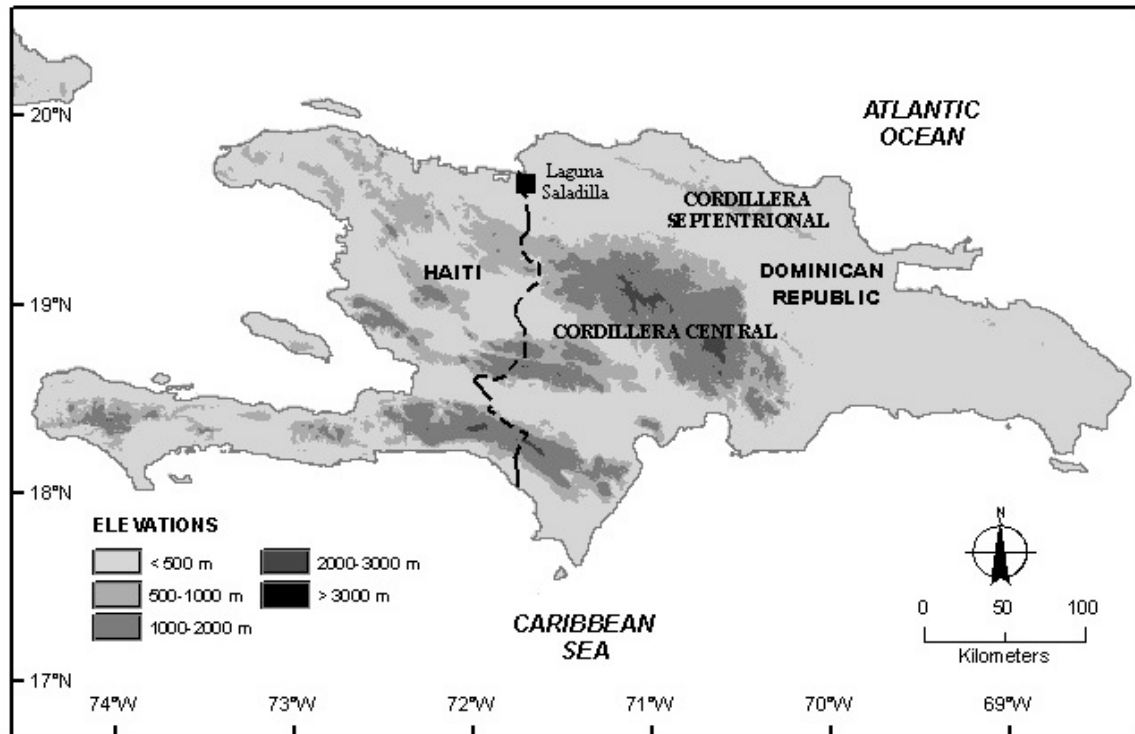


Figure 3.1: The island of Hispaniola. Laguna Saladilla (■) is located in the Dominican Republic.

Laguna Saladilla is underlain by sedimentary Quaternary alluvium (French and Schenk 1997) and is around 3 km southwest of the inferred western extension of the Cordillera Septentrional fault system (Dolan and Mann 1998; Mann et al. 1998). GPS measurements performed since 1994 show that the region is moving at a rate of ca. 11.6 mm/yr (Calais et al. 2002; Mann et al. 1998). No seismic events within the immediate vicinity of Laguna Saladilla have occurred during the last century (Mann et al. 1998), but movement of the nearby western extension of the Septentrional Fault system may have played some role in altering the route of the Río Masacre.

An 8.51 m long sediment core was taken from the northwest end of the lake in 2001. Diatoms and shells at the base of the core indicate that the lake was saline in the past, but over time the lake gradually freshened, became brackish by around 3500 cal yr BP (calibrated years before 1950) and then fresh around 2500 cal yr BP, based on radiocarbon dating and other analyses of the core (Caffrey and Horn 2010; Chapter 5). The freshwater phase of the lake began at a sediment depth of around 371 cm, and is marked by a pronounced decrease in sedimentation rate from 0.29 cm/yr from 3646–2488 cal yr BP to 0.15 cm/yr from 2488 cal yr BP to present. One possible source of the change in the sediment accumulation rate may be movement of the Río Masacre, which currently flows into the southwestern end of the lake. Based on relict stream channels observed on satellite images, the Río Masacre may at one stage have bypassed Laguna Saladilla and drained directly into the Atlantic Ocean. A later rerouting of the river to enter Laguna Saladilla could partly account for the late Holocene changes in salinity and sedimentation rates detected in our sediment analyses. Images from 2003

show the river draining into Laguna Saladilla from the southeast end of the lake, showing that changes in river position have occurred in recent decades.

3.4 Methods

We ran 26 GPR transects across Laguna Saladilla using a 400 MHz antenna to identify subaqueous depositional facies and deltas deposited by the Río Masacre (Appendix III). The antenna was positioned inside on the bottom of a motorized fiberglass boat. GPS coordinates were collected at the beginning and end of each transect. Transects were limited to areas of the lake accessible to the boat, so in many places transects could not begin at the shoreline where vegetation (mostly *Typha*) or shallow sand bars were present.

The GPR system was operated in continuous data collection mode with a 160 ns recording time window. A total of 94,250 reflection traces were collected over 18,937 m, an average of 5.57 traces per meter. As only the beginning and ends of lines had position information, we aimed to equally space traces along the lines by keeping the boat moving at a continuous speed during data collection. The positioning of the traces in space is fairly accurate away from the ends of the profiles, where there may be some error in placement as the boat sped up at the beginning of the transect and then slowed down at the end.

Post acquisition processing included time-shifting all profiles to a common time zero (t_0). We applied gains after collection to enhance the reflections from the sediment-water interface. Amplitude data were first processed using GPR Process (Conyers 2004), in which the amplitudes of the waves generated from the sediment-water interface were

re-sampled. Those relative amplitudes were then given x and y coordinates within the overall grid. When all amplitudes had an accurate x and y value in the overall grid, they were imported into Surfer software (Golden software 2010) and plotted to show spatial variations in the amplitude of the reflections generated at the water-sediment interface. Areas between transects were interpolated to create an amplitude surface. These values were gridded to produce an image of these variations. That image was later fit to a transect map using GPS data and Adobe Photoshop.

Estimated water depths were calculated based on the two-way travel time (ns) of the reflected waves from the lake surface to the sediment surface below (using Equation 3.1). These data were used to generate a bathymetric map. Thirteen lake surface sediment samples were collected using a LaMotte bottom sampling dredge. Dredge sample locations were chosen based on where changes in sedimentological conditions were observable, such as by the mouth of Río Masacre or in the center of the lake, where we hypothesized that changes in sedimentological conditions would affect the deposition of sand- to clay-sized particles and possibly generate subaqueous features, such as deltas or sand aprons.

Particle sizes were determined using a Beckman Coulter LS 13 320 series laser diffraction particle size analyzer. Samples were pretreated with hydrogen peroxide (H_2O_2) for 48 hours and dried in a 100 °C oven overnight to remove organic residues before 0.5 g of each sample was run through the instrument. Percent water, organic matter, and carbonate content were estimated for each sample using loss-on-ignition (Dean 1974) performed on subsamples of 1 cm³ volume. All of the samples contained small percentages of organic matter (mean = 5.34%, standard deviation 1.24%) that was

not included in RDP calculations because overall percentages and variations between samples were judged to be too small to influence RDP values.

The RDP of each sample was calculated based on mean values calculated from Davis and Annan (1989) and Geophysical Survey Systems (1987; Table 3.1 and Equation 3.2).

$$\epsilon_{bulk} = (\%_{O_{sand}} \times \epsilon_{sand}) + (\%_{O_{silt}} \times \epsilon_{silt}) + (\%_{O_{clay}} \times \epsilon_{clay}) \quad \text{(Equation 3.2)}$$

Where;

ϵ_{bulk} = The total sample volume RDP

$\%_{O_{sand}}$, $\%_{O_{silt}}$, $\%_{O_{clay}}$ = Percent sand, silt, and clay, respectively.

ϵ_{sand} , ϵ_{silt} , ϵ_{clay} = Relative dielectric permittivity of sand, silt, and clay, respectively (Table 3.1).

The coefficient of reflectivity is calculated by measuring differences in the RDP at the interface of two materials. The greater the contrast between the RDP of the underlying sediment and that of the overlying water or sediment, the higher the coefficient of reflectivity. Therefore, a sand delta ($RDP_{max} = 30$) below a layer of water ($RDP = 80$) should result in a higher coefficient of reflectivity compared to a clay layer ($RDP_{max} = 40$) below the same water layer. The coefficient of reflectivity (R) of the propagating electromagnetic wave when it encountered the underlying sediment-water interface was calculated using Equation 3.3 (after Neal 2004).

Table 3.1: Average relative dielectric permittivity values from Davis and Annan (1989) and Geophysical Survey Systems (1987). Mean values were used to calculate Laguna Saladilla reflection coefficients and associated electrical properties of the materials.

Material	RDP (Davis and Annan 1989)	Mean ϵ_r used to calculate Laguna Saladilla results	Mean electromagnetic wave velocity (v , m/ns^{-1})
Saturated sand	20–30	25	0.060
Silts	5–30	17.5	0.072
Clay	5–40	22.5	0.063
Freshwater	80	80	0.034

$$R = \frac{(\sqrt{\epsilon_{water}} - \sqrt{\epsilon_{bulk}})}{(\sqrt{\epsilon_{water}} + \sqrt{\epsilon_{bulk}})} \quad \text{(Equation 3.3)}$$

Where;

R = The coefficient of reflectivity (the coefficient for vertical incidence between two perfectly dielectric materials) at a buried surface

ϵ_{water} = RDP of the overlying material (water, 80)

ϵ_{bulk} = RDP of the underlying material (sediment, Equation 3.2)

The amount of energy reflected is the result of a change in wave amplitude that occurs when energy is reflected from a discontinuity. In this case, it is the interface between the sediment and the overlying water (Conyers 2004). Coefficient of reflectivity results should range between -1 and +1, and are proportional to the amount of energy reflected. High amplitude reflections occur at the interface of two relatively thick, dissimilar layers; low amplitude reflections result when RDP changes gradually with depth. In the case of Laguna Saladilla, it would be expected that the coefficient of reflectivity would be closer to zero at the interface between underlying sediments that have high percentages of water. Conversely, R values would be higher where underlying sediments have low percentages of water.

3.5 Results

Mean water depth for Laguna Saladilla was calculated to be 1.18 m based on two-way travel time of the direct wave to the first subsurface plane of reflection (mud-water interface) (Figure 3.2). Mean GPR penetration was calculated to be 3.1 m (Figure 3.3 and Figure 3.4). No evidence was found of lake bottom multiples (Moorman 2001).

GPR wave amplitudes vary across the lake (Figure 3.3). Areas of the highest amplitude are found mostly along the southern shoreline, particularly in the southeast and southwest corners. A third area of high amplitude is found along the northeast shore. Lowest amplitudes were recorded at the northwest edge of the lake and in the middle of the western half of the lake, next to a region that shows high amplitudes.

Particle size analysis results are listed in ascending order based on R values (Table 3.2 and Figure 3.3). The mean ϵ_r of the dredge samples was calculated to be 39.78 with a mean R of 0.18. Samples with the highest percentages of water appear to generally share an inverse relationship to R, with the exception of samples D3 and DR1. R values are inversely related to percent silt, with the exception of samples D9 and DR1A.

Based on aerial photographs and satellite imagery of the lake (Figure 3.5a–c), the sampling position for the sandiest dredge sample (DR2) was a former delta of the Río Masacre (Figure 3.5b). DR2 also has the lowest reflectivity coefficient ($R = 0.08$) of all of the dredge samples. Dredge D3 was taken approximately 80 meters northwest of DR2 and showed considerably less sand (0.06%); this sample was composed of mostly silt-sized (52.51%) sediment. The other dredge samples with measurable amounts of sand (DR1, DR1A, D5) were taken near the present-day mouth of the Río Masacre. Sample D6 collected in the northwest end of the lake contained the highest percentage (16.28%)

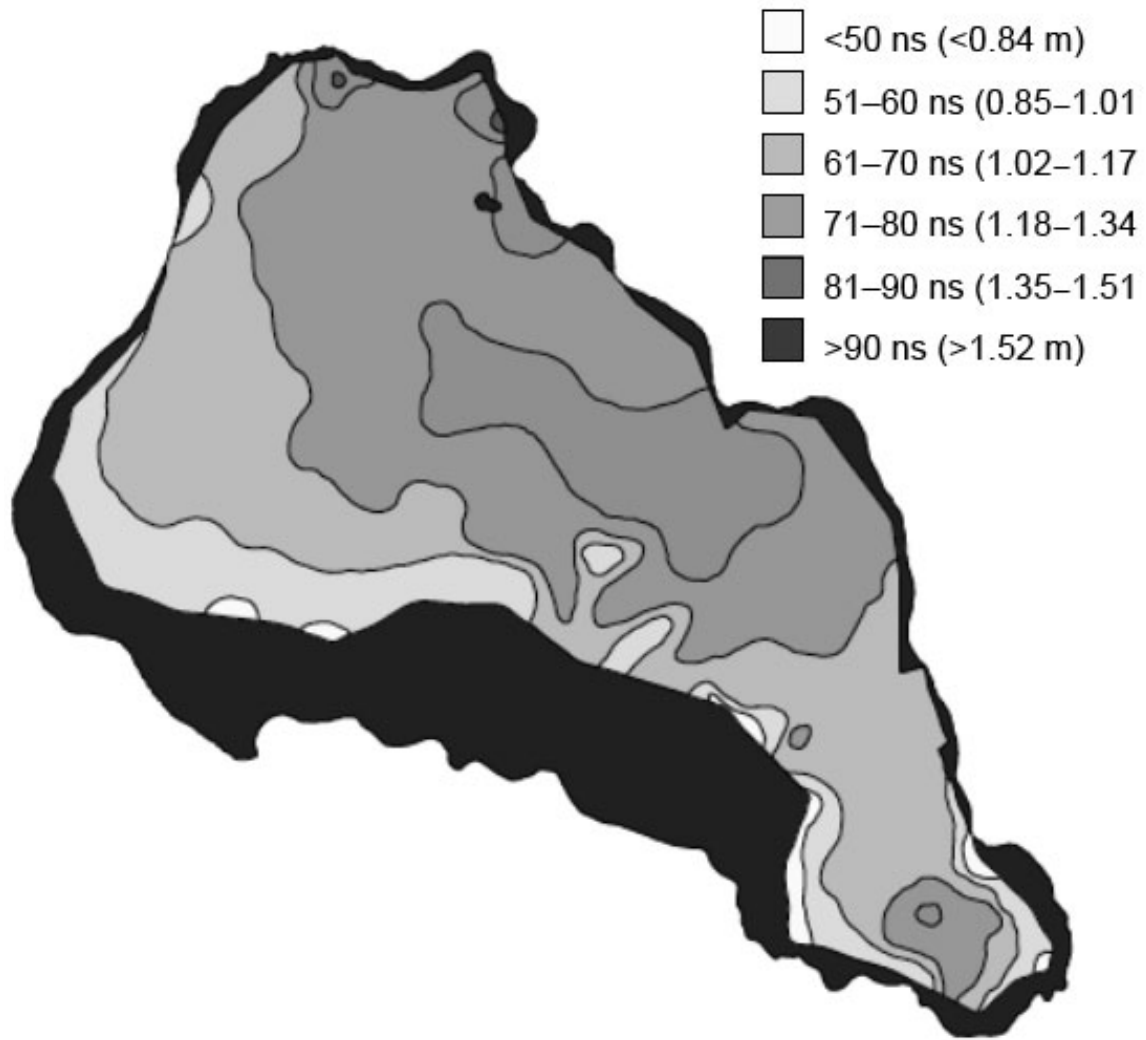


Figure 3.2: Bathymetric map of Laguna Saladilla developed using two-way travel time (ns) to estimate water depth (meters). Black shading denotes areas where obstacles such as mats of *Typha*, shallow water, or an island prevented the collection of GPR data and in which depths cannot be interpolated.

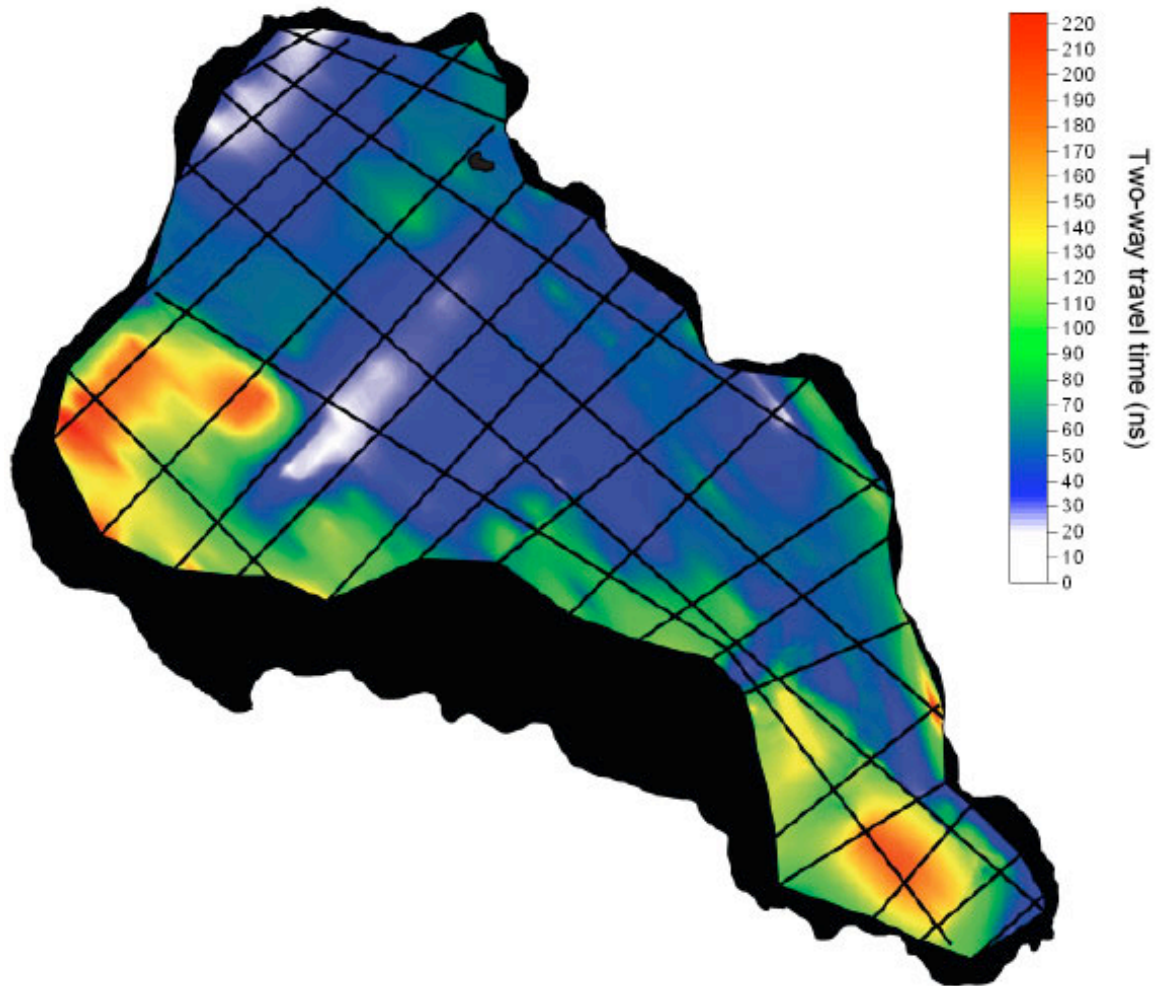


Figure 3.3: Amplitude map of 400 MHz frequency reflection data from Laguna Saladilla. Lines show approximate location of transects based on GPS data taken at ends of each transect. Black shading denotes areas where obstacles such as mats of *Typha*, shallow water, or an island prevented the collection of GPR data and in which data cannot be interpolated.

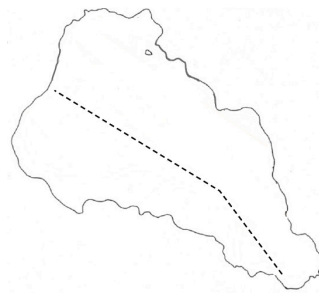
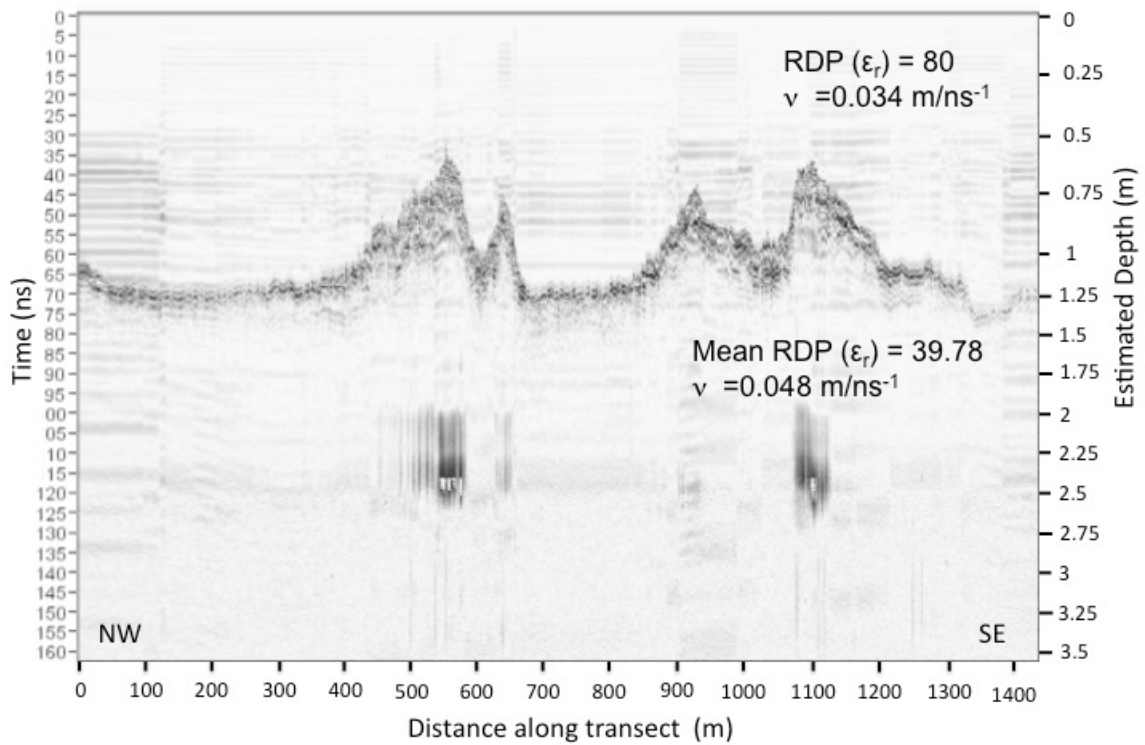


Figure 3.4: 400 MHz reflection profile from Laguna Saladilla. Four peaks represent remnant sand bars that remain from when the Río Masacre discharged into the southeast end of Laguna Saladilla. Estimated depth is based on the mean RDP of samples listed in Table 3.2. A mean RDP value was used to mitigate lateral variations in subsurface radar-wave velocity. Inset below shows the path of the transect.

Table 3.2: Dredge sample particle size analysis results with calculated total sediment volume RDP (ϵ_{bulk}) and coefficient of reflectivity (R) of the sediment-water interface.

Sample ID	% Clay	% Silt	% Sand	Total volume RDP (ϵ_{bulk})	Mean ϵ_{bulk}	Coefficient of reflectivity (R)	Mean R
DR2	3.43	30.47	66.1	30.34–14.92	22.63	0.24–0.40	0.306
DR1A	15	79	6	31.50–5.90	18.70	0.23–0.57	0.348
D6	21.9	78.1	0	32.19–5.00	18.60	0.22–0.60	0.349
DR1	17.5	80.4	2.1	31.75–5.32	18.53	0.23–0.59	0.350
D1	20.1	79.9	0	32.01–5.00	18.51	0.23–0.60	0.350
D7	20.2	79.8	0	32.02–5.00	18.51	0.22–0.60	0.350
D9	20.3	79.7	0	32.03–5.00	18.52	0.22–0.60	0.350
DR3	21.1	78.9	0	32.11–5.00	18.56	0.22–0.60	0.350
D5	12.7	83.4	3.9	31.27–5.59	18.43	0.23–0.58	0.351
D2	18.8	81.2	0	31.88–5.00	18.44	0.23–0.60	0.351
D4	17.2	82.8	0	31.72–5.00	18.36	0.23–0.60	0.352
D8	15.1	84.9	0	31.51–5.00	18.26	0.23–0.60	0.353
D3	16.5	83.4	0.1	31.65–5.02	18.33	0.23–0.60	0.353

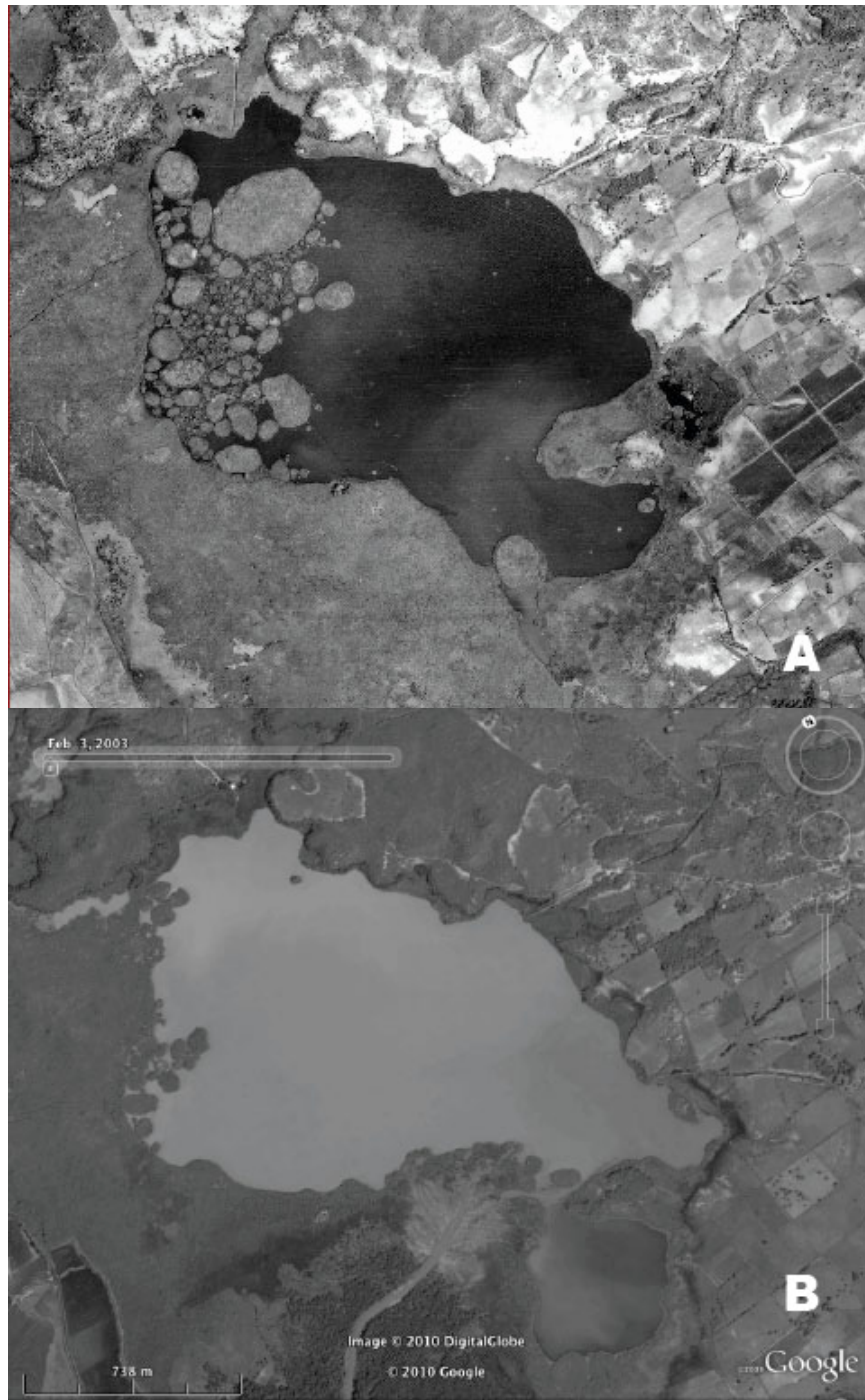


Figure 3.5a: Aerial photograph showing position of the Río Masacre in 1984. Figure 3.5b: The position of the Río Masacre in 2003 (©DigitalGlobe 2010 and ©Google 2010).

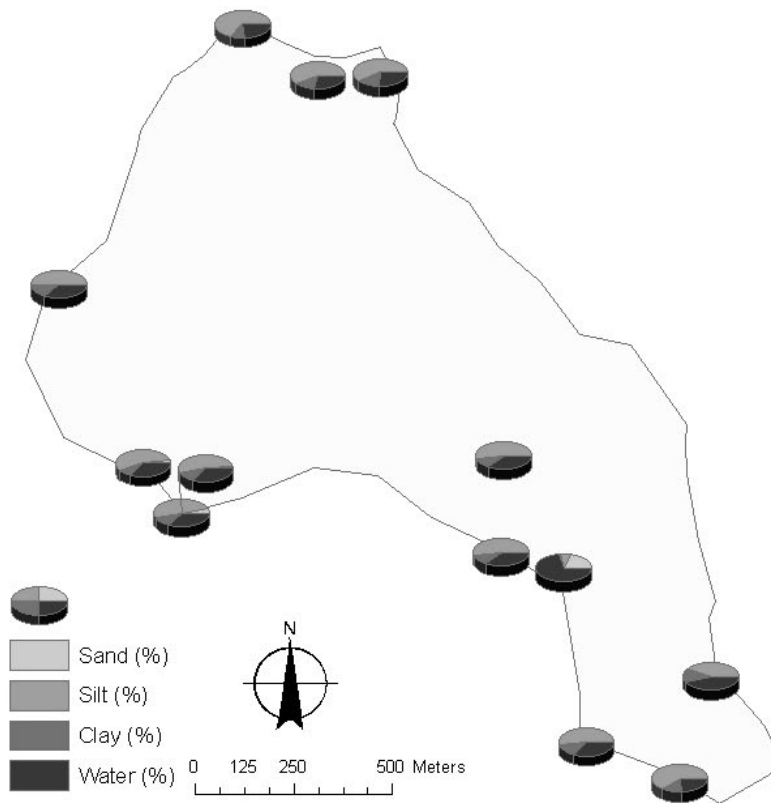


Figure 3.5c: The position of the Río Masacre in 2004 (©DigitalGlobe 2010 and ©Google 2010). Figure 3.5d: The particle size distribution of sand- to clay- sized sediment in dredge samples from Laguna Saladilla.

of clay-sized sediment (Figure 3.5d). Sample D4 was taken from near the center of the lake, where the mean sediment RDP was calculated to be 39.60 ($R = 0.17$).

3.6 Discussion

Based on paleoenvironmental proxies (mangrove pollen and diatoms), Laguna Saladilla became fresh around 2500 cal yr BP, at a depth of 3.71 m in our sediment core (Caffrey and Horn 2010; Chapter 5). This freshening may have been partly driven by the rerouting of the Río Masacre to Laguna Saladilla around that time. GPR analyses show three regions with higher than average amplitudes within the lake that appear to correspond to previous positions of the Río Masacre over the past 27 years.

Maps based on the GPR data do not show any other high amplitude regions within the lake that could correspond to other positions of the Río Masacre over the past 2600 years. However, this is not surprising given the relatively shallow energy penetration of our GPR. Any relict sand deltas deposited by the Río Masacre thousands of years ago would be buried several meters deeper than our GPR data could identify. Based on water chemistry data, neither carbonates nor iron oxides appeared to have greatly hindered penetration (Lebron et al. 2004; Pipan et al. 2000; Havholm et al. 2003). More likely, underlying electrically conductive clays, such as kaolinite (-1 to -15 cmol/kg) or chlorite (-10 to -40 cmol/kg; Rich and Bonnet 1975), could have prevented deeper penetration.

Dredge samples with the highest percentages of sand correspond to regions with high amplitudes because of the greater dissimilarity in the RDP of sand compared to silt- or clay-rich lake bottom sediments. However, percentages of sand in all but one dredge sample overall remained relatively low. This may be due to loss of sediment from the

dredge while retrieving samples. Alternatively, sandier samples may have been located closer to the lakeshore, in areas we could not reach with our boat without running aground. Red areas in the amplitude map appear to be regions with high percentages of saturated sand that would have a low porosity and would therefore be more reflective than saturated clays that have a higher porosity. More porous samples would result in lower reflectivity values as they would contain more water, which also makes up the overlying layer. Calculated reflectivity results appear to show the opposite trend. Loss-on-ignition performed on the dredge samples showed that the sandiest sample (DR2) had the highest water content, which may account for why reflectivity values for sample DR2 are low. This may also be the result of greater compaction of clay- to silt-sized particles. However, it is more likely that these values result from higher percentages of silt that has lower mean ϵ_r values.

Reflectivity results suggest that percentages of silt may play an important role in influencing ϵ_{bulk} ; however, this is probably due to our choice of mean ϵ_r values (Table 3.1). Saturated ϵ_r has a wide range of values that could complicate any R calculations. Minor changes in grain shape, orientation, and packing were shown by Collinson and Thompson (1989) to play a role in wave reflection.

While the wave amplitude data appear to show a relationship with changes in particle size, the GPR image outputs (e.g. Figure 3.4) do not indicate where a transition from predominantly sand to silt occurs. Instead, the terminus of the deltas must be estimated based on changes in the angle of depositional features. However, this was not unexpected as Mellett (1995) also noted the lack of a clearly discernable sand to silt

boundary in their analyses of Ball Pond, CT. Instead, Mellett (1995) took sediment cores where he observed changes in the subsurface bedding plane.

3.7 Conclusion

The aim of this research was to examine the subaqueous features of Laguna Saladilla and determine whether changes in particle size could be identified using GPR. Our research showed that a number of sandy deltas were identifiable from the 26 profiles collected across the lake. Based on variations in wave amplitude data, areas with known delta deposits appear to have the highest wave amplitudes. This is most likely due to the lower porosity of sand resulting in higher wave reflectance than silt- to clay- sized particles that have medium to high porosity values, respectively.

Our results from Laguna Saladilla highlight how a qualitative approach only involving the analysis of GPR data (such as Figure 3.4) may not show changes in sediment composition (sand vs. silts and clays) as effectively as examining spatial changes in wave amplitude (Figure 3.3). Our analyses were somewhat limited by poor penetration (<5 m) caused by underlying electrically conductive clays. However, dredge samples of surface sediments show lower reflectivity values in the sandiest samples. This is most likely because of the higher silt content in these samples. Based on Davis and Annan's (1989) values, mean silt dielectric permittivity was lowest (Table 3.1), which resulted in lower ϵ_{bulk} and R values. Overall, this research shows the sensitivity of GPR to changes in particle sizes in lacustrine environments.

Our method is useful because it is relatively quick to execute (less than one day of fieldwork), and does not require taking multiple sediment cores from across the lake. We

were not able to discern areas of transition from primarily clay-sized to silt-sized sediment across the lake, but we found that examining changes in amplitude was an effective method of identifying subaqueous sand deposits.

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CHAPTER 4

A REGIONAL PERSPECTIVE ON THE CARIBBEAN CHARCOAL RECORD AND THE ROLE OF HUMANS AND CLIMATE IN DRIVING FIRE OCCURENCE

This chapter is in preparation for submission to the *Journal of Paleolimnology* by Maria A. Caffrey and Sally P. Horn. My use of “we” in this chapter refers to my co-author and myself.

Abstract

Charcoal preserved in lake sediments is commonly used to reconstruct past trends in fire occurrence. However, interpretation of the charcoal record is often complicated, as changes in charcoal values could represent natural changes in climate, anthropogenic burning, or both. Here, we examine sedimentary charcoal records from three lakes on the Caribbean islands of Hispaniola and Puerto Rico: Lake Miragoane in Haiti, Laguna Saladilla in the Dominican Republic, and Laguna Tortuguero in Puerto Rico. All records are based on microscopic charcoal fragments quantified from pollen slides. We used archeological evidence to tie burning episodes to human activity. We discuss the role of increasing winter insolation over the Holocene in driving increases in charcoal deposition, particularly around 5000 cal yr BP. Our analysis indicates that a previous interpretation of the role of humans in driving fires at Laguna Tortuguero may not have taken into account possible insolation-driven shifts in winter drying that may have led to increased fire frequencies and possibly more intense fires. A decrease in charcoal in Laguna Tortuguero around 3200 cal yr BP may be a signal of human alteration of the

environment that changed fire frequencies and/or intensity. Taking a regional approach to interpreting these records allowed us to distinguish periods of synchronous, climate-driven burning from more localized anthropogenic burning.

Keywords: fire, Taino, orbital forcing, Greater Antilles, Hispaniola, Puerto Rico

4.1 Introduction

The ecological and anthropological role of fire within the tropics has been the focus of research for several decades (e.g. Lugo et al. 1981; Denevan 1992; Chazdon 2003; Bowman et al. 2009; Cochrane 2009). Charcoal preserved in soil profiles or lake sediments has been used as evidence for past burning at local (Sanford and Horn 2000) and regional to global (Power et al. 2008, 2010) scales. While the use of charcoal as a paleoenvironmental proxy is well established, interpretations of temporal trends in fire occurrence revealed by charcoal records are more difficult to resolve. An increase in charcoal influx may coincide with the establishment or expansion of human settlement, or it may signal a change in climatic conditions, or a combination of these factors. An increase in charcoal may signal the beginning of a new fire regime (e.g. a shift from a natural to an anthropogenically-managed regime; Marlon et al. 2008) or a response to a cyclical change in climate and environment (e.g. ENSO and its associated impact on subtropical North Atlantic high sea level pressure; Giannini et al. 2010).

The complications and uncertainties described above have resulted in conflicting interpretations of paleofire records from the Caribbean. One approach to resolving the question of whether an increase in charcoal is most likely due to a change in climate or in

anthropogenic activity is to use additional paleoenvironmental proxies, such as pollen or stable oxygen isotopes, to disentangle human and climate signals. However, this approach requires the presence of definitive anthropogenic pollen indicators (such as maize pollen), appropriate biogenic carbonates for isotope analyses, or other suitable proxies that may not be available at all sites.

We employed an alternative approach for examining multiple sites to obtain a regional perspective. By comparing local to regional trends, we can determine whether an increase in sedimentary charcoal is the result of burning by humans (locally, within that particular watershed, or at up to an island-wide scale) or of climate-induced increases in wildfire activity that occur regionally (island-wide up to the scale of the entire Caribbean). We examine published charcoal records from Lake Miragoane, Haiti and Laguna Tortuguero, Puerto Rico that were interpreted as records principally driven by climate and anthropogenic activity, respectively. To this, we add results from our work at Laguna Saladilla, Dominican Republic. The aim of our analysis is to determine (1) whether changes in charcoal influx across all three sites are temporally synchronous, and (2) whether the timing of increases in burning coincide with increases in seasonal insolation, as suggested by Hodell et al. (1991). We also discuss the role of other climatic phenomena and associated biogeographic and anthropogenic impacts as drivers of trends in fire occurrence.

4.2 Previous Research

Relatively few paleoenvironmental records exist for islands of the Caribbean and adjacent tropical Atlantic, with much of the research having taken place over the last two

decades (e.g. Burney et al. 1994; Kjellmark 1996; Higuera-Gundy et al. 1999; Kennedy et al. 2006; Lane et al. 2008, 2009, in press). Microscopic charcoal preserved in lake sediments has been used in a number of sites to reconstruct local fire history.

Brenner and Binford (1988) first reported on the paleolimnology of Lake Miragoane with preliminary research based on a short test core that spanned an estimated 1000 years. Hodell et al. (1991) later recovered a longer core, and developed a 10,500-yr oxygen isotope record from biogenic carbonates. They interpreted their high-resolution record to reflect changes in rainfall caused by insolation-driven shifts in the mean summer position of the intertropical convergence zone (ITCZ). To demonstrate this, they qualitatively compared their stable oxygen isotope curves to the annual range of insolation (August minus February values) calculated for 10°N latitude at 1000-yr intervals through the Holocene. They used this technique because changes in many paleorecords “can be explained by orbitally induced (Milankovich) variations in seasonal insolation which modified the intensity of the annual cycle” (Hodell et al. 1991, p. 790). They further commented that “superimposed on the orbitally forced climate trends are more abrupt climate events that result from complex, nonlinear interactions in the ocean-atmosphere system,” and stressed that such shifts in climate provide important context for interpreting the biogeography of Caribbean islands and the development of human culture through the wider circum-Caribbean region.

Hodell et al. (1991) found evidence of an increasingly mesic environment at Lake Miragoane from 8200–2500 cal yr BP that was later cited by Burney et al. (1994) in their interpretation of peaks in charcoal values during the mid-Holocene at Laguna Tortuguero, Puerto Rico. Burney et al. (1994) attributed the observed large peaks in charcoal around

that time to human arrival because they considered the climate to have been too wet to allow natural fires. However, prior to their analysis of the Tortuguero record, the earliest archeological evidence of human presence on Puerto Rico was from ca. 3200 cal yr BP at Caño Hondo (date calibrated by us from 3010 ± 70 ^{14}C yr BP; Rouse 1992). Burney et al. (1994) attributed the 2000-yr difference between the Tortuguero charcoal peak linked to human arrival, and the archeological data from Rouse (1992), to a lack of archeological remains (i.e. pottery, abandoned settlements) on the island. Archeological remains from Viginier III, Haiti, indicated that humans arrived on Hispaniola by ca. 6370 cal yr BP (calibrated by us from 5580 ± 80 ^{14}C yr BP; Moore 1991).

In later Lake Miragoane research, Higuera-Gundy et al. (1999) interpreted changes in vegetation around the site based on pollen and charcoal analysis of the Miragoane sediment profile. As at Laguna Tortuguero, they also found an increase in charcoal values during the mid-Holocene, when the climate was wetter. However, they rejected the idea that increased charcoal values reflected anthropogenic burning at that time. Instead, they pointed to changes from dry forest vegetation types (Holdridge 1945) to vegetation with more fire-adapted, moist forest trees. Higuera-Gundy et al. (1999) interpreted their pollen and charcoal record as showing climatically-driven changes in vegetation and fire frequencies, except for the period after ca. 1030 cal yr BP, when Tainos, and later Europeans, inhabited and deforested the region.

Burney et al. (1994) reported both graminoid (grass) and non-graminoid charcoal from the period of increased burning. Non-graminoid charcoal, presumed to be from trees and shrubs, was overshadowed by abundant grass charcoal, suggesting extensive grassy vegetation. However, poor pollen preservation precluded the study of pollen assemblages

(David Burney, pers. comm. with S. Horn 1997). Thus, no pollen evidence is available that can be compared to that of Higuera-Gundy et al. to determine whether a change to fire-adapted vegetation also occurred around Laguna Tortuguero.

One possible way to determine whether a charcoal record reflects human activity or natural climate variability is to interpret peaks in charcoal as the result of increased fire intensity (Burney 1997). Burney (1997) suggested that human-ignited fires tend to be set when conditions will create a low intensity fire that will not burn out of control (typically during wetter periods in the year), whereas natural fires are typically ignited on drier days when maximum pre-drying has occurred. This assumes that a natural fire is not ignited during a wetter phase when more lightning is present (Higuera-Gundy et al. 1999; Kennedy et al. 2006). Quantifying fire intensity and other variables such as burn area, burn intensity, fire frequency, scorched biomass, and carbon release are complicated by various biological, geographical, and climatic influences on fuels and burn patterns, as well as charcoal transport and deposition (Nevle and Bird 2008).

Other researchers have attempted to distinguish natural from anthropogenic fires in sediment records by looking for agricultural pollen types, such as maize (*Zea mays* subsp. *mays*), in lake sediments. Lane et al. (2008) found maize pollen in lake sediments dated to ca. 890 cal yr BP at Las Lagunas, Dominican Republic, presently the earliest evidence of Ostionoid (Taino) maize agriculture from an interior (non-coastal) site in Hispaniola. Other pollen evidence of maize in Hispaniola has been reported from El Jobito, Dominican Republic (believed to date from ca. 930 cal yr BP; Garcia Arevalo and Tavares 1978), and Lake Miragoane, Haiti (ca. 450 cal yr BP; Higuera-Gundy et al. 1999). A very early age reported for maize pollen in a shallow soil profile at the

Dominican El Curro site (ca. 3400 cal yr BP) is probably based on intrusive grains and is hence unreliable (Ortega and Guerrero 1981; Lane et al. 2008). Macroscopic remains (cobs, cupules, and kernels) dating to ca. 700 cal yr BP were recovered from the archeological site En Bas Saline, Haiti (Newsom and Deagan 1994) located approximately 50 km west of our Laguna Saladilla study site.

In addition to the records of maize in Hispaniola, evidence of maize in the form of starch grains has been found at the Maruca and Puerto Ferro archeological sites in Puerto Rico (Bonzani and Oyuela-Caycedo 2006). Pagan et al. (2005) suggested that the maize dated from the Archaic period, which would correspond to ca. 4000–2200 cal yr BP, while macroremains of maize at the Tutu site on nearby St. Thomas were dated to much later, ca. 810–610 cal yr BP (Newsom and Pearsall 2003).

Overall, however, relatively little evidence of maize cultivation has been found to date in the Caribbean (Newsom and Deagan 1994; Newsom and Wing 2004; Newsom 2006) most likely because early inhabitants relied heavily on marine resources and on root crops rather than maize (Keegan 2000; Lane et al. 2008).

4.3 Study Sites Description

4.3.1 Laguna Saladilla, Dominican Republic

Laguna Saladilla (19°36' N, 71°42' W; ca. 2 masl; maximum depth, <2 m), is a large (ca. 220 ha) freshwater lake located approximately 5 km inland from the Atlantic coastline of Hispaniola, near the border between the Dominican Republic and Haiti (Figure 4.1). The Río Masacre flows into the southwestern end of the lake from the Cordillera Central, but the lake has no outflowing rivers.

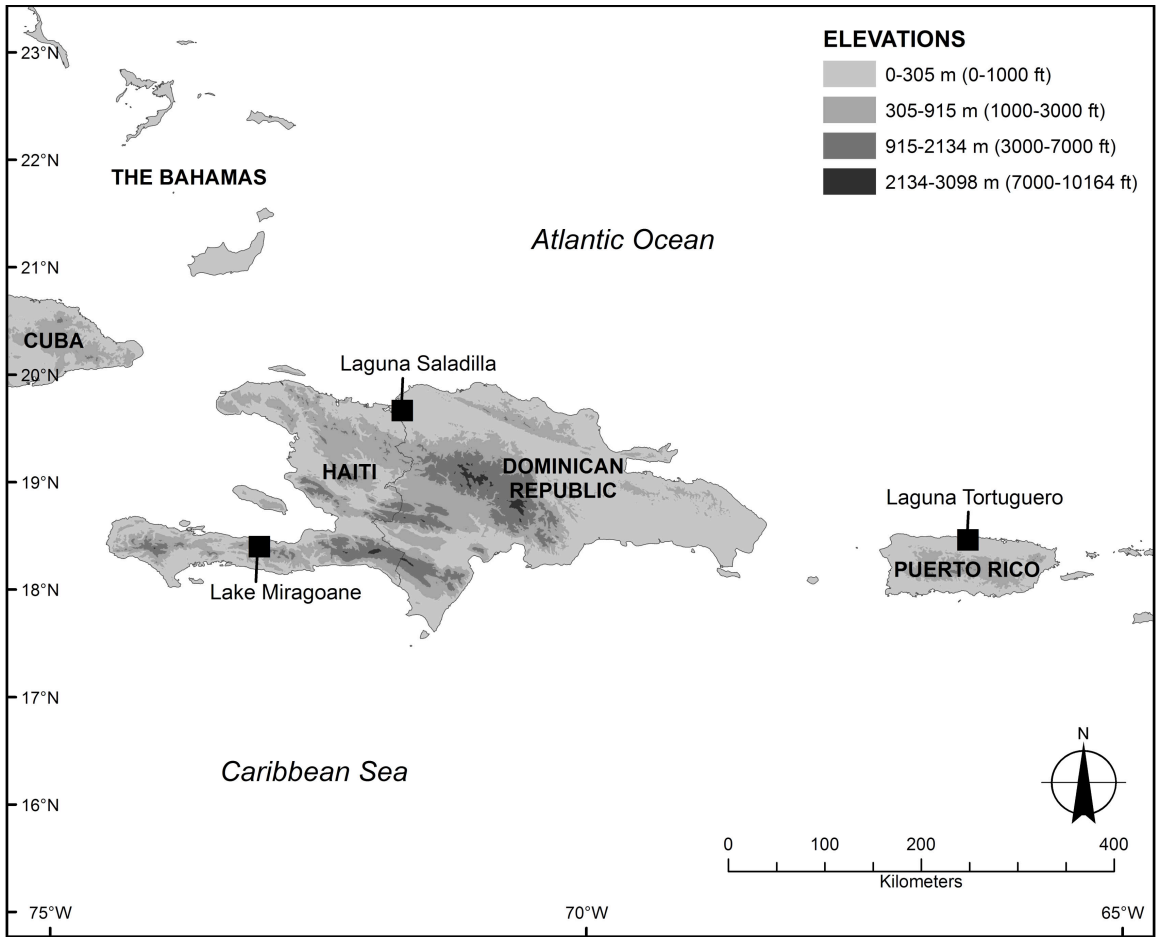


Figure 4.1: Location of Lake Miragoane, Laguna Saladilla, and Laguna Tortuguero in the northeastern Caribbean.

In 2001, an 851 cm sediment core was recovered from the northern end of the lake. Diatoms, mangrove (*Rhizophora*) pollen, and mollusk shells show that the lake was saline before transitioning to brackish and eventually freshwater conditions by ca. 2500 cal yr BP (Caffrey and Horn 2010; Chapter 5). Changes in sedimentation rates in the Saladilla profile and evidence of paleochannels of the Río Masacre on modern aerial imagery suggest that shifts in the course of the Río Masacre may be partly responsible for this freshening of the lake. Prior to 3500 cal yr BP, when the lake started to become less saline, the Río Masacre may have bypassed the lake and flowed directly into the Atlantic Ocean.

The Río Masacre could possibly transport a small amount of charcoal from fires in pine forests of the Cordillera Central to Laguna Saladilla, so the record we present here should be considered a regional charcoal record. Burning is frequent in the highlands, where the forest is dominated by the fire-adapted pine, *Pinus occidentalis* (Horn et al. 2000; Speer et al. 2004; Martin and Fahey 2006; Kennedy and Horn 2008).

Laguna Saladilla is in a relatively dry region of Hispaniola (<700 mm yr⁻¹ precipitation), with annual temperatures that range between 22 °C in the winter and 30 °C in the summer (Bolay 1997). The lake is presently surrounded by low woodlands composed of small trees and shrubs, such as *Bursera simaruba* and various Leguminous species, with xerophytic succulents in the understory. East of Laguna Saladilla are agricultural fields managed by the nearby farming community of Carbonera, founded in 1959 (Augelli 1962).

During fieldwork at Laguna Saladilla in December 2009 (dry season), we observed evidence of burning in the form of clouds of smoke visible on the horizon each

afternoon, from fires burning in neighboring Haiti, approximately 1 km west of the lake. However, we did not observe areas of burned vegetation near the lake in December 2009, nor burned areas or smoke during visits to the lake during the wet seasons of 2001 and 2002.

4.3.2 Lake Miragoane, Haiti

Lake Miragoane (Etang de Miragoane; 18°24' N, 73°05' W; ca. 20 masl) is located on Haiti's southern peninsula (approximately 5 km inland) (Brenner and Binford 1988). The lake is deeper (42 m) and more than three times larger (706 ha) than Laguna Saladilla (Hodell et al. 1991). A smaller lake to the east of Lake Miragoane, Petite Etang Miragoane, is separated by a marshland. Lake Miragoane and Petit Etang Miragoane drain via the Canal de Sud to the Caribbean Sea to the north.

The region averages 1000–2000 mm yr⁻¹ precipitation with mean annual temperatures of 25–27 °C. The site lies within the tropical lowland dry forest life zone (Holdridge 1945), but the area is presently deforested with mainly only economically important tree taxa, such as *Manifera indica* (mango) and *Cocos nucifera* (coconut), or successional types such as *Cecropia*, *Trema*, and *Bursera* (Brenner and Binford 1988; Higuera-Gundy et al. 1999).

4.3.3 Laguna Tortuguero, Puerto Rico

Laguna Tortuguero (18°27' N, 66°26' W; ca. 1 masl) is a large (ca. 220 ha) lagoon located less than 0.5 km from the north shore of Puerto Rico. No rivers drain into the lake, but it is connected to the Atlantic Ocean by a drainage canal constructed in 1940

(Soler-Lopez et al. 2006). The lake was designated as a nature reserve in 1979 and is currently used only for recreation. Burney et al. (1994) described the lake as oligohaline; however, it is surrounded by salt-intolerant aquatic plants that suggest storm surges are infrequent. In February 2011, one of us (M. Caffrey) observed a number of palm trees growing in ca. 30–45 cm deep water along the shore, suggesting that water levels had been lower recently. A number of invasive species, such as the Australian "pine" *Casuarina*, were also present along the shore.

4.4 Methods

Sediments from Laguna Saladilla were collected in 2001 using a Colinvaux-Vohnout (C-V) locking piston corer (Colinvaux et al. 1999). The upper sediments (mud-water interface) were collected using a plastic tube fitted with a rubber piston, and extruded into bags at 2-cm intervals in the field. The C-V core sections were transported to the University of Tennessee in the original aluminum core tubes, which were opened in the lab.

Microscopic charcoal was quantified on pollen slides using the point counting technique outlined by Clark (1982), which yields charcoal area values. Charcoal was sampled at approximately 10 cm intervals through the sediment profile. Each sample was prepared with standard chemical treatments (HCl, KOH, HF, acetolysis; Appendix I) to isolate pollen and charcoal (Fægri and Iversen 1989). One tablet containing an artificial pollen control, spores of *Lycopodium* ($n = 13,911 \pm 689$; Maher 1997), was added to each sample to calculate charcoal area concentrations (mm^2/cm^3), which were converted to

influx values ($\text{mm}^2 \text{ charcoal/cm}^2/\text{yr}$) by multiplying by the sedimentation rate at each sampled level.

Charcoal data from Laguna Tortuguero were obtained from Burney et al. (1994), based on their study of a sediment core recovered in 1987 using a square-rod piston corer. Burney et al. (1994) quantified charcoal on pollen slides prepared at ca. 26 cm intervals through the core, following methods outlined by Patterson et al. (1987), in which charcoal is tallied by size classes. Burney et al. (1994) graphed charcoal concentrations as the total area of graminoid and non-graminoid charcoal per cm^3 sediment, and separately reported counts for each charcoal type in each of the eight size classes. For our analysis, we used the total charcoal particle concentration for each level, to be consistent with the datasets from Laguna Saladilla and Lake Miragoane, in which graminoid and non-graminoid charcoal was not differentiated.

Charcoal concentration data from Lake Miragoane were taken from Higuera-Gundy et al. (1999), based on charcoal counts on pollen slides from a core obtained in 1985 using a square-rod piston corer. The Laguna Tortuguero and Lake Miragoane charcoal concentrations in fragments/cm^3 were converted to charcoal influx ($\text{fragments/cm}^2/\text{yr}$) by multiplying by the sedimentation rate (cm/yr).

Materials for AMS radiocarbon dating were taken from locations in the Laguna Saladilla sediment profile where a change in sediment composition was observable or where preliminary pollen and charcoal analyses revealed a change in environment. We aimed to date discrete terrestrial plant macrofossils (mainly charcoal fragments or wood), but dated bulk sediment at some levels where discrete material was not present.

Dates from all three sites were calibrated to years before present (where present = 1950) using the CALIB 6.0 computer program (Stuiver and Reimer 1993) and the dataset of Reimer et al. (2009). The weighted mean calibrated age was calculated based on the probability distributions of the calibrated ages (Telford et al. 2004). Laguna Tortuguero age determinations were based on standard bulk sediment radiocarbon dating of detrital gyttja and laminated algal gyttja with fine shells (Burney et al. 1994). Dated intervals spanned depths of 9–24 cm, required by the use of standard radiocarbon dating. Depths are reported as ranges (Table 4.2), with mean depths used to construct sediment chronologies.

Lake Miragoane age determinations were based on AMS radiocarbon dating of ostracod shells (*Candona* sp.). Based on paired radiocarbon dates from ostracod remains and wood at a depth of 233 cm, Hodell et al. (1991) reported that the ostracod dates appeared to have a hard water error of around 1000 years. Higuera-Gundy et al. (1999) consequently constructed their sediment chronology using radiocarbon ages corrected for the hard water lake effect (HWLE). To compare the Lake Miragoane data with Laguna Saladilla and Laguna Tortuguero, we calibrated the HWLE-corrected radiocarbon dates using CALIB 6.0.

Mean daily insolation curves for 15°N were constructed and compared to the charcoal influx profiles from the three lakes to look for possible relationships between insolation and fire activity. This approach is partly based on research of Hodell et al. (1991), who compared changes in the Lake Miragoane $\delta^{18}\text{O}$ record to changes in the annual range of insolation values (August insolation minus February). Mean daily insolation curves for the solstices and equinox were compared to charcoal results.

4.5 Results

4.5.1 Core Descriptions

The 851 cm sediment core from Laguna Saladilla contains shells mixed with alternating sections of muddy marl and sand in its lower section, from the base to 718 cm depth (8031 to ca. 4000 cal yr BP). The sediment above 718 cm consists of organic-rich clayey silts, with the exception of the upper 130 cm of sediment (<396 cal yr BP), which is a mixture of fine to coarse peat and organic sediment.

Burney et al. (1994) described their 782 cm sediment core from Laguna Tortuguero as composed of homogenous black detrital material from 782–302 cm depth (ca. 6800–2783 cal yr BP), overlain by a unit of fine-grained algal gyttja that is laminated until 200 cm (1958 cal yr BP), where the core transitions to sandy gyttja. The sediment is detrital gyttja from 165 cm to the top of the core.

Higuera-Gundy et al. (1999) retrieved a 767 cm core from the deepest part of Lake Miragoane. The core is described as being relatively geochemically uniform, although the upper mud-water interface sediment core had higher organic sediment values and was more stratified (Higuera-Gundy 1991).

4.5.2 Chronologies

Sediment chronologies were constructed based on calibrated radiocarbon ages (Tables 4.1 and 4.2). Plotted by depth, the Laguna Saladilla radiocarbon ages show a generally linear trend (Figure 4.2a). However, sedimentation rates changed dramatically in two intervals of the record: between 792 and 730 cm, and at about 300 cm. Pollen and diatom analyses have shown that these changes in sedimentation rate correspond to shifts

Table 4.1: Laguna Saladilla radiocarbon results.

Lab number ⁱ	Depth (cm) ⁱⁱ	$\delta^{13}\text{C}$ (‰)	Uncalibrated ^{14}C age (cal yr BP)	Calibrated age range $\pm 2\sigma$ (cal yr B.P.) ⁱⁱⁱ	Area under probability curve	Weighted mean ^{iv} (cal yr B.P.)	Material dated
AA82654	73	-28.1	175 \pm 32	34 to -2 116-71 227-134	0.195 0.076 0.534	160	Bulk sediment
AA82659	88	-26	184 \pm 32	296-252 33 to -2 78-74 99-81 114-106 224-136 300-254	0.195 0.194 0.006 0.023 0.009 0.551 0.218	164	Wood
β 174192	127	-15.3	280 \pm 40	3 to 0 169-153 344-282 465-346	0.004 0.044 0.360 0.593	353	Plant material
AA82664	161	-19.1	907 \pm 33	914-742	1.000	835	Bulk sediment
β 228998	199	-28.8	1230 \pm 40	1266-1063	1.000	1163	Wood
β 160457	251	-25	1770 \pm 60	1825-1543 1857-1853	0.997 0.003	1691	Wood
β 160458	273	-29.9	2320 \pm 40	2168-2162 2242-2178 2460-2302 2636-2697	0.005 0.168 0.037 0.827	2327	Wood
AA82655	284	-30.6	2375 \pm 36	2491-2336 2607-2603 2677-2642	0.939 0.003 0.057	2425	Wood
AA82652	326	-28.3	2401 \pm 34	2499-2344 2613-2596 2692-2638	0.859 0.025 0.116	2454	Wood
AA82656	331	-26.4	2404 \pm 34	2501-2345 2535-2535 2613-2595 2694-2637	0.845 0.001 0.028 0.126	2458	Wood
β 176225	370	-28.0	3800 \pm 40	4032-4007 4299-4081 4354-4327 4385-4369 4404-4393	0.020 0.931 0.029 0.013 0.007	4191	Wood and bark

AA82666	373	-27.8	2591 ± 40	2532–2503	0.032	2699	Bulk sediment
				2593–2536	0.101		
				2637–2614	0.095		
				2779–2696	0.771		
AA82661	411	-29.8	2443 ± 34	2546–2356	0.644	2518	Wood
				2575–2560	0.023		
				2617–2579	0.097		
				2702–2634	0.236		
AA82667	495	-25.7	2527 ± 41	2484–2470	0.015	2606	Charcoal
				2746–2485	0.985		
AA82653	557	-24.7	2758 ± 34	2929–2777	0.979	2850	Bulk sediment
				2945–2935	0.021		
AA82657	592	-29.0	3080 ± 35	3373–3215	1.000	3300	Wood
β176226	625	-29.2	2690 ± 40	2861–2747	1.000	2801	Plant material
AA82663	654	-22.4	3231 ± 42	3558–3377	1.000	3455	Bulk sediment
AA82668	692	-28.3	3364 ± 42	3544–3479	0.171	3601	Plant material
				3694–3546	0.829		
AA82660	712	-28.7	3364 ± 35	3536–3484	0.118	3602	Wood
				3691–3553	0.882		
β160459	715	-27.2	3420 ± 40	3732–3571	0.837	3680	Wood
				3776–3743	0.060		
				3826–3789	0.103		
AA82662	717	-22.5	3687 ± 36	4095–3910	0.939	4025	Bulk sediment
				4145–4118	0.061		
AA82665	730	-21.8	3687 ± 61	4032–4007	0.022	4229	Bulk sediment
				4416–4081	0.978		
AA82651	792	-26.2	6623 ± 46	7573–7436	1.000	7511	Wood
AA82658	819	-26.9	6760 ± 41	7676–7569	1.000	7618	Wood
β160460	845	-27.8	7210 ± 40	8070–7954	0.794	8031	Wood
				8159–8085	0.206		

ⁱ Letters before lab numbers denote samples processed at the University of Arizona Mass Spectrometry Laboratory (AA) or Beta Analytic, Inc. (β).

ⁱⁱ Depth below the mud-water interface.

ⁱⁱⁱ Calibrated age ranges calculated using Calib 6.0 (Stuiver and Reimer 1993) and the dataset IntCal09 (Reimer et al. 2009).

^{iv} Weighted mean of the probability distribution of the calibrated age.

Table 4.2: Lake Miragoane (LM) and Laguna Tortuguero (LT) radiocarbon results.

Site ⁱ	Lab number ⁱⁱ	Depth (cm) ⁱⁱⁱ	Uncalibrated ¹⁴ C age (¹⁴ C cal yr BP)	Calibrated age range $\pm 2\sigma$ (cal yr B.P.) ^{iv}	Area under probability curve	Weighted mean (cal yr B.P.) ^v	Material dated
LM	AA6703	22	1085 \pm 60	-1 to -4 151–9 275–173	0.013 0.638 0.349	119	Ostracods
LM	AA5814	216	2780 \pm 55	1825–1558 1858–1852	0.994 0.006	1704	Ostracods
LM	AA6704	233	2680 \pm 60	1475–1416 1713–1476	0.096 0.904	1589	Ostracods
LM	AA6705	233	1655 \pm 60	1698–1411	1.000	1557	Wood
LM	AA5815	321	4110 \pm 60	3190–3162 3454–3201	0.026 0.974	3329	Ostracods
LM	AA5816	418	4780 \pm 60	4300–3981 4316–4310 4356–4324 4406–4367	0.925 0.004 0.036 0.035	4161	Ostracods
LM	AA5817	520	6945 \pm 65	6943–6639	1.000	6778	Ostracods
LM	AA5818	622	9005 \pm 75	8619–8608 9032–8627 9077–9060	0.006 0.984 0.010	8860	Ostracods
LM	AA5369	671	9700 \pm 90	9945–9525 10010–9991 10039–10025 10130–10062	0.945 0.008 0.006 0.041	9702	Ostracods
LM	AA5952	718	10,300 \pm 85	10692–10257	1.000	10,489	Ostracods
LM	GX13055	753	10,230 \pm 160	12429–11332 12522–12471	0.981 0.019	11,936	Bulk organic
LT	β 54719	120–139	1490 \pm 80	1545–1280	1.000	1392	Detrital gyttja
LT	β 24613	218–227	3940 \pm 120	4033–4006 4712–4081 4725–4712 4815–4753	0.012 0.942 0.003 0.043	4383	Algal gyttja

LT	β22349	439–458	3640 ± 80	3804–3720 4157–3807 4175–4175 4223–4205	0.070 0.919 0.000 0.011	3964	Detrital gyttja
LT	β54720	628–647	4560 ± 70	5016–4976 5333–5032 5355–5347 5368–5357 5465–5371	0.032 0.819 0.005 0.006 0.138	5201	Detrital gyttja
LT	β22350	757–781	5960 ± 90	7015–6555 7149–7127	0.990 0.010	6800	Detrital gyttja

ⁱ LM = Lake Miragoane, LT = Laguna Tortuguero.

ⁱⁱ Letters before lab numbers denote samples processed at the Accelerator Mass Spectrometry Laboratory (AA), Geochron Laboratories (GX), or Beta Analytic, Inc. (β).

ⁱⁱⁱ Depth below the mud-water interface.

^{iv} Lake Miragoane calibrated ages are based on radiocarbon dates corrected for hard water lake effect by Higuera-Gundy et al. (1999). Calibrated age ranges calculated using Calib 6.0 (Stuiver and Reimer 1993) and the dataset IntCal09 (Reimer et al. 2009).

^v Weighted mean of the probability distribution of the calibrated age.

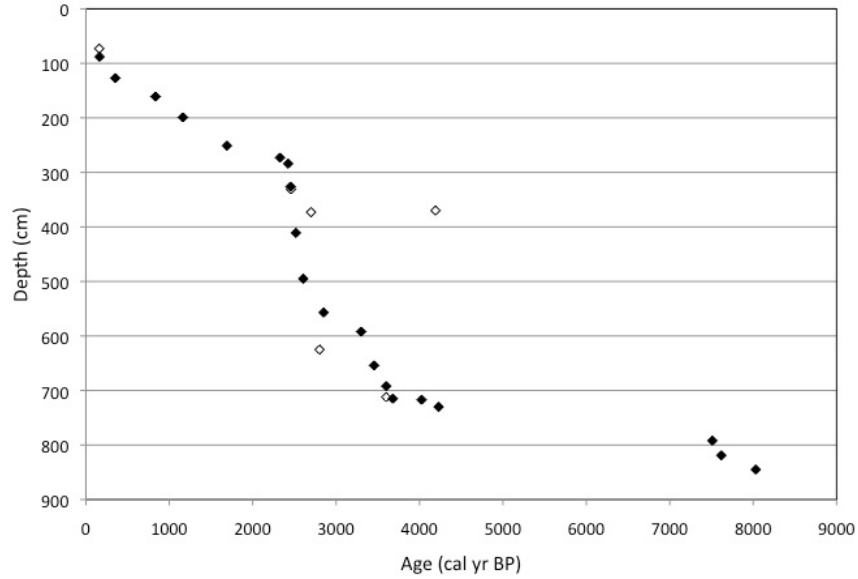


Figure 4.2a: Age-depth diagram for Laguna Saladilla based on calibrated dates from Table 1. Hollow markers indicate dates that were excluded from chronology.

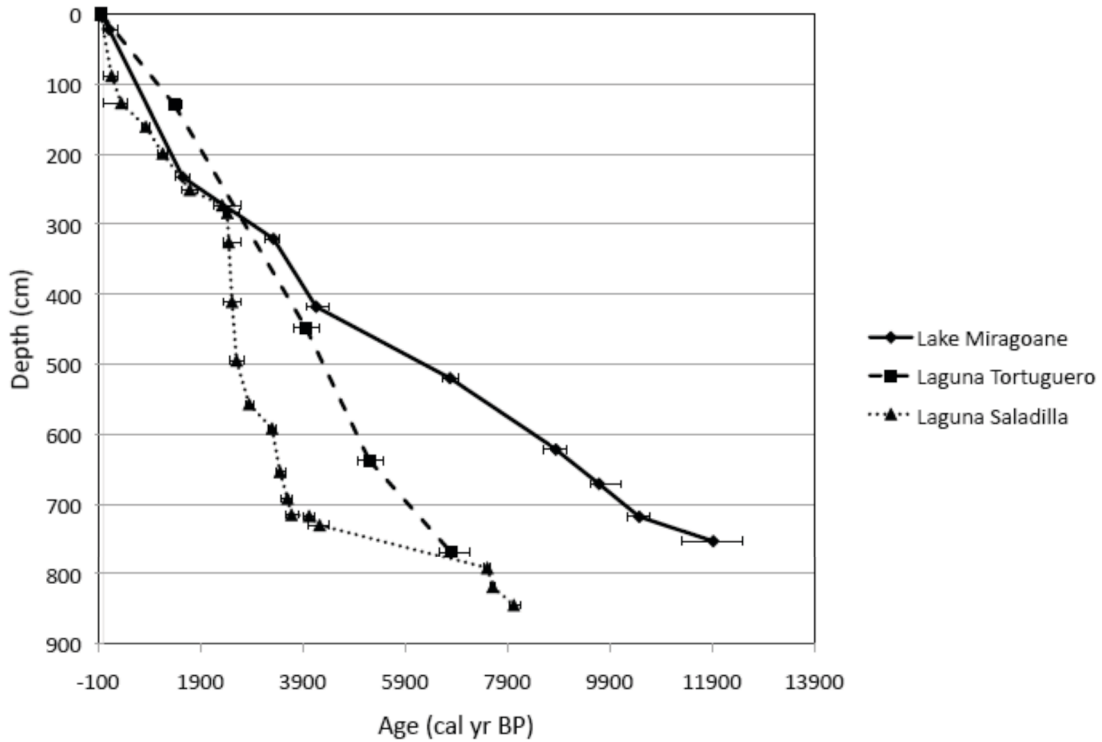


Figure 4.2b: Age-depth diagrams for Laguna Saladilla, Laguna Tortuguero, and Lake Miragoane based on calibrated dates from Tables 4.1 and 4.2. Error bars represent the ± 2 sigma calibrated age range.

in lake conditions from marine to brackish and from brackish to its current freshwater state (Chapter 5).

Six radiocarbon dates were excluded from the Laguna Saladilla sediment chronology. β 176225 and β 176226 are out of line with other results, possibly due to contamination of the profile by old wood remobilized in a storm (β 176225) or to the accidental capture of younger sediment at the end of a core tube during extraction (β 176226). The other three excluded radiocarbon dates (AA82656, AA82666, AA82660) are consistent with the sediment chronology based on the calibrated age ranges, but interpolations based on mean weighted calibrated ages would result in negative sedimentation rates. AA82654 is also within the range of expected values for that depth, but was excluded because the weighted mean age would result in an incorrect four-year increase in sediment accumulation rate that would not be consistent with sediment accumulation rates preceding and superseding the dates at that level.

Burney et al. (1994) excluded date β 24613 from the Laguna Tortuguero sediment chronology, and we have done so here. This date appears to be approximately 2000 years too old, possibly because of a hard water error introduced by shell fragments in the bulk sediment submitted for radiocarbon dating.

Higuera-Gundy et al. (1999) used uncalibrated radiocarbon dates in their study of microfossils and isotope ratios in the Lake Miragoane record. To compare their record to other sites, we had to calibrate the dates, and in doing so we found that the mean calibrated ages of dates AA5814 and AA6705 are inverted (Table 4.2). We used AA6705 and excluded AA5814 because the former date was on a wood fragment, rather than an ostracod shell, and thus would not be affected by hardwater lake error (Hodell et al. 1991;

Higuera-Gundy et al. 1999). AA6704 was excluded because this date was on an ostracod shell at the same level as the wood fragment.

Plotted together by depth, the calibrated ages of the Miragoane, Tortuguero, and Saladilla records reveal similar sedimentation rates in the upper ca. 275 cm of the records, which corresponds in all three cases to the last ca. 2300 calibrated years (Figure 4.2b). Lake Miragoane is the oldest of the records (basal date = 11,938 cal yr BP). It has the lowest sedimentation rate overall, and the lowest sedimentation rate before 2300 cal yr BP. Laguna Tortuguero is the youngest sediment record (basal date = 6800 cal yr BP). Below ca. 275 cm, the lake shows an intermediate sediment accumulation rate. Laguna Saladilla had the highest overall sedimentation rate, with some distinct changes as previously noted. The apparent sedimentation rate was low between ca. 7800 cal yr BP and 3600 cal yr BP, but at 3600 cal yr BP the lake entered a phase of very rapid sediment accumulation. At 273 cm (2327 cal yr BP), sediment accumulation slowed.

4.5.3 Charcoal

Changes in charcoal influx were compared to each other and to archeological evidence of humans in the region (Figures 4.3 and 4.4). Maximum charcoal fragment influx values were highest at Laguna Tortuguero. All sites show an increase in charcoal values during the later Holocene. Laguna Tortuguero is first to show an increase in values at 5201 cal yr BP, when values more than quadruple from the earlier four levels. The peak in values is next evident in Lake Miragoane at 5033 cal yr BP. Small amounts (≤ 60 per fragments/cm²/yr) of charcoal are recorded from 11,812 cal yr BP to 5033 cal yr BP,

except for two peaks at 10,104 and 5649 cal yr BP. However, values jump by almost a factor of 10 at 5033 cal yr BP.

A layer of shells in Laguna Saladilla sediment core prevented the collection of close-interval charcoal samples around 5000 cal yr BP. A sample from 5235 cal yr BP indicated higher charcoal influx than one at 7967 cal yr BP, and four samples from 4100–4800 cal yr BP, but the major increase occurred at ca. 3600 cal yr BP.

Our comparison of insolation curves with the three charcoal records revealed winter (December 21) insolation values to show a closer overall match with changes in charcoal values (Figure 4.3) than curves for summer or equinoxal insolation (not shown). The Lake Miragoane record is characterized by relatively high values throughout the record with three peaks at 4050, 3646, and 3354 cal yr BP that were greater than 1 standard deviation from the Lake Miragoane mean; however, the highest Lake Miragoane charcoal value is found at 916 cal yr BP. Following this peak, values remain relatively high, but stable from 398 cal yr BP to present.

Laguna Saladilla values show a gradual general increase over time that is punctuated by two large (within two standard deviations from the mean) peaks at 2593 and 2427 cal yr BP. Values decrease after these peaks with only a slight rise in values around 1467 cal yr BP. Values are low until a final peak in values is found at 44 cal yr BP. Laguna Tortuguero values are high from 5201–3454 cal yr BP (mean for the period = 545.2 fragments/cm²/yr); however, values rapidly decrease after the highest peak in the record at 3455 cal yr BP. A small peak in values is found at 1853 cal yr BP.

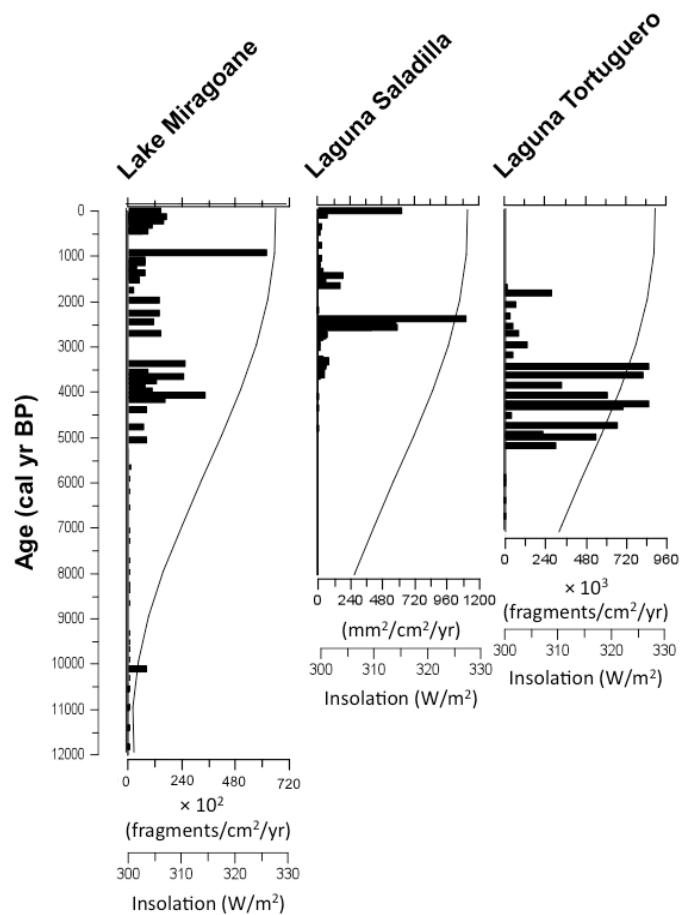


Figure 4.3: Changes in charcoal influx (black bars) compared to changes in winter insolation (grey dotted line) over the past 12,000 cal yrs BP. Insolation values are mean daily values at 15°N on December 21 calculated using Analyseries 2.0 (Paillard et al. 1996; Lasker et al. 2004).

4.6 Discussion

Laguna Tortuguero charcoal records show an increase in values around 5201 cal yr BP while Lake Miragoane charcoal values begin to increase by 5033 cal yr BP. The Laguna Saladilla record is incomplete for this interval because of a shell layer that prevented sampling between 7967 and 5235 cal yr BP. Whether burning commenced at all three sites simultaneously cannot be determined without contiguous sampling of charcoal in the sediment profiles, but clear similarity exists in the charcoal curves. The upswing in charcoal in all three records in the later Holocene suggests a possible regional driver of fire activity that may have affected records across the Caribbean. Burney et al. (1994) suggested that the charcoal peak at Laguna Tortuguero could signal burning by initial human settlers in Puerto Rico; however, it appears that this is a regional phenomenon. Burney et al. (1994) pointed out that Hodell et al. (1991) described the period as being regionally wetter based on the $\delta^{18}\text{O}$ data from Lake Miragoane. However, Higuera-Gundy et al. (1999) found that the wetter conditions resulted in a change in vegetation around Lake Miragoane to include more forest taxa that may have generated more fuel (litter) for natural combustion. Increased fire frequencies could be attributed to stormier conditions with more lightning present as a source of ignition, as suggested by Higuera-Gundy (1999). However, Burney (1997) used Hodell et al.'s (1991) paleoclimate reconstruction to infer that burning during the wetter phase is more likely the result of humans because natural wildfires should decrease (presumably because fuels are less likely to ignite or fires to spread). While humans were in Hispaniola by ca. 6370 cal yr BP (Moore 1991), the earliest archeological evidence for people in Puerto Rico dates to ca. 3200 cal yr BP (Rouse 1992).

Comparing the charcoal records to mean daily winter insolation (Figure 4.3) suggests that burning in the region began to increase when winter insolation increased. Progressively drier winters would favor increased burning and/or more intense fire in the region. Presently fires occur in the northern hemisphere tropics during the dry season (typically from January–March) with peak burning occurring in late February and March after fuels have dried (Uhl et al. 1988; Martin and Fahey 2006). Increased insolation on December 21 would have resulted in increased drying times for fuels, which could lead to earlier fires that were possibly more intense and/or more frequent because more dried fuel was available. The gradual increase in charcoal fragments over time after 5000 cal yr BP, particularly in Laguna Tortuguero but also at Laguna Saladilla, and to a lesser extent in Lake Miragoane, would seem to indicate that drier winters influenced the fire ecology of the region.

A link with climate, however, does not preclude a role for humans at this time. It is possible that fires were set by humans but may have burned out of control due to pre-drying driven by winter insolation (Kaufman et al. 2003). Fires set by humans could have spread more easily or been more intense (spreading from the surface to tree crowns) because of increasingly dry conditions over time. However, the archeological evidence of lithic–archaic age Caribbean groups indicates that early people were foragers who relied heavily on marine resources, gathered roots and berries, and hunted rodents and iguanas (based on extensive marine mollusk evidence and stone pestle and mortar remains at early sites; Keegan 1994; Newsom 2006). A decline in island mammals (particularly sloths) around 5000–4500 cal yr BP in Hispaniola was reported by Steadman et al. (2005) as evidence of regional expansion of human populations and impacts on the

environment. However, they pointed out that sloth remains have not been reported in any Caribbean archeological sites and that no remains have been found in any context on Puerto Rico.

The increase in charcoal values during the mid-late Holocene therefore is more likely driven by climate than humans, specifically increasingly drier winter conditions leading to more frequent and/or intense burning during the dry season. The decrease in Laguna Tortuguero charcoal influx after 3454 cal yr BP, when winter insolation values were still increasing, would seem to indicate other factors were involved at that time. A decrease in charcoal values in the Hispaniolan records is not observable at the same time, although both records show gaps where charcoal fragments were not counted at those levels.

Lower average charcoal influx values appear in Laguna Tortuguero at 3211 cal yr BP, within less than a decade of Rouse's estimated time of earliest human arrival on Puerto Rico (Figure 4.4). Maize starch grains dated from archeological sites indicate that crop cultivation may have begun on the island at this time (Bonzani and Oyuela-Caycedo 2006). Normally, the initiation of agricultural activity is associated with increased burning, so the reduced charcoal influx values at Laguna Tortuguero at this time seem paradoxical. Possibly, the effect of agricultural development was to somehow increase human control over wildfires during the dry season, when fires were more likely to burn out of control. People at that time would not have been able to suppress large fires, but they may have influenced fire frequencies by changing the vegetation in the region and altering the fuel balance and timing of burning.

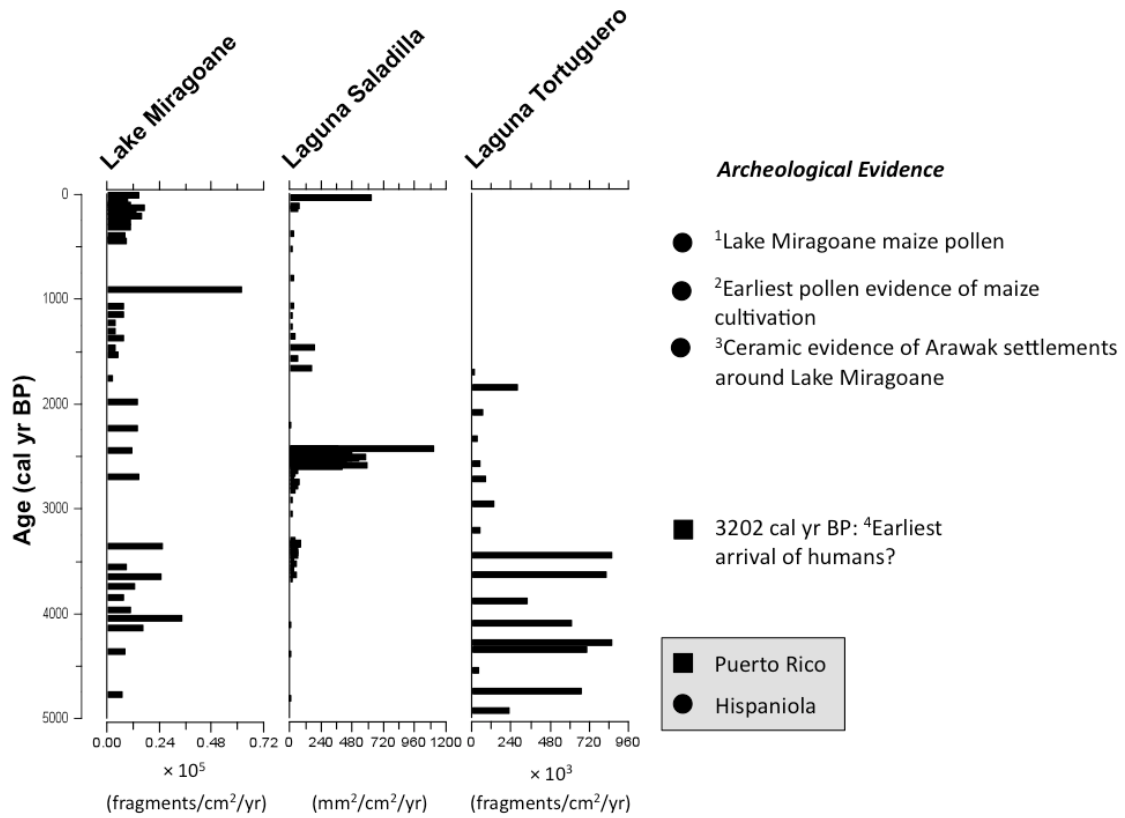


Figure 4.4: A closer view of charcoal influx records from Laguna Saladilla, Lake Miragoane, and Laguna Tortuguero spanning the last 5000 cal yr BP. Archeological evidence is based on ¹Higuera-Gundy et al. (1999), ²Garcia Arevalo and Tavares (1978) and Lane et al. (2008), ³Brenner and Binford (1988), and ⁴Rouse (1992). Evidence by Moore (1991) shows humans arrived in Hispaniola by 6373 cal yr BP.

In a review paper on inter-island paleoecology, Burney (1997) stated that human-set fires are typically ignited during wetter periods of the year, whereas climate-induced burning is more likely to take place during the dry season. Humans may also use fire more regularly to control fuel loads and so fire frequencies may also increase for shorter durations and/or over smaller areas than natural fires.

A period of depressed charcoal values is evident in the Lake Miragoane record from 1758–1073 cal yr BP. Higuera-Gundy (1999) found this to be a drier period that resulted in the return of less fire-adapted lowland dry forest taxa (*Phyllostylon*, *Cordia*, *Sapindus*). Ceramic evidence from nearby archeological sites suggests the Taino settled in the region at roughly this time (ca. 600 CE or 1350 cal yr BP; Brenner and Binford 1988). However, charcoal values are depressed for about 300 years before the earliest evidence of indigenous people visiting or settling around Lake Miragoane. Therefore, the decrease in Lake Miragoane values at that time more likely reflects drier conditions that altered the vegetation within the watershed and changed the fire regime. A regionally drier period is also reflected by extremely low charcoal values in the Laguna Tortuguero profile from around 1707 cal yr BP to present.

Decreasing summer moisture could also explain the two peaks in charcoal at 1670 and 1467 cal yr BP at Laguna Saladilla. These peaks may represent a period of increased fire frequency and/or a single large fire event. A peak in values could also be created when a fire burns closer to the lake, although it is impossible to determine fire distance using microscopic charcoal (Patterson et al. 1987; Whitlock and Millspaugh 1996). A large stand-replacing fire would have had a great impact on the surrounding vegetation and may have facilitated a change in vegetation from more mesic taxa to those more

adapted to progressively drier conditions. No archeological evidence exists of human settlement in the region at this time, although this does not preclude the possibility that humans could have ignited fires at that time. Given the current lack of archeological data and the evidence of drier conditions from Lake Miragoane and Laguna Tortuguero, we find it more likely that lightning-ignited fire(s) explain this peak in the Laguna Saladilla charcoal record.

A large peak followed by a decrease in Lake Miragoane charcoal values at 916 cal yr BP signals the arrival of agriculturalists in the region (Higuera-Gundy 1999; Rouse and Moore 1984). The charcoal increase occurs at around the same time that Lane et al. (2008) found evidence of maize cultivation at Las Lagunas, in the Hispaniolan interior. Higuera-Gundy et al. (1999) do not report evidence of maize pollen until ca. 500 cal yr BP; however, this is not surprising as early agriculturalists typically did not extensively cultivate maize and would more commonly use maize intermittently rather than as a staple crop (Rouse 1992).

A small increase in charcoal influx can also be observed at Laguna Saladilla, although the increase is less than one standard deviation from the mean charcoal influx. Therefore, it is unclear whether the minor increase in values is part of the natural fire regime of the region or ignited by humans. One final large increase in Laguna Saladilla charcoal influx occurs at an estimated 44 cal yr BP (1906 CE). This charcoal peak is within the period of regional population expansion following the withdrawal of the Spanish Army in 1865, after the War of Restoration (Matibag 2003). The high charcoal influx indicated by this sample could also be associated with the establishment of the agricultural town of Carbonera (Augelli 1962) one km east of the lake in 1959 CE.

4.7 Conclusion

The archeological record for the Caribbean is still somewhat sparse (Rouse 1992; Keegan 2000; Newsom 2006). Sedimentary charcoal records such as the three discussed here can complement and possibly extend the archeological record; however, charcoal records at these sites and others in the wider American tropics region are also driven by climate (Power et al. 2010).

By taking a more regional approach to analyzing the charcoal record, we have shown that burning began around the mid-late Holocene, particularly at ca. 5000 cal yr BP around Laguna Tortuguero and Lake Miragoane. Burney et al. (1994) stated that burning at that time was the result of human arrival on Puerto Rico. However, Higuera-Gundy et al. (1999) interpreted the increase in burning as due to increased natural ignition (lightning). Based on our own record coupled with those of Burney et al. (1994) and Higuera-Gundy et al. (1999), we proposed that increased winter insolation could explain the increase in charcoal influx at all sites. An increase in winter insolation would have resulted in increasingly drier winters that would have prompted progressively earlier dry season burning. Whether peaks in microscopic charcoal influx resulted from more frequent fires or more intense burning cannot be resolved, but drier conditions would have facilitated both changes. The source of ignition for these drier fuels is also debatable, and may have involved both climate and humans. With a progressively earlier onset of the dry season, fires could have been set by humans but burned out of control more often.

Charcoal influx also changes later in the Holocene, when the archeological record (Rouse 1992) shows humans were present in Puerto Rico as well as Hispaniola.

Interpretations of charcoal data from Lake Miragoane at this time are complicated by pollen data that show that vegetation within the region changed in response to warmer temperatures. Changes in fuel types are associated with a decrease in fires near Laguna Tortuguero, although lower intensity surface fires or fires outside of the watershed may also be reflected by lower charcoal after 3211 cal yr BP. Good chronological agreement between the archeological record and decreasing Laguna Tortuguero charcoal values seems to suggest that humans may have played at least a minor role in modifying the fire regime at that time, possibly by burning during the wetter seasons in order to have more controlled, lower intensity fires (Burney 1997).

All of these records are hindered by a lack of contiguous sampling. Having charcoal samples at the same time intervals could clarify the synchronicity of the changes between sites. The spacing of samples undoubtedly resulted in many fires and potentially changes in fire regime being missed. More study of sedimentary charcoal at these and other sites is warranted, as a companion to efforts to discover and date further archeological evidence of the extent and activities of Caribbean peoples during the mid- to late-Holocene, and to understand the long-term interplay between climate and human activity.

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CHAPTER 5

HOLOCENE CLIMATE AND ENVIRONMENTAL CHANGE IN NORTH COASTAL HISPANIOLA: A MULTI-PROXY RECORD FROM LAGUNA SALADILLA, DOMINICAN REPUBLIC

This chapter is in preparation for submission to the journal *Quaternary Research* by Maria A. Caffrey, Sally P. Horn, Kurt A. Haberyan, and Kenneth H. Orvis. My use of the word "we" in this chapter refers to my co-authors and myself.

Abstract

On a global scale, islands represent a small area, but they contain varied habitats that are sensitive to changes in environmental conditions. We reconstructed changes in vegetation and environmental conditions over the mid- to late Holocene based on pollen, microscopic charcoal, and diatoms in an 851 cm lake sediment core from Laguna Saladilla near the north coast of the Dominican Republic (19° 39' N, 71° 42' W; ca. 2 masl). This large lake (ca. 220 ha) lies in the rainshadow of the Cordillera Septentrional, in a dry vegetation zone dominated by xerophytic shrubs, cacti, and grasses.

Paleoenvironmental proxies were sampled at relatively close (ca. 10 cm) intervals spanning ca. 8031 cal yr BP. However, diatoms and pollen were poorly preserved in sediments deposited prior to ca. 3639 cal yr BP. Assemblages are well constrained chronologically by 26 radiocarbon dates, mostly on discrete material. To facilitate interpretation of shifts in diatom assemblages in the Saladilla profile, we characterized spatial variations in the modern diatom community and lake conditions using analyses of

sediment dredges, water samples, and limnological data collected across the lake. Changes in *Rhizophora* (red mangrove) pollen percentages and diatom assemblages in the sediment core suggest large changes in salinity and water depth. *Rhizophora* percentages were highest around 7650 cal yr BP when mollusk shells in the core suggest the lake was marine. The lake became progressively brackish ca. 3500 cal yr BP, followed by a transition ca. 2500 cal yr BP to its current freshwater conditions. Peaks in pollen percentages and charcoal concentrations correlate temporally with records from other Greater Antillean sites. Pollen of fire-adapted taxa, particularly *Pinus*, increased in the last 800 years. Amaranthaceae pollen and *Fragilaria* spp. diatoms also increased, with both types likely responding to increasingly drier conditions that resulted in increased burning.

Keywords: pollen, diatoms, charcoal, drought, *Rhizophora*, sea-level

5.1 Introduction

The Caribbean region has undergone a number of transitions in climate over the Holocene and has been hypothesized as sharing important climatic teleconnections with Mexico and Central America over the same period (Metcalf 1995, Metcalfe et al. 2000). Our knowledge of variations in climate is primarily based on paleoclimatic reconstructions, but relatively few analyses have been carried out in the region. Researchers have analyzed lake sediments to characterize changes in environment on the Caribbean islands of Hispaniola (Lake Miragoane: Higuera-Gundy et al. 1999; Las Lagunas: Lane et al. 2009, in press), Cuba (Laguna de la Leche: Peros et al. 2007a),

Jamaica (Wallywash Great Pond: Holmes 1998), and Puerto Rico (Laguna Tortuguero: Burney et al. 1994), and on Andros Island in the adjacent tropical Atlantic (Church's Blue Hole: Kjellmark 1996). But none of these studies of sedimentary proxies have used diatoms (unicellular algae) as indicators of environmental change.

Laguna Saladilla in the Dominican Republic (19°39' N, 71°42' W) is a lowland lake in a very dry region that was relatively underused by humans until the arrival of Europeans. Our record thus likely reflects primarily climate-driven changes in environment prior to 1492 CE. Our data extend knowledge of these climatic changes within the region.

We characterized spatial variations in modern lake conditions using analyses of sediment dredges, water samples, and limnological data collected across the lake, and compared these data to diatom, pollen, microscopic charcoal, and geochemical analyses of the Laguna Saladilla sediment core. Our analyses of surface sediments allowed us to characterize the present-day diatom community in Laguna Saladilla, and provided a firmer basis for interpreting changes in diatom taxa in the past. We use the results of our modern and paleoenvironmental analyses to determine how changes in climate (evaporation/precipitation) and sea level in the past affected the environment around Laguna Saladilla. Changes in salinity indicators in the sediment record show that the lake has undergone a transition in salinity over the past ca. 8000 years that was driven by changes in climate and possibly tectonic processes. Changes in relative sea level (RSL) may have played an indirect role in altering the paleolimnology of the lake.

5.2 Literature Review

5.2.1 Caribbean Climate Reconstructions

One of the most widely cited climate reconstructions from the Caribbean region is the work on a sediment core from Lake Miragoane, Haiti (Hodell et al. 1991; Higuera-Gundy et al. 1999). They reconstructed changes in summer precipitation based on oxygen isotope ($\delta^{18}\text{O}$) ratios in ostracods and linked these changes to variations in the mean annual position of the intertropical convergence zone (ITCZ). They conjectured that northward movement of the mean ITCZ position altered the timing of the summer rainy season by forcing an earlier displacement of the North Atlantic high and weakening of the easterly trade winds (Hodell et al. 1991). A more northerly (higher) mean position of the ITCZ in the Caribbean from ca. 8200–5300 cal yr BP resulted in generally wetter conditions at that time. As the mean annual position of the ITCZ began to decrease after the mid-Holocene, lake levels in Lake Miragoane began to decrease. Hodell et al. (1991) found a two-step increase in $\delta^{18}\text{O}$ values beginning ca. 3200 cal yr BP that indicated a return to drier conditions by ca. 2500 cal yr BP.

Changes in the position of the ITCZ through the Holocene have also been examined using titanium and iron concentrations in laminated sediments in the Cariaco Basin, Venezuela (Haug et al. 2001). Fluctuations in sea surface temperatures and salinity have operated over 200–400 year cycles with minima that coincide with drier periods in Mexico (Nyberg et al. 2002).

Kennedy et al. (2006) also inferred drier conditions at ca. 2500 cal yr BP in the Valle de Bao, Dominican Republic, as did Burney et al. (1994) in Laguna Tortuguero, Puerto Rico. Charcoal records from the region show that charcoal influxes increase from

ca. 5000 cal yr BP (Chapter 4), with trends that have been attributed to both changes in climate (Higuera-Gundy et al. 1999) and human expansion (Burney et al. 1994).

5.2.2 Holocene Relative Sea Level Rise

The melting of the Pleistocene glaciers has had a significant impact on mean global sea levels over the Holocene. Given the proximity of Laguna Saladilla to the coast, a deviation in sea level could affect its limnology in several ways, for example, by altering the position of the phreatic zone of the aquifer, or changing the susceptibility of the lake to inundation by storm surges and tsunamis.

Bard et al. (1990) estimated changes in Caribbean sea level over the past 130,000 yrs BP using coral (*Acropora palmata*) from Barbados. Their data show that sea level was 85 m lower during marine isotope stage 3 (ca. 30,000 yrs BP) and that sea level rose at rates of ca. 3.7–2.5 m per century following the glacial meltwater pulses of ca. 13,500 and 11,000 yrs BP. Their data show that sea levels gradually rose through the Holocene, although they do not specify at what rate.

Peros et al. (2007a, 2007b) found that changes in relative sea level (RSL) in Laguna de la Leche, Cuba during the Holocene affected salinity as well as lake level. They found the lake was possibly inundated by ocean waters ca. 4200 cal yr BP, but the later expansion of mangroves ca. 1700 cal yr BP separated the lake from direct marine influences. However, they did not specify how many meters RSL may have risen at ca. 4200 cal yr BP. For mangrove to become established around the site, they hypothesized a decrease in RSL at ca. 1700 cal yr BP.

5.3 Site Description

Laguna Saladilla is a large (220 ha, 2 masl) freshwater lake located ca. 5.3 km from the Atlantic coastline in the Dominican Republic (Figure 5.1). The site is in one of the drier regions of the country, located in the rain shadow of the Cordillera Septentrional east of the lake (Bolay 1997). Average annual temperature is 26.4 °C (WMO 2011). Precipitation is estimated to be less than 700 mm per year, and mainly results from polar outbreaks from the north that occur in the autumn and early winter (Bolay 1997). Lake levels are also bolstered during drier periods by the Río Masacre, which currently flows into the lake from the Cordillera Central to the south. Laguna Saladilla currently has no surface outflow. Satellite images of the region show former river channels that bypassed the lake and led directly to sea. Ground penetrating radar analyses of the lake also show that the river has discharged into the southeast end of the lake in the past, before establishing its current position at the southwest end of the lake (Chapter 3).

The lake is underlain by Quaternary alluvium (French and Schenk 2004) with a northwesterly trending ridge (ca. 38 masl) of upper Cretaceous–post-Eocene marine (limestone) strata that separates the lake from the Río Chacuey ca. 3 km to the northeast. Mann et al. (1998) inferred that the western extension of the Septentrional Fault Zone runs more or less directly underneath the current path of the Río Chacuey. Based on GPS measurements performed since 1994, the region is moving at a rate of ca. 11.6 mm/yr (Calais et al. 2002, Mann et al. 1998). The last significant recorded earthquake within the region was in 1842 CE, an event apparently strong enough to have triggered a tsunami (McCann 2006).

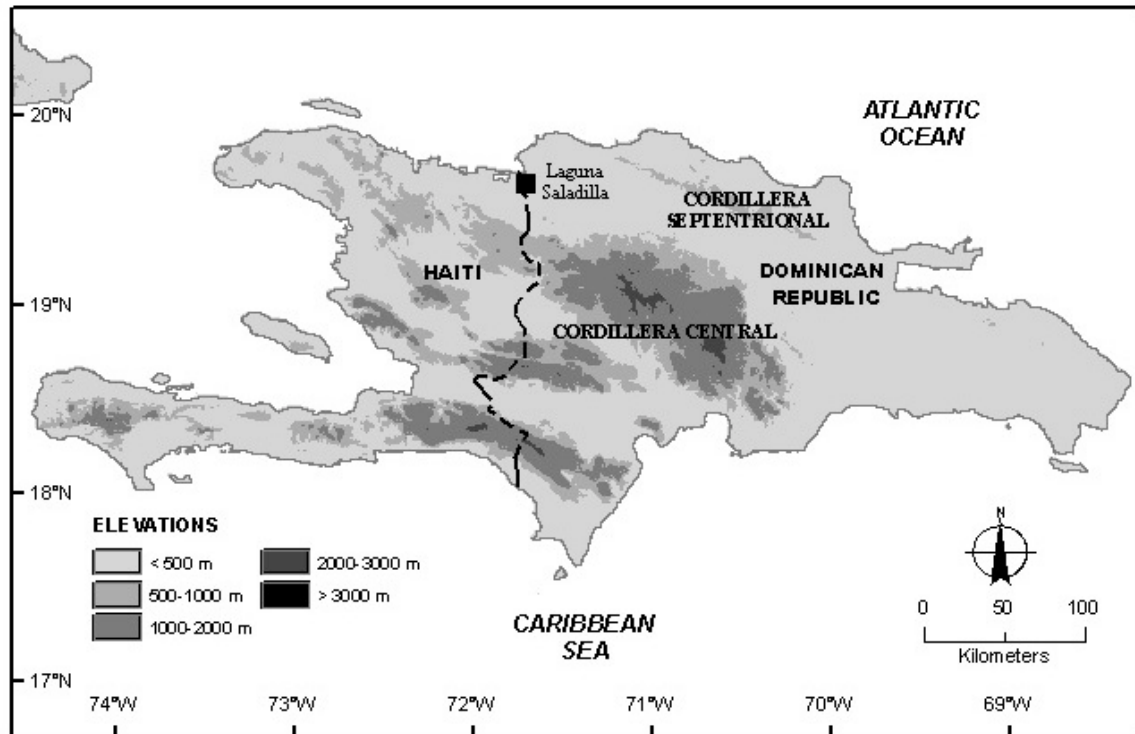


Figure 5.1a: The island of Hispaniola. Laguna Saladilla (■) is located in the Dominican Republic.

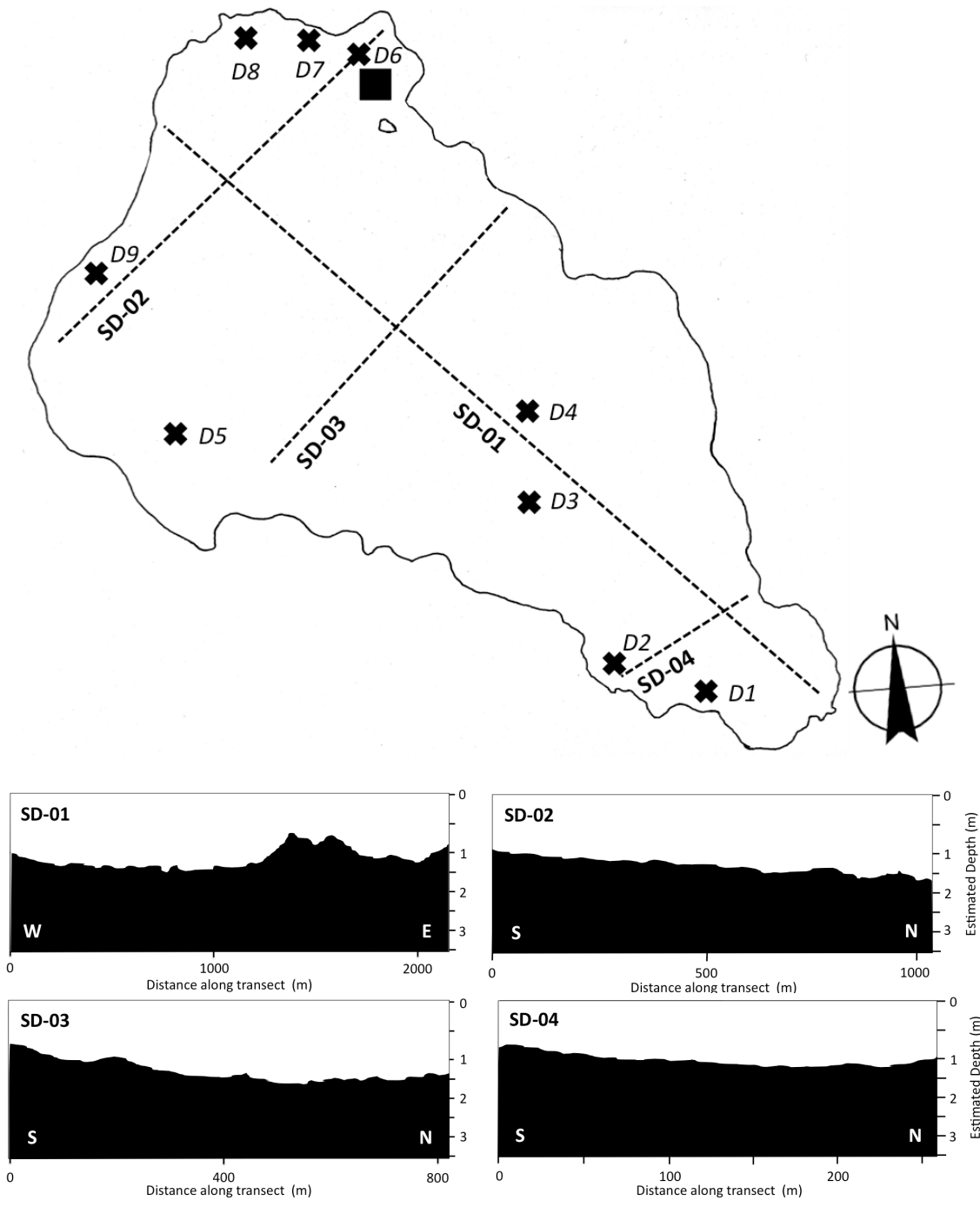


Figure 5.1b: A sediment core (■) was extracted from the northwest end of Laguna Saladilla. Bathymetric profiles were generated using ground penetrating radar across each transect indicated by dashed lines. Modern diatom and water samples were collected across the lake (D1–D9), shown above with a ✕. Estimated depths across transects are based on two-way travel time of ground penetrating radar (Chapter 3).

Laguna Saladilla is bordered by cropland to the north and east, and seasonally dry scrub and forest to the south. Marsh with some forest islands extends from the west edge of the lake to the border with Haiti, beyond which are agricultural lands, some highly denuded. Prior to the establishment of the settlement of Carbonera in 1959 (Augelli 1962), the local vegetation was some type of subtropical dry forest (Tasaico 1967). However, detailed descriptions of the regional vegetation are lacking, partly due to lack of study and partly due to pervasive modification by humans, particularly after the arrival of Europeans on Hispaniola in 1492 CE (Rouse 1992).

Holdridge (1945) described the Hispaniola dry forest region as comprising two divisions: "dry types" and "arid types." He did not delineate where the boundaries between the two types can be found, but characterized "dry type" forests as containing trees such as *Cassia spectabilis*, *Cordia alliodora*, and *Lysiloma*. "Arid type" dry forests have more members of the Cactaceae family, such as *Stenocereus fimbriatus*, *Cephalocereus* sp., *Opuntia moniliformis*, and *Pereskia* sp.. No cacti were observed around Laguna Saladilla during our fieldwork, but they were spotted within the region. We also observed specimens of *Caesalpinia pauciflora* and *Exostema spinosum*.

Laguna Saladilla is less than 3 km south of an extensive area of mangroves protected within the Manglares de Estero Blanco National Park. Red mangroves (*Rhizophora mangle*) dominate the stand. Saline and alkaline savannas and marshes with halophytic grasses and herbs occur inland of the mangroves (Bolay 1997).

Despite the current extent of croplands within the region, archaeological evidence of human inhabitants prior to 1492 CE appears lacking. Indigenous peoples may have

visited the area as it is only ca. 50 km southeast of the archeological site En Bas Saline, Haiti that has been dated by Newsom and Deagan (1994) to around 1140 CE.

5.4 Methods

We cored Laguna Saladilla in the summer of 2001 using a Colinvaux-Vohnout (C-V) locking piston corer (Colinvaux et al. 1999) operated through a wooden platform atop two anchored rubber craft. The upper sediments (mud-water interface) were collected using a plastic tube fitted with a rubber piston. The mud-water interface core was extruded in 2 cm increments in the field. The deeper core sections were transported to the University of Tennessee in their original aluminum core tubes and opened and described in the laboratory.

Material for accelerator mass spectrometry (AMS) radiocarbon dating was extracted from the core from sections where abundant datable material was present or at transitions in sedimentary properties (color, texture, shell layers). We mainly dated discrete material (charcoal, wood, other plant remains), but dated bulk sediment at seven levels where sufficient quantities of discrete material were not available. Radiocarbon dates were calibrated using CALIB 6.0 software (Stuiver and Reimer 1993) and the dataset of Stuiver et al. (2010). The weighted mean ages were calculated from the probability distributions of the calibrated ages (Telford et al. 2004) and used to estimate ages by linear interpolation.

Pollen and loss-on-ignition (Dean 1974) samples were taken at 10–12 cm intervals (Appendix IV) through the profile. *Lycopodium* control spores (Stockmarr 1971; Maher and Stockmarr 1981) were added to pollen samples before standard chemical

preparation (HCl, KOH, HF, acetolysis, safranin stain; Appendix I), following Fægri and Iversen (1989). Samples were mounted in silicone oil and counted at 400× magnification to a pollen sum of 250 grains excluding fern spores, indeterminate pollen, and aquatic pollen types. Dinoflagellates were also tallied outside of the pollen sum; no attempt was made to identify taxa. Microscopic charcoal was quantified on pollen slides using point counting, following Clark (1982). Microscopic manganese oxide fragments were observed during pollen counting and were also quantified using point counting, as a possible proxy for limnological conditions. Manganese fragments were differentiated from charcoal particles based on their circular–octagonal shape and light transmittance under magnification.

Diatoms samples were taken at ca. 10 cm intervals (Appendix IV) and treated with 30% hydrogen peroxide following the procedure outlined by Renberg (1990). Samples were mounted in naphrax resin (Flemming 1954) and counted to a sum of 250 diatoms per slide at 400× magnification. Diatoms were identified based on images and descriptions by Navarro (1982), Foged (1984), Metzeltin and Lange-Bertalot (2007), and Hein et al. (2008) (Appendix II). Diatoms were also enumerated in nine surface sediment samples collected from Laguna Saladilla in December 2009 using a LaMotte bottom-sampling dredge. Two water samples were collected at each dredge location for separate analysis of anions (filtered) and cations (filtered and acidized with 2–3 drops concentrated nitric acid). The water samples were refrigerated and their chemistry was determined using a Dionex ICS-2000 Ion Chromatography System.

5.5 Results

5.5.1 Chronology

Twenty-six radiocarbon dates were obtained on material extracted from the Saladilla sediment core (Table 5.1). A basal radiocarbon date of 8031 cal yr BP was obtained on wood at 845 cm depth. The radiocarbon dates display a generally linear relationship with depth (Figure 5.2; $y = 0.1005x + 160.48$), with two distinct changes in sedimentation rate, at ca. 3680 cal yr BP and ca. 2425 cal yr BP that correspond to changes in salinity in the lake.

Six radiocarbon dates were not included in the Laguna Saladilla sediment chronology. Radiocarbon dates $\beta 176225$ and $\beta 176226$ were judged erroneous based on the age-depth model (Figure 5.2). The material dated may reflect contamination of the profile by storm processes that remobilized older wood ($\beta 176225$), or by the accidental capture of younger sediment at the end of a core tube during extraction ($\beta 176226$). Three of the excluded radiocarbon dates (AA82656, AA82666, AA82660) have two sigma calibrated age ranges that are consistent with dates above and below; however, using their calculated weighted mean ages would result in negative sedimentation rates. AA82654 is also within the range of expected values for that depth, but was excluded because the weighted mean age would result in an unlikely four-year increase in sediment accumulation rate that would not be consistent with sediment accumulation rates preceding and superseding the dates at that level.

The age-depth diagram indicates relatively slow sedimentation rates from 8031–3680 cal yr BP (lowest ca. 130 cm of the sediment core). This lower part of the core consists of sandy marl with abundant shells and concentrations of small (ca. 2-cm)

Table 5.1: Laguna Saladilla radiocarbon results.

Lab number ⁱ	Depth (cm) ⁱⁱ	$\delta^{13}\text{C}$ (‰)	Uncalibrated ^{14}C age (cal yr BP)	Calibrated age range $\pm 2\sigma$ (cal yr B.P.) ⁱⁱⁱ	Area under probability curve	Weighted mean (cal yr B.P.) ^{iv}	Material dated
AA82654^v	73	-28.1	175 \pm 32	34 to -2 116-71 227-134 296-252	0.195 0.076 0.534 0.195	160	Bulk sediment
AA82659	88	-26	184 \pm 32	33 to -2 78-74 99-81 114-106 224-136 300-254	0.194 0.006 0.023 0.009 0.551 0.218	164	Wood
β 174192	127	-15.3	280 \pm 40	3 to 0 169-153 344-282 465-346	0.004 0.044 0.360 0.593	353	Plant material
AA82664	161	-19.1	907 \pm 33	914-742	1.000	835	Bulk sediment
β 228998	199	-28.8	1230 \pm 40	1266-1063	1.000	1163	Wood
β 160457	251	-25	1770 \pm 60	1825-1543 1857-1853	0.997 0.003	1691	Wood
β 160458	273	-29.9	2320 \pm 40	2168-2162 2242-2178 2460-2302 2636-2697	0.005 0.168 0.037 0.827	2327	Wood
AA82655	284	-30.6	2375 \pm 36	2491-2336 2607-2603 2677-2642	0.939 0.003 0.057	2425	Wood
AA82652	326	-28.3	2401 \pm 34	2499-2344 2613-2596 2692-2638	0.859 0.025 0.116	2454	Wood
AA82656	331	-26.4	2404 \pm 34	2501-2345 2535-2535 2613-2595 2694-2637	0.845 0.001 0.028 0.126	2458	Wood
β 176225	370	-28.0	3800 \pm 40	4032-4007 4299-4081 4354-4327 4385-4369 4404-4393	0.020 0.931 0.029 0.013 0.007	4191	Wood and bark

AA82666	373	-27.8	2591 ± 40	2532–2503 2593–2536 2637–2614 2779–2696	0.032 0.101 0.095 0.771	2699	Bulk sediment
AA82661	411	-29.8	2443 ± 34	2546–2356 2575–2560 2617–2579 2702–2634	0.644 0.023 0.097 0.236	2518	Wood
AA82667	495	-25.7	2527 ± 41	2484–2470 2746–2485	0.015 0.985	2606	Charcoal
AA82653	557	-24.7	2758 ± 34	2929–2777 2945–2935	0.979 0.021	2850	Bulk sediment
AA82657	592	-29.0	3080 ± 35	3373–3215	1.000	3300	Wood
β176226	625	-29.2	2690 ± 40	2861–2747	1.000	2801	Plant material
AA82663	654	-22.4	3231 ± 42	3558–3377	1.000	3455	Bulk sediment
AA82668	692	-28.3	3364 ± 42	3544–3479 3694–3546	0.171 0.829	3601	Plant material
AA82660	712	-28.7	3364 ± 35	3536–3484 3691–3553	0.118 0.882	3602	Wood
β160459	715	-27.2	3420 ± 40	3732–3571 3776–3743 3826–3789	0.837 0.060 0.103	3680	Wood
AA82662	717	-22.5	3687 ± 36	4095–3910 4145–4118	0.939 0.061	4025	Bulk sediment
AA82665	730	-21.8	3687 ± 61	4032–4007 4416–4081	0.022 0.978	4229	Bulk sediment
AA82651	792	-26.2	6623 ± 46	7573–7436	1.000	7511	Wood
AA82658	819	-26.9	6760 ± 41	7676–7569	1.000	7618	Wood
β160460	845	-27.8	7210 ± 40	8070–7954 8159–8085	0.794 0.206	8031	Wood

ⁱ Letters before lab numbers denote samples processed at the University of Arizona Mass Spectrometry Laboratory (AA) or Beta Analytic, Inc. (β).

ⁱⁱ Depth from the mud-water interface.

ⁱⁱⁱ Calibrated age ranges calculated using Calib 6.0 (Stuiver and Reimer 1993) and the dataset IntCal09 (Reimer et al. 2009).

^{iv} Weighted mean of the probability distribution of the calibrated age.

^v Dates in bold were not used to construct the chronology (see chronology section).

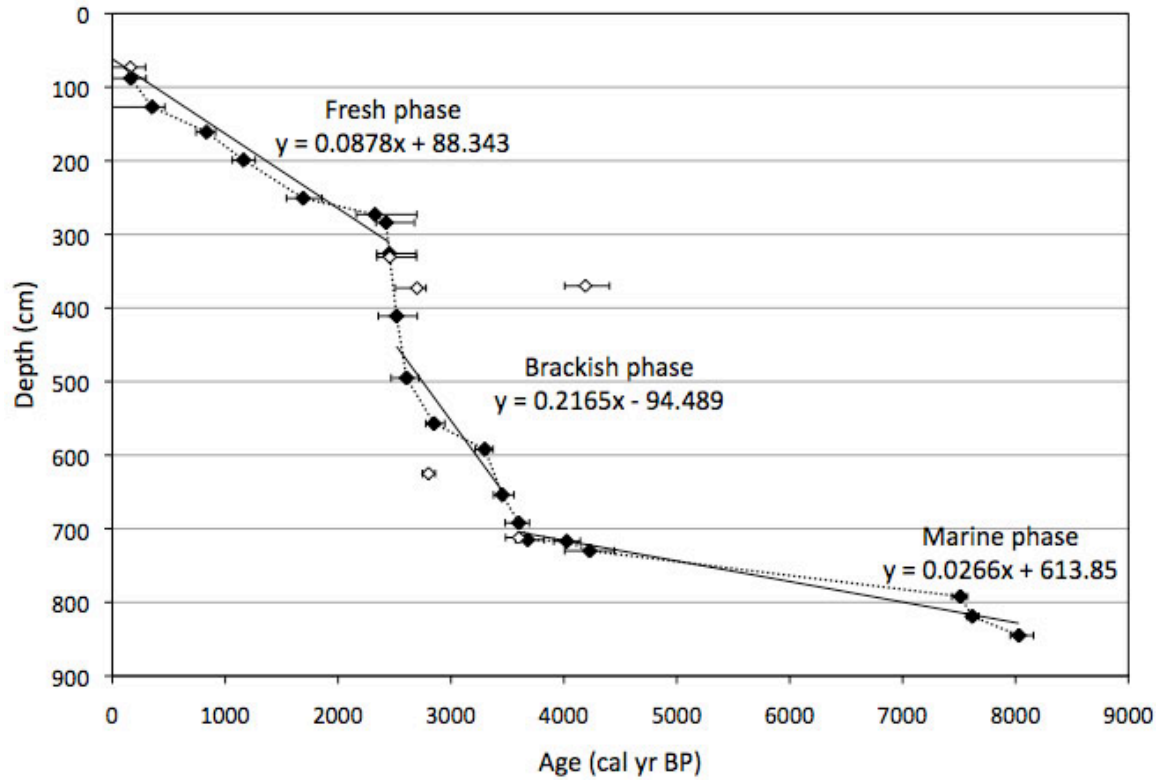


Figure 5.2: Age-depth diagram for Laguna Saladilla based on calibrated dates from Table 5.1. Hollow markers indicate dates that were excluded from the chronology. Error bars represent the ± 2 sigma calibrated age range. Dashed line represents interpolated changes in sediment accumulation rates between solid markers. Solid lines with equations represent the slope of sediment accumulation during the respective fresh, brackish, and marine phases.

clumps of soil with embedded organics. Portions of the stratigraphy suggest disturbance, and we cannot exclude the possibility that our calculated low sedimentation rate is due to a hiatus in the core before 4229 cal yr BP. To test for this, we would need to date additional material between 792–730 cm in the profile, but this is not possible because of a lack of discrete organic material among the carbonate shells and sandy sediments.

Sediment accumulation rates increased markedly from 3680–2425 cal yr BP, and then decreased from 2425 cal yr to the present. Based on ground penetrating radar analyses, Caffrey et al. (Chapter 3) suggested that these changes in sedimentation resulted from changes in the position of the Río Masacre. They identified several paleodeltas along the south and northeast shore of the lake that indicate that the Río Masacre, and possibly the Río Chacuey, flowed into the lake from different positions in the past; at some time(s) in the lake's history, the Río Masacre may not have entered the lake.

5.5.2 Pollen

Pollen was prepared from 82 levels of the sediment core. Pollen concentrations were often low and some levels required counting multiple slides to reach a 250 grain pollen sum. Even then, samples from 36 levels had insufficient pollen and were excluded (Appendix IV). The remaining 46 used in our reconstruction cover the period from 7967 to 44 cal yr BP, but with gaps in the record due to poor preservation from 7967–7650 cal yr BP, and above and below a sample at 5235 cal yr BP (gaps are 7602 to >5235 cal yr BP, and <5235 to 3639 cal yr BP) (Figure 5.3). We determined pollen zones based on observed changes in all of the proxies discussed here. Three broad zones were identified

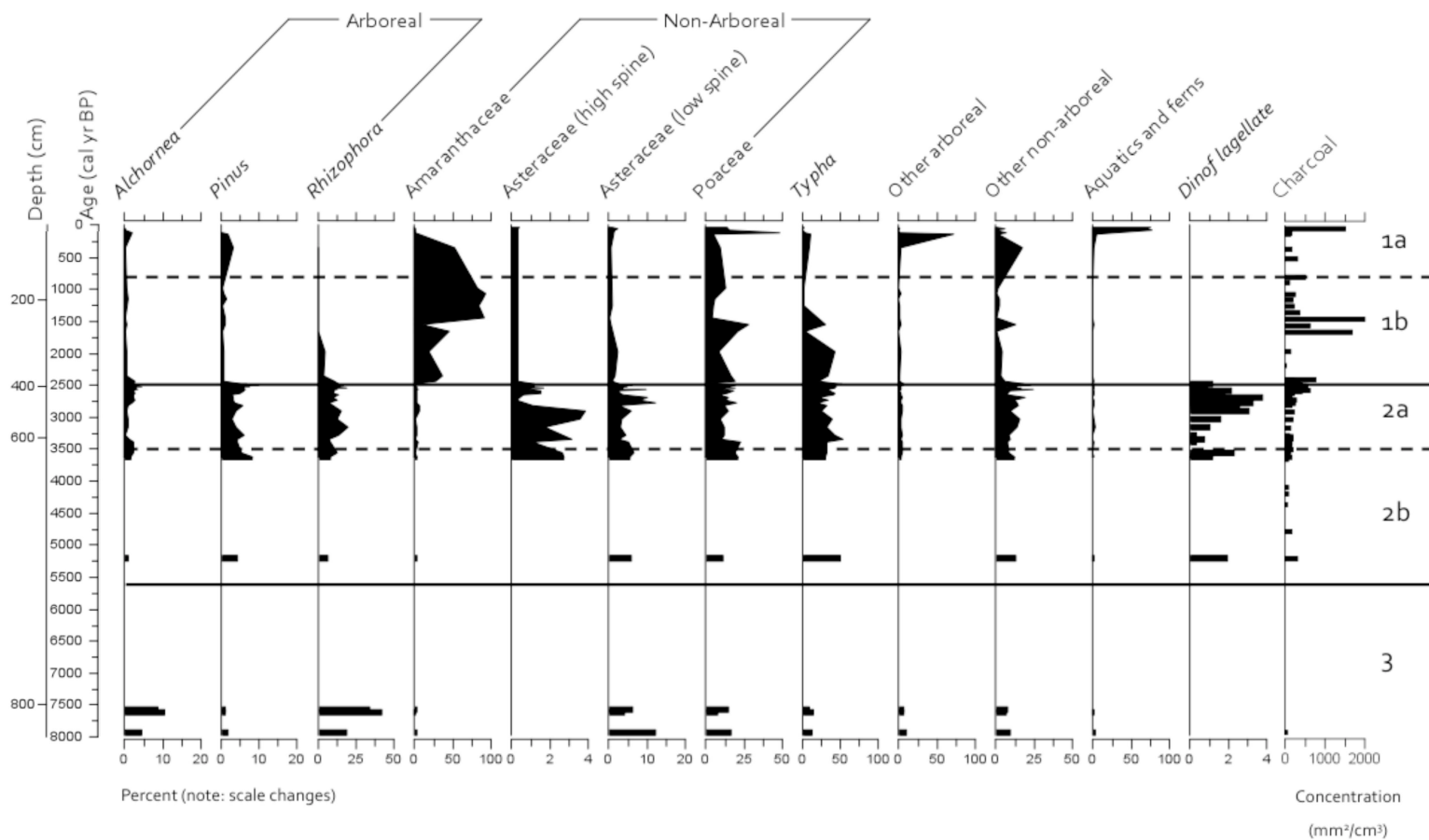


Figure 5.3: Percent pollen of selected taxa from the Laguna Saladilla profile, plotted by age in calibrated radiocarbon years. The composite categories in the pollen diagram include the following taxa: Other arboreal: Arecaceae, Piperaceae, and 28 other arboreal taxa that averaged less than 1%. Other non-arboreal: *Ambrosia*-type, Cyperaceae, Leguminosae, *Polygonium*, Rubiaceae and 31 other non-arboreal taxa that averaged less than 1%. Aquatics and ferns: *Polypodium* and 6 aquatic taxa that averaged less than 1%.

that represent when the water was more saline (possibly marine), before it transitioned through brackish to fresh conditions.

Zone 3 (ca. 7967–5550 cal yr BP) was delineated based on an abundance of marine shells (Appendix V). However, pollen preservation at this time was poor, and layers of shells and sand prevented the sampling of pollen at close intervals. The pollen assemblages we determined were dominated by arboreal pollen, particularly the red mangrove *Rhizophora*, which reached its peak value (41.8%) at ca. 7650 cal yr BP, below a gap in the pollen record resulting from a layer of sand that prevented sampling. This part of zone 3 is also marked by relatively high values of *Alchornea* (up to 10.4%), which reaches its maximum for the record in this zone.

Zone 2 (5550–2500 cal yr BP) is represented by mostly non-arboreal pollen, particularly Poaceae, *Typha*, and Asteraceae. Low-spine pollen types from the Asteraceae family dominate throughout zone 2; however, high-spine types of Asteraceae appear above the pollen gap, reaching a maximum near the middle of zone 2a. *Pinus* and *Rhizophora* are the most common arboreal pollen types in zone 2. Percentages of both types increase within zone 2b (5550–3500 cal yr BP) and fluctuate within zone 2a (3500–2500 cal yr BP). Dinoflagellates first appear in zone 2b and peak in abundance near the top of zone 2a. Charcoal values also show a gradual increase over this period.

Non-arboreal pollen percentages are highest in zone 1, from ca. 2500 cal yr BP to present. Arboreal types show a steep decline at ca. 2500 cal yr BP. *Rhizophora* is virtually absent after ca. 1980 cal yr BP. *Pinus* percentages show a slight rise to the top of zone 1a, but not to their level in zone 2.

The high non-arboreal percentages in zone 1 are primarily from Amaranthaceae and Poaceae. A large peak in charcoal concentration at ca. 1467 cal yr is accompanied by a large increase in Amaranthaceae percentages. Percentages of Amaranthaceae peak in zone 1b, with values over 84% in 4 levels between 1467 and 1077 cal yr BP. *Typha* pollen percentages decline within zone 1b and are generally remain low in zone 1a.

5.5.3 Diatoms and water chemistry

Laguna Saladilla is presently circumneutral with little variation in water chemistry across the lake, indicating the lake has a high degree of mixis (Table 5.2). No evidence of human interference with the water chemistry is apparent. Values of potassium, nitrate, and nitrite were all extremely low. However, alkalinity, calcium, and magnesium values reveal that the lake is well buffered.

Lake bathymetry varies to a small degree, mostly resulting from a number of deltas along the south shore of the lake (Chapter 3). While the lake is relatively shallow (ca. 1.18 m), secchi disk measurements revealed low transparency (ca. 0.75 m).

Surface diatom data show a general change in species composition from southeast to northwest across the lake (Figure 5.4). Samples D1–D5 display relatively high percentages of *Amphora* spp., *Cocconeis placentula*, *Cocconeis* spp., *Navicula*, and *Synedra* spp.. Surface samples D6–D9 were dominated by species of *Nitzschia*, particularly *Nitzschia punctata*.

Diatom samples were taken from 74 levels in the sediment core, and 51 levels had sufficient diatoms for a count of 250 valves. The same zones discussed above for pollen were applied to the sediment core diatom data. Diatom preservation was particularly poor

Table 5.2: The physical and chemical properties of Laguna Saladilla. Water chemistry data are based on water samples collected across the lake in December 2009 (see methods). Water depth was calculated based on two-way travel time of ground penetrating radar signals over twenty-six transects across the lake (Chapter 3).

MEASUREMENT	MEAN	RANGE (D1–D9)
<i>Field measurements:</i>		
Unfiltered pH	7.2	6.8–8.4
Filtered pH	7.7	7.1–7.9
Temperature (°C)	28.9	27.8–29.6
Alkalinity (as CaCO ₃ , ppm)	232.2	180– >240
Total hardness (as CaCO ₃ , gpg)	13.5	7–15
Total chlorine (mg/L)	Undetectable	Undetectable
Nitrate (ppm)	Undetectable	Undetectable
Nitrite (ppm)	Undetectable	Undetectable
Secchi disk (cm)	74.8	54–90
Water depth (m)	1.2	0.6–1.7
<i>Laboratory measurements:</i>		
Fluoride (ppm)	0.1	0.1–0.2
Chloride (ppm)	27.7	22.3–43.0
Bromide (ppm)	0.1	0–0.2
Nitrite (ppm)	0.1	0–0.6
Nitrate (ppm)	0.3	0.1–0.4
Sulfate (ppm)	20.3	13.5–40.7
Sodium (ppm)	20.5	15.1–35.7
Potassium (ppm)	0.7	0.5–1.0
Magnesium (ppm)	13.5	10.5–19.1
Calcium (ppm)	19.5	15.8–25.1
Alkalinity (as CaCO ₃ , ppm)	178.7	157.0–209.0

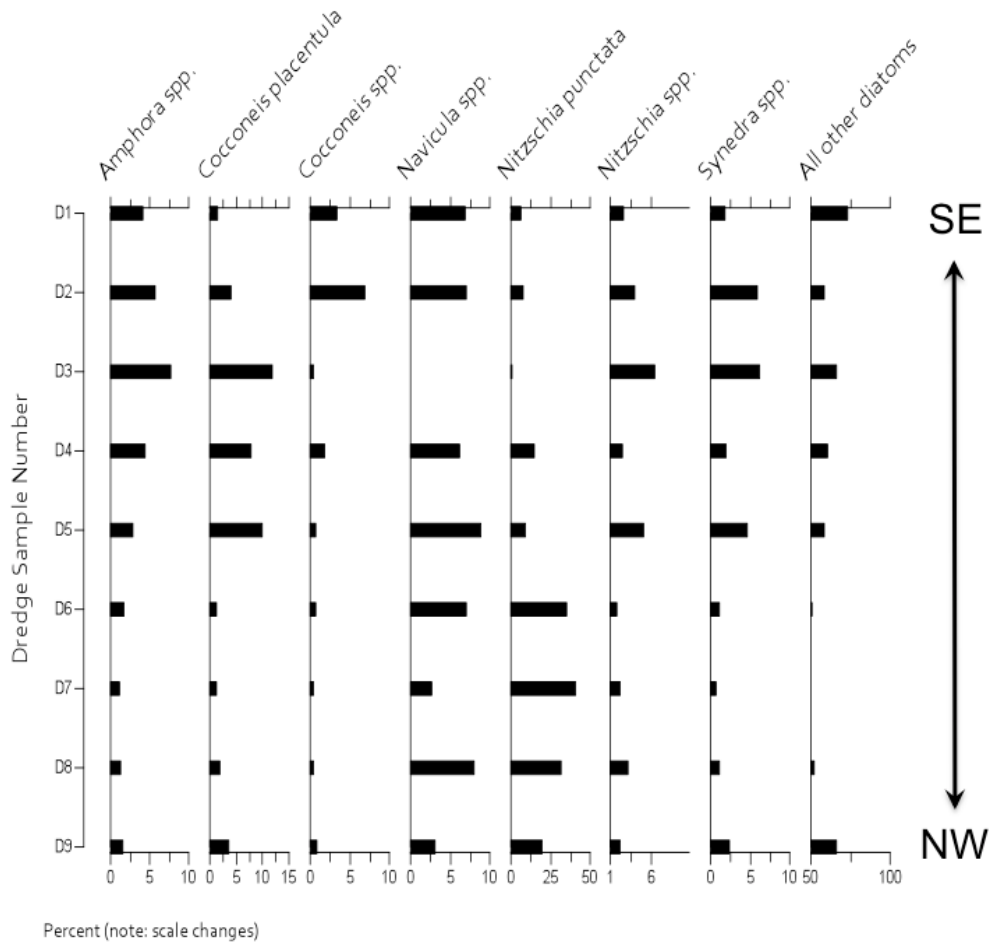


Figure 5.4: Percent diatoms found in lake surface sediment samples obtained using a dredge at various locations across the lake. Samples D1–D4 were collected to the southeast of transect SD-03, and samples D5–D9 were collected to the northwest of transect SD-03 (Figure 5.1b).

in the lower part of the sediment profile, so our diatoms record begins in zone 2b, at ca. 3639 cal yr BP (Figure 5.5).

Species of *Navicula* dominate zone 2b (3639 cal yr BP–2500 cal yr BP), along with species of *Diploneis* (ca. 1.4–10.8%) and *Cyclotella striata* (ca. 14.6–25.9%). Percentages of *Navicula* and *Diploneis* remain high in zone 2a, although percentages of *Encyonopsis cf. braunii* and *Amphora* also increase. Percentages of *Cocconeis* spp. are high at the top of the zone.

The zone 2a/1b boundary is marked by major shifts in assemblages. Species of *Cocconeis* spp. briefly flourish (42.7–63.4%) at ca. 2514–2506 cal yr BP. *Cyclotella meneghiniana* also expands (90.5–74.7%) for a short (ca. 15 year) period at ca. 2476 cal yr BP. *Fragilaria*, particularly *Fragilaria construens* (86.9%) increase in zone 1b, while *Amphora* spp., *Cocconeis* spp., *Diploneis* spp., *Encyonopsis braunii*, and *Navicula* spp. decline from their peak values in zone 2. Species of *Nitzschia* changes from predominantly *Nitzschia punctata* in zone 2 to *Nitzschia frustulum* in zone 1. Percentages of *Mastogloia* spp. begin to increase toward the top of zone 1b.

In zone 1a, *Mastogloia* spp. decrease at the beginning of the zone, but then increase from ca. 117 cal yr BP to the top of the sediment profile. While percentages of *Cocconeis* spp. were identified in the surface sediment dredge samples, species of *Mastogloia* spp. were not present. Percentages of *Cyclotella meneghiniana* slightly increase in zone 1a in two sample levels dated to ca. 664 and ca. 523 cal yr BP (25.3 and 34.6%, respectively), although values do not approach those of zone 1b. Peaks in *Navicula* spp., *Nitzschia frustulum*, *N. punctata*, and *Terpinsoe musica* (not shown) also occur at the top of the profile.

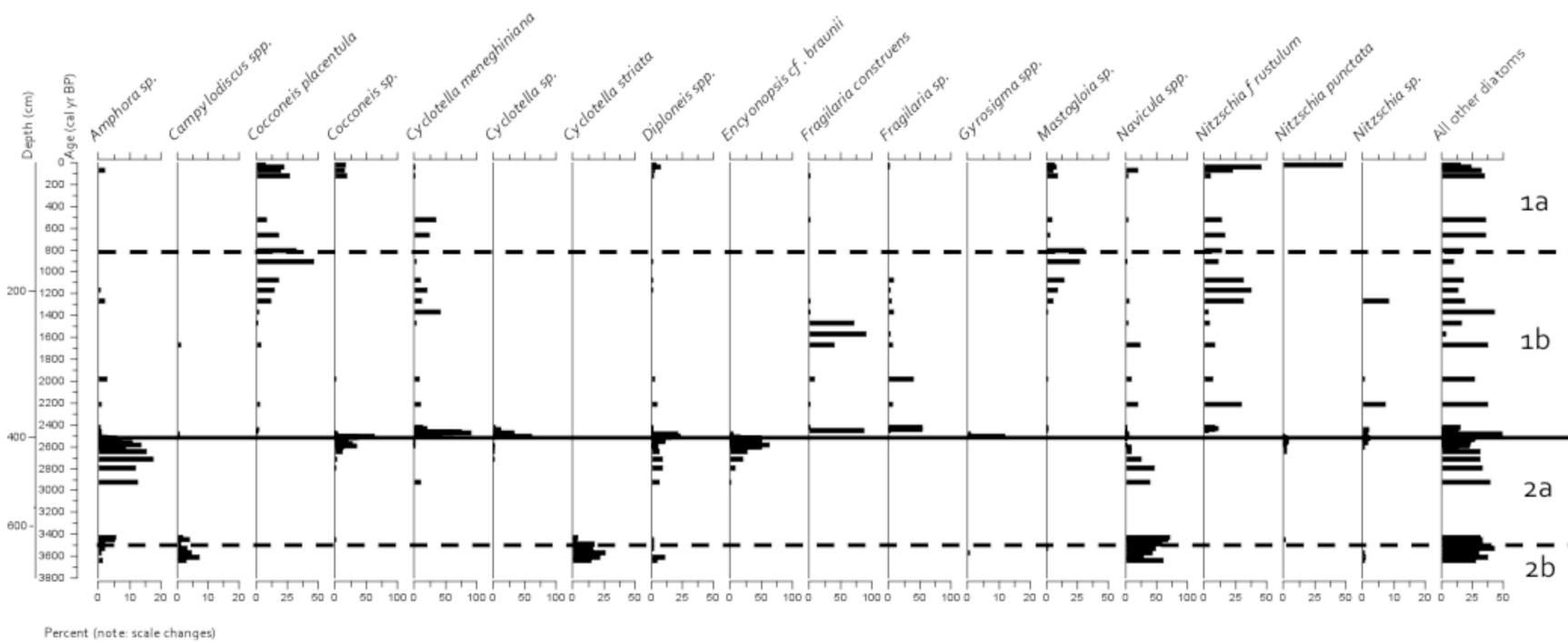


Figure 5.5: Percentages for selected diatom taxa in the Laguna Saladilla sediment profile, plotted by age in calibrated radiocarbon years. A total of 105 taxa were identified in the samples. The “All Other Diatoms” category includes a large number of types found in low percentages (below 10% in all samples).

5.5.4 Other Geochemical Analyses

Loss-on-ignition was measured at 78 levels throughout the sediment core (Figure 5.6). Mean percent organic matter content (OM) values were 22.9%, although this value is somewhat skewed by two sections of the profile with highly organic sediment at 2427–1980 and 168–68 cal yr BP. OM percentages fluctuate slightly from ca. 3500–2500 cal yr BP, during the same period when pollen percentages are more variable. At the zone 2a/1b boundary (ca. 2427 cal yr BP), organic content increases sharply and bulk density values decrease by ca. 0.3 g/cm³.

Manganese fragments were present from the bottom of the core to ca. 381 cal yr BP. However, they were found in low concentrations (average ca. 493 mm²/cm³) from the base of the core until ca. 2520 cal yr BP. A very large peak in manganese fragment area is found at 2499 cal yr BP, with a value more than nine times the average (ca. 4530 mm²/cm³). After ca. 2499 cal yr BP, average manganese fragment concentrations decrease (ca. 101 mm²/cm³).

5.6 Discussion

5.6.1 Marine phase (Zone 3; 8031–5550 cal yr BP)

Zone 3 is characterized by large quantities of *Rhizophora* pollen, poor diatom preservation, slow sediment accumulation rates, and moderate concentrations of manganese. A number of marine shell fragments (for example, *Corbula* cf. *contracta* and *Corbula aequivalvis*; Appendix V) were also identified during this period, which we interpret as a marine phase.

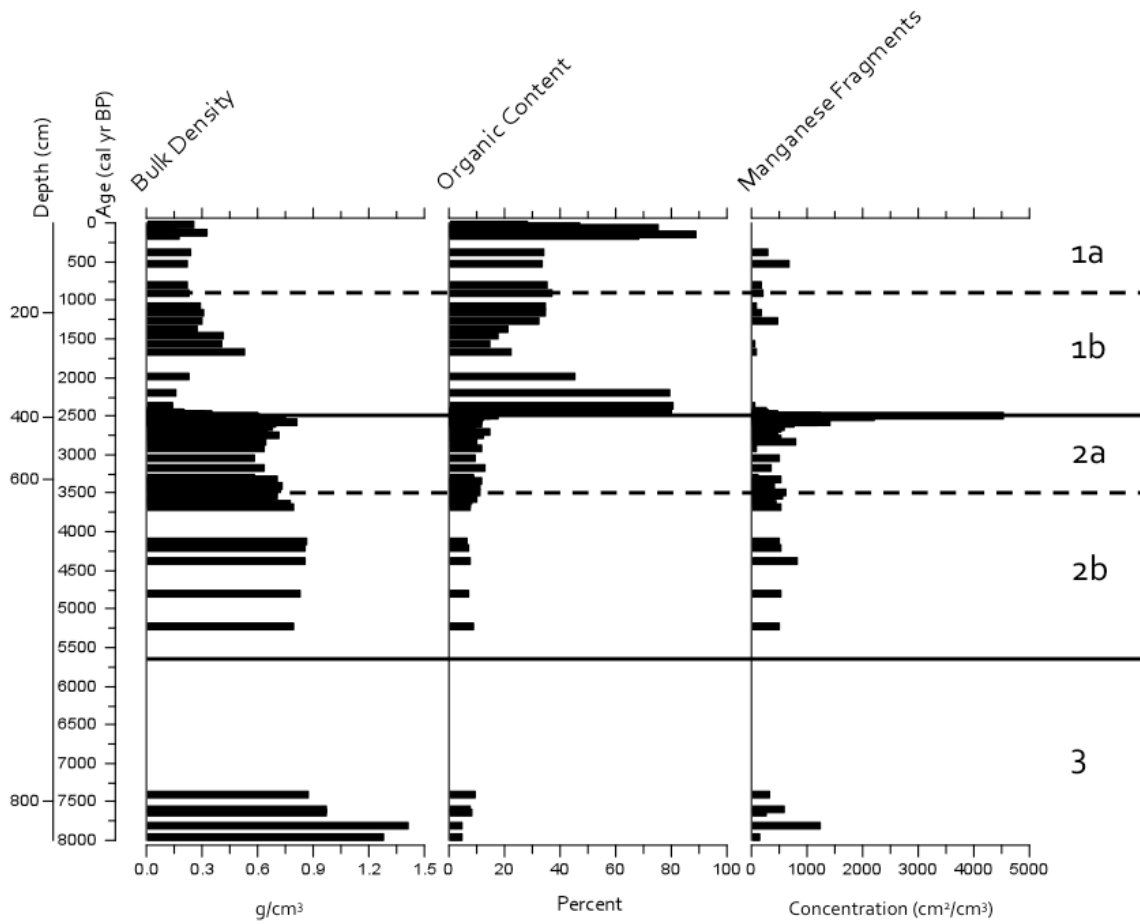


Figure 5.6: Bulk density, organic content, and manganese concentrations in the Saladilla profile, plotted by age in calibrated radiocarbon years. Percent organic matter is on a dry mass basis.

Manganese deposition could have occurred through runoff from mineral-laden sediment, aerobic remineralization of sediment organic matter, or suboxic diagenesis. Manganese is also found in marine sediment cores (Ehrlich, 1963; Bender et al. 1966; Zhang et al. 2008). However, given that the Lake Miragoane record reflects wetter conditions at this time, we assume that manganese in Laguna Saladilla reflects reduced conditions and the formation of seasonal–annual anoxia in the lower water column that commonly develop in deep water (Schaller et al. 1997; Brown et al. 2000). The lake today is relatively shallow (Table 5.2) and the water chemistry data suggest that it is chemically well mixed and does not show any evidence of stratification or seasonal turnover. However, if the lake were deeper, a steeper thermocline would exist from the warmer water at the surface to the colder water at the bottom.

Marine conditions reflected by the shells found in the sediment core could have been the result of RSL rise in the early Holocene (Bard et al. 1990). The shells do not show significant breakage or loss of periostracum or luster that could indicate deposition by storms or hurricanes. However, RSL was lower in the early Holocene than it is today (Bard et al. 1990; Peros et al. 2007a, 2007b), so it more likely that changes in position of either the Río Chacuey or Río Masacre could have created an outlet to the coast from Laguna Saladilla. This could also explain why sediment accumulation rates during this time appear to be low, as the lake could have been an open system. Peros et al. (1997a) found increases in salinity in Laguna de la Leche, Cuba at later periods in the Holocene that they attributed to RSL rise coupled with storm surges. While it is possible that changes in salinity around Laguna Saladilla were augmented by storm surges, increases in water level would have had to result from the lower Río Chacuey to the east because

the lake is behind a ca. 38 m limestone ridge that increases in height towards the northwest.

Changes in the osmotic pressure and position of the phreatic zone of the underlying aquifer would have also resulted from changes in RSL; however, pollen and shells that reflect marine conditions could not have been deposited in the lake sediments via subsurface flow.

The presence of *Rhizophora* pollen during zone 3 undoubtedly reflects the prevalence of red mangroves in the region. Whether or not they were growing at Laguna Saladilla is unclear. That no other mangrove swamp pollen types, such as *Avicennia germinans*, *Conocarpus erectus*, or *Acrostichum aureum* (Peros 2007b), were found at the same levels may indicate that mangroves were not growing at the site, but nearby, with *Rhizophora* pollen grains dispersed by wind.

Pollen and charcoal could not be closely sampled from the base of the core to 5235 cal yr BP, which prevented high-resolution vegetation analyses. Archeological evidence shows that humans inhabited the island of Hispaniola as early as ca. 6373 cal yr BP (Moore 1991), but pollen is not preserved well enough in Laguna Saladilla to be able to determine whether any anthropogenic activities took place near the site around that time.

5.6.2 Marine to Brackish phase (Zone 2; 5550–2500 cal yr BP)

Increasing *Pinus* percentages during this period most likely reflect increases in pine forest in the Cordillera Central, where *Pinus occidentalis* is common above 2000 m elevation (Speer et al. 2004). Higuera-Gundy et al. (1999) attributed increases in *Pinus*

pollen in Lake Miragoane to increasing fire activity from ca. 6521–3108 cal yr BP.

Increased pine pollen at Saladilla and Miragoane also matched evidence of increased fire at Laguna Tortuguero in Puerto Rico (Chapter 4), and are part of a trend that appears linked to increasing winter dry season insolation ca. 5000 cal yr BP. Microscopic charcoal concentrations at Laguna Saladilla increase steadily through zone 2, suggesting increases in fire frequency or intensity.

Hodell et al. (1991) showed that changes in insolation ca. 5000 cal yr BP led to changes in the intensity of the annual cycle that resulted in higher summer precipitation in southwestern Hispaniola. Enhanced seasonality could have led to higher lake levels in addition to increased burning during the dry season. However, the saline conditions of the lake also indicate that indirect changes in RSL played a significant role in raising lake levels.

Progressive increases in precipitation and runoff during zone 2 led to a shift to less saline (brackish) conditions. *Rhizophora* is still present, but less prevalent. Manganese concentrations reveal the lake was deep enough to generate seasonal or annual anoxia.

Sediment accumulation rates abruptly increase ca. 3680 cal yr BP, coincident with an increase in $\delta^{18}\text{O}$ at Lake Miragoane that Hodell et al. (1991) interpreted to signal higher evaporation/precipitation ratios and overall drier conditions. A rapid increase in sedimentation rate could have resulted from the lake becoming a closed basin. Despite increased salt water intrusion (via the aquifer or surface canals) brought about by gradually rising RSL compared to the early Holocene, drier conditions would have resulted in increased evaporation and reduced discharge from the rivers surrounding the

lake. No shells of marine taxa are found after ca. 3680 cal yr BP due to the lake becoming hydrologically isolated from the sea.

The presence of tropical benthic diatom types, such as *Amphora* spp. and *Cyclotella striata* (not shown), reveal that the lake was still relatively deep. Other taxa found at that level, such as *Diploneis* spp. and *Navicula* spp. have been found in both brackish and freshwater conditions. However, a small number of species from each genus in zone 2 were identified to be marine/brackish species (*Diploneis bombus* and *Navicula yarrensis*), which also suggests that the lake was brackish. Similarly, dinoflagellates could be indicative of freshwater or saline conditions, although most dinoflagellates are marine species.

Pollen and loss-on-ignition data show rapid changes between ca. 3500–2500 cal yr BP. Rapidly changing pollen percentages could indicate oscillations in lake levels that eroded nearshore sediments and moved them to the core site. However, diatom, charcoal, and dinoflagellate data generally do not show the same fluctuations and indicate a more gradual change in conditions. The erosion of nearshore sediments laden with manganese nodules could also explain the large peak in manganese fragments at the zone 2a/1a boundary ca. 2499 cal yr BP.

5.6.3 Freshwater phase (Zone 1; 2500 cal yr BP to present)

We interpret the large peak in *Cyclotella meneghiniana* to signal the transition to drier conditions, based on the work of Mitrovic et al. (2010) who found that, under laboratory conditions, *Cyclotella meneghiniana* grew in a linear fashion with temperature, where maximum growth occurs in water temperatures of ca. 25 °C, but

decreases above 28 °C. The *Cyclotella meneghiniana* peak is followed by a large increase in shallow freshwater species, such as *Fragilaria construens* (Watts and Bradbury 1982). Manganese concentrations drop after ca. 2499 cal yr BP, reflecting lower lake levels, and marine diatom taxa disappear as the lake becomes fresher. This may be due to periodic inputs of fresh water from the Río Masacre that drains from the Cordillera Central (Chapter 3). Sediment accumulation rates also decrease, perhaps in response to less frequent surface runoff during drier conditions.

Consecutive peaks in *Fragilaria construens* and *Fragilaria* spp. were observed following peaks in charcoal, particularly at ca. 2454 and ca. 1569 cal yr BP. These peaks in charcoal were followed by increases in Amaranthaceae pollen, and seem to indicate burning within the basin that washed charcoal into the lake. Changes in *Fragilaria* percentages appear to be in response to the disturbance, possibly due to temporary changes in lake pH or water clarity. Gradual changes in *Fragilaria* are observable before or after each peak in charcoal, which suggests that the taxon is not as sensitive to periods of drying prior to burning. Metcalfe (1995) found increases in *Fragilaria*, particularly *Fragilaria pinnata*, in the Zacapu Basin of Mexico that she attributed to more open water conditions (because it was found with planktonic species), although she noted that it was also found above volcanic ash layers in the sediments, possibly indicating that species were responding to fluxes in silica. It appears that *Fragilaria* spp. in Laguna Saladilla are not changing in response to open water or increases in silica, but instead flourishing during periods of disturbance.

Percentages of *Pinus* and *Rhizophora* both decrease in zone 1b, as Amaranthaceae and other herbaceous pollen types come to dominate under drier conditions. The high

Amaranthaceae percentages likely reflect higher populations of weedy amaranths on lakeshores, and possibly also halophytes of the former Chenopodiaceae family growing in nearby saline or alkaline savannas (Costa and Davy 1992). At ca. 800 cal yr BP, percentages of Amaranthaceae decrease and percentages of *Pinus* increase slightly. These shifts may signal human impacts in the region. The last ca. 800 years are marked by increases in the diatoms *Sellaphora* spp., *Rhopalodia*, and *Cocconeis* spp., all taxa that are present in modern surface sediments, particularly in dredge samples D1–D5, collected from sites where the lake water showed slightly higher alkalinity. A large peak in charcoal at ca. 44 cal yr BP, and a peak in grass pollen, may indicate land clearance and burning associated with expanding human settlement in the 20th century.

5.7 Conclusion

Stratigraphic analyses of lacustrine sediments provide powerful tools for reconstructing past environments. The records that result from these analyses are key to understanding present-day climate mechanisms and how the natural environment may responds to anthropogenic climate change in the future.

Laguna Saladilla has a complex hydrologic history that has been significantly impacted by changes in RSL, insolation, and the fluvial dynamics of the Río Masacre. Due to the aridity of the site relative to other regions on the island, humans are not expected to have had a significant impact on our record. Changes in pollen, diatoms, charcoal, and sediment geochemistry appear to reflect naturally driven changes in environment until possibly the last ca. 800 years.

At the base of the Laguna Saladilla record, we interpret high percentages of *Rhizophora* (red mangrove) pollen to indicate a marine environment. The presence of microscopic charcoal is observed at ca. 5200 cal yr BP, when increases in charcoal at other sites in the Caribbean region suggest increased climate-driven burning.

Diatoms are not well preserved in the record until ca. 3639 cal yr BP, around the time of a rapid increase in sediment accumulation. Diatom data suggest a shift from marine to brackish conditions, resulting from increased precipitation.

Laguna Saladilla was freshwater by ca. 2500 cal yr BP. Peaks in charcoal coincide with increases in Amaranthaceae pollen that indicate a drier climate. As a result of the drier climate, the lake also became shallower over time.

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CHAPTER 6

CONCLUSIONS

In Chapter 1 of this dissertation, I listed the following main objectives for my research: (1) reconstruct how and when Laguna Saladilla changed from an estuarine water body to the freshwater lake that it is today; (2) examine evidence for climate and environmental change during the lake's freshwater period by documenting pollen and diatom assemblages, microscopic charcoal concentrations, and the organic content of the sediments at close intervals; and (3) compare my results to other Caribbean records of Holocene environmental change to reveal regional patterns.

Chapter 3 used GPR analysis to examine whether any evidence of tectonic alterations of the lake could be found. I was able to image to a depth of ca. 3.1 m, however, the depth resolution of my analyses was limited to the upper ca. 30 cm of the sediments in the basin. I used the GPR results to delineate the position of three paleodeltas within the lake. These deltas were most likely deposited by the Río Masacre. Other paleodeltas may exist deeper in the sediments, below the depth resolution of the GPR. These results show that the sediment balance within Laguna Saladilla has been variable over time, depending on when the Río Masacre (and possibly the Río Chacuey) flowed into the lake and deposited sediment.

Coupling these GPR results with radiocarbon dates and other proxy data suggests that changes in the position of the rivers could partly explain why Laguna Saladilla became fresher, particularly during the last ca. 2500 years, when pollen and diatom data show that the climate became drier. Combining results of charcoal analyses with data

from Lake Miragoane in Haiti (Higuera-Gundy et al. 1999) and Laguna Tortuguero in Puerto Rico (Burney et al. 1994) led to the interpretation that changes in winter insolation had a significant impact on burning within the Caribbean region (Chapter 4). Pollen and diatom data agree with those of Higuera-Gundy et al. (1999), who showed that changes in spring insolation values may have resulted in wetter conditions during other periods in the year. Intensified seasonality during the mid-Holocene could explain why Laguna Saladilla became brackish as increased precipitation began to mix with the more saline waters of the lake. However, for the lake to progress from brackish to freshwater, the basin would have needed to lose its surface connection to the Atlantic Ocean, and rates of evaporation could not have significantly exceeded precipitation.

Before Laguna Saladilla became brackish, the water was saline from the inception of the lake until ca. 5550 cal yrs BP. The GPR data do not clarify whether the lake was open to the ocean or instead subjected to periodic storm surges that washed in saltier water. RSL research by Bard (1990) and Peros et al. (2007a, 2007b) indicates that sea levels were lower in the early Holocene, so it seems unlikely that the shoreline reached the lake. However, the Río Chacuey to the northeast of the lake could have been diverted to the lake. The presence of the marine shells in the lake sediments also indicates that the lake was open to seawater at times in the past.

Figure 1.3 in the introduction to this dissertation illustrated two scenarios under which Laguna Saladilla could have become saline. Based on the literature and evidence discussed in Chapters 2, 3, and 5, a change in the course of at least one of the surrounding rivers (scenario 1.3c) appears to offer the best explanation of why the lake could have been saline early in its history. Changes in sea level or tectonics also could have altered

the position of the aquifer, resulting in salt water intrusion into the lake (scenario 1.3b), particularly from ca. 5550–3500 cal yrs BP, when proxy indicators show the lake was brackish. The GPR analyses did not reveal evidence of relict shorelines or paleochannels.

Based on the three objectives discussed in Chapter 1 and above, eight research questions were posed that can now be answered.

Q1: How has vegetation near the lake changed over the past ca. 8000 years?

Pollen samples from 7650 cal yr BP show large amounts (42%) of mangrove (*Rhizophora*) pollen near the lake. No evidence of other mangrove swamp pollen types, such as *Avicennia germinans*, *Conocarpus erectus*, or *Acrostichum aureum*, were found in the sediment profile, which may indicate that mangroves were not growing at the site, but nearby. Vegetation around Laguna Saladilla was predominantly *Typha* from ca. 3500–2500 cal yr BP. From ca. 2500 cal yr BP to present, mangroves declined and non-arboreal taxa, particularly Amaranthaceae and Poaceae, became more abundant. A small increase (<4%) in pine (*Pinus*) was observed ca. 800 cal yr BP.

Q2: What trends are apparent in fire occurrence based on sedimentary charcoal?

Comparing the Laguna Saladilla charcoal record to Lake Miragoane and Laguna Tortuguero suggests that fire occurrence within the region increased beginning ca. 5000 cal yr BP. In Laguna Saladilla, charcoal influx (Chapter 4) and concentrations (Chapter 5) rose from ca. 3500–2400 cal yr BP, and then declined and stayed low for ca. 700 years. This late Holocene interval of low charcoal concentration and influx was followed

by charcoal peaks at ca. 1670 and 1467 cal yr BP. Values subsequently declined, and then peaked again near the top of the record, at 44 cal yr BP.

Q3: Does the Saladilla sediment profile preserve evidence of human influences on the environment (e.g. agricultural pollen, pollen indicators of clearing of the dry forest vegetation, charcoal evidence of increased burning)?

I found no pollen evidence of agriculture in the Laguna Saladilla profile. However, a peak in charcoal ca. 44 cal yr BP (1906 CE) coincides with the historic expansion of regional populations. Grass pollen also shows a spike at the top of the profile that may indicate historic agricultural disturbance. Pollen was not well preserved in sediments deposited from 44 cal yr BP to present, precluding the identification of evidence of recent shifts in vegetation. Other peaks in charcoal predate evidence of maize on Hispaniola, although the fires they signal may have been ignited by humans to clear land for other crops, or for other activities, including the hunting of small mammals and iguana. Although humans were on the island of Hispaniola by ca. 6373 cal yr BP (Chapter 4), the Laguna Saladilla record contains no conclusive evidence of their presence (Chapter 5).

Q4: How does the microscopic charcoal record compare with records from Haiti and Puerto Rico, and what do these patterns suggest about the impact of changes in insolation on regional fire occurrence?

The microscopic charcoal record at Laguna Saladilla compares fairly well with records from Lake Miragoane and Laguna Tortuguero. All records show generally rising

charcoal influx during the later Holocene. A comparison of charcoal influx to winter insolation shows these increases occurred at the same time insolation values were increasing. However, insolation values continued to increase when Laguna Tortuguero showed a decrease in influx values. This decline in charcoal influx paradoxically occurred at around the same time archeological evidence first documents human presence on Puerto Rico (Chapter 4). Lake Miragoane and Laguna Tortuguero both show an increase in charcoal influx at ca. 5000 cal yr BP that seems to suggest a regional driver (such as drier dry seasons), but the sites do not record synchronous declines in charcoal influx. This pattern may be due to humans entering the sites at different times and altering the vegetation or fire frequencies/intensity in different ways. Unfortunately, due to a layer of shells and a change in the sedimentation rate in the Laguna Saladilla profile, charcoal samples were not measured at intervals close enough to ca. 5000 cal yr BP to be able to determine whether Laguna Saladilla shows the same increase in charcoal influx as the other sites. However, values do appear to increase in the later Holocene until ca. 2427 cal yr BP. After 2500 cal yr BP, summer rain decreases and the vegetation around Laguna Saladilla changes in response, changing fuel loads and burning patterns. This interpretation of a climatic influence on fuel loads was also used by Higuera-Gundy et al. (1999) to explain changes in charcoal influx at Lake Miragoane in the late Holocene.

Q5: What is the timing and nature of the change from brackish to freshwater conditions at Laguna Saladilla?

Shells and limited pollen data suggest the lake was marine from ca. 8000–5550 cal yr BP. Pollen and diatoms enumerated at close intervals above the marine section of

the core show that the lake became more brackish from ca. 5550–2500 cal yr BP. No paleoshorelines were found at the lake. However, diatom data suggest the lake was deeper from ca. 3500–2500 cal yr BP. Diatoms also indicated a freshening of the lake and decreasing lake levels after ca. 2500 cal yr BP (Chapter 5).

Q6: Does GPR show evidence of paleodeltas within the lake that could indicate shifts in the positions of surrounding rivers?

Sand deltas were found in three locations where the Río Masacre presently flows into the lake or did previously (Chapter 3). Sand aprons interbedded with hemipelagic muds were not found around the periphery of the lake (Figure 1.4). However, attempts to locate such sand aprons were complicated by extensive vegetation mats that prevented the mapping of the lake with GPR. Changes in radar energy velocity at the edges of sand fans (deltas) indicated that hemipelagic muds may have been interbedded at their far edges, where sediment deposition patterns would be affected by seasonal variations in rates of runoff and river discharge. Changes in radar energy velocity were measured by changes in the coefficient of reflectivity of the underlying sediments. Layers of sand were indicated by lower reflectivity coefficients.

Q7: How did diatom communities change over time at Laguna Saladilla?

Diatoms were not well preserved in the lowermost section of the Laguna Saladilla core. The diatom record begins at ca. 3639 cal yr BP and shows a number of marine and oligohaline diatom types, such as *Amphora* sp., *Diploneis* spp., and *Encyonopsis* cf. *braunii*. Diatom communities changed ca. 2500 cal yr BP to include more freshwater

species, such as *Nitzschia frustulum* and *Cocconeis placentula*. The diatoms *Cyclotella meneghiniana* and *Fragilaria construens* were identified after ca. 2500 cal yr BP, particularly at ca. 2454, 1569, and 1467 cal yr BP, when the lake became fresher.

Q8: How do modern-day diatom communities vary within Laguna Saladilla?

Metcalf (1988) recommended that multiple modern diatom samples be taken from across a lake to inform paleoenvironmental analyses. Water chemistry results (Table 5.2) show that Laguna Saladilla is well mixed, but GPR analyses showed variations in bathymetry and surface sediment type across the lake that could affect diatom communities. Over the last century, the Río Masacre has moved from the southeast to southwest side of the lake (Chapter 2), which has altered the underlying sediments from east to west across the lake. Analyses of modern surface diatoms revealed changes in diatom community composition across the lake (Figure 5.4) that may relate to limnological conditions. For example, species of *Navicula* spp. and *Nitzschia* spp. are mainly found toward the west side of the lake, where the lake is deeper and the bottom is not as sandy.

Present diatom communities are generally consistent with diatom assemblages in the last ca. 200 years of the Saladilla record. Modern diatom assemblages could have been affected by human activities around the lake. However, changes in the position of the Río Masacre across the lake could also alter the diatom assemblages.

Lacustrine sediment records provide powerful tools for reconstructing past environments, necessary for understanding present-day climate mechanisms and how the

natural environment many respond to anthropogenic climate change in the future. This doctoral dissertation research investigated the impact of tectonic and climatic processes on the character of Holocene lacustrine sediments in Hispaniola using a combination of GPR and environmental proxy data from an 8.51 m-long sediment core recovered from Laguna Saladilla, Dominican Republic. Using GPR in combination with pollen, diatom, and charcoal analyses revealed the lake has undergone a number of transformations. Changes in climate were reflected in pollen, diatoms, and other paleoenvironmental proxies from the sediment core (Chapter 5). Changes in climate were also found by comparing changes in microscopic charcoal influx to data from other Caribbean sites (Chapter 4). A clear change in regional charcoal influx is indicated ca. 5000 cal yr BP that was most likely due to changes in climate. Later changes in vegetation and diatom communities suggest that humans could have been present from ca. 800 cal yr BP, but evidence is not definitive.

Interpreting the climate record is also complicated by the changing position of the Río Masacre. GPR was used to map paleodeltas along the southern shoreline. Most recently, the Río Masacre has altered the sediment budget, and therefore limnology, of the lake.

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APPENDICES

APPENDIX I: POLLEN AND MICROSCOPIC CHARCOAL

PROCESSING PROCEDURE

The following procedure, known as the JR2-HCl procedure in the Laboratory of Paleoenvironmental Research, was used to process sediment samples from Laguna Saladilla for pollen and microscopic charcoal analysis. Samples were processed in 15 ml Nalgene® polypropylene centrifuge tubes. The centrifuge used was an IEC model CL bench top centrifuge with a 6 x 15 ml swinging bucket rotor. All centrifugations were carried out at the highest speed.

1. Add 1 *Lycopodium* tablet to each centrifuge tube (n = 13,911).
2. Add 10 ml 10% HCl, and let reaction proceed; slowly fill tubes until there is 10 ml in each tube. Stir well, and place in hot water bath for 3 minutes. Remove from bath, centrifuge for 2 minutes, and decant.
3. Add hot distilled water, stir, centrifuge for 2 minutes, and decant. Repeat for a total of two washes.
4. Add 10 ml 5% KOH, stir, and place in boiling bath for 10 minutes, stirring after 5 minutes. Remove from bath. Centrifuge 2 minutes and decant.
6. Wash 4 times with hot distilled water. Centrifuge for 2 minutes each time.
7. Fill tubes about 1/2 way with distilled water, stir, and pour through 125 µm mesh screen, collecting liquid in a labeled beaker underneath. Use distilled water to wash the screen, and to wash out any material remaining in the centrifuge tube.

8. Centrifuge material from beaker by repeatedly pouring beaker contents into correct tube, centrifuging for 2 minutes, and decanting.
9. Add 10 ml of 49% HF and stir. Place tubes in bath for 20 minutes, stirring after 10 minutes. Centrifuge 2 minutes and decant.
10. Add 10 ml 10% HCl. Stir well, and place in hot water bath for 3 minutes. Remove from bath, centrifuge for 2 minutes, and decant.
11. Add 10 ml hot Alconox® solution, made by dissolving 4.9 cm³ dry commercial Alconox® powder in 1000 ml distilled water. Stir well and let sit for 5 minutes. Then centrifuge and decant.
12. Add more than 10 ml hot distilled water to each tube. Stir, centrifuge for 2 minutes, and decant. Assuming that no samples need retreatment with HF, continue washing with hot distilled water as above for a total of 3 water washes.
13. Add 10 ml of glacial acetic acid, stir, centrifuge for 2 minutes, and decant.
14. Make acetolysis mixture by mixing together 9 parts acetic anhydride and 1 part concentrated sulfuric acid. Add about 8 ml to each tube and stir. Remove stirring sticks and place in boiling bath for 5 minutes. Stir after 2.5 minutes. Centrifuge for 2 minutes and decant.
15. Add 10 ml glacial acetic acid, stir, centrifuge for 2 minutes and decant.
16. Wash with hot distilled water, centrifuge and decant.
17. Add 10 ml 5% KOH, stir, remove sticks, and heat in vigorously boiling bath for 5 minutes. Stir after 2.5 minutes. After 5 minutes, centrifuge for 2 minutes and decant.
18. Add 10 ml hot distilled water, centrifuge for 2 minutes, and decant for a total of 3 washes.

19. After decanting last water wash, use the vortex genie for 20 seconds to mix sediment in tube.
20. Add one drop safranin stain to each tube. Use vortex genie for 10 seconds. Add distilled water to make 10 ml. Stir, centrifuge for 2 minutes, and decant.
21. Add a few ml TBA, use vortex genie for 20 seconds. Fill to 10 ml with TBA, stir, centrifuge for 2 minutes, and decant.
22. Add 10 ml TBA, stir, centrifuge 2 minutes and decant.
23. Vibrate samples using the vortex genie to mix the small amount of TBA left in the tubes with the microfossils. Centrifuge down vials.
24. Add several drops of 2000 cs silicone oil to each vial. Stir with a clean toothpick.
25. Place uncorked samples in the dust free cabinet to let the TBA evaporate. Stir again after one hour, adding more silicone oil if necessary.
26. Check samples the following day; if there is no alcohol smell, cap the samples. If the alcohol smell persists, give them more time to evaporate.

APPENDIX II: DESCRIPTIONS OF DIATOM TAXA IDENTIFIED IN THE
SEDIMENTS OF LAGUNA SALADILLA

This alphabetical list of diatom taxa encountered in the Saladilla sediment samples builds upon prior work by Kurt Haberyan (Haberyan, unpublished data). Descriptions are based on the sources referenced and my own observations. Underlined references in parentheses indicate source used to identify types.

Achnanthes exigua Grunow 1880 (Foged 1984) is a type species (lectotype) of the genus *Achnanthes*. Type is a cosmopolitan oligohalobe, preferring more alkaline conditions. Synonym(s) include *Achnanthes exigua* var. *heterovalva* Krasske 1923.

Achnanthes inflata (Kützing) Grunow 1880 (Foged 1984) is a type species (lectotype) of the genus *Achnanthes*. Type is a cosmopolitan oligohalobe, preferring more alkaline conditions. Synonym(s) include *Stauroneis inflata* Kützing 1844 and *Achnanthidium inflatum* (Kützing) Hutton 1883.

Actinocyclus spp. Ehrenberg 1837 (Navarro 1982) is described in Guiry and Guiry (2010) as "Cells barrel-shaped, probably mainly epiphytic on seaweeds but often encountered in nearshore plankton. Plastids numerous, discoid. Valves circular (rarely elliptical or triangular) with radial sectoring; valve face planar or concentrically waved. Surface corrugate with tiny external pores (too small to be seen by SEM) and a single marginal 'pseudonodulus'; sometimes with a distinct rim at the junction of face and mantle. Mantle often distinct with large, simple rimoportula openings. Some species with stepped mantles. Valve framework bullulate. Internally, areolae seen to

be arranged in variously organised fascicles with domed closing vela and conspicuously expanded rimoportulae usually angled to the valve rim. Psedonodulus in a clear area. Copulae open. Valvocopula massive, fimbriate, underlapping a shelf projecting from the valve rim. Other copulae (2 or more) smaller. There are 378 species (and infraspecific) names in the Guiry and Guiry (2010) database at present, of which 30 have been flagged as currently accepted taxonomically." Type is rare and only found in warm waters in the sublittoral–littoral zone.

Actinoptychus splendens (Shadbolt) Ralfs ex Pritchard 1861 (Navarro 1982) is a type species (lectotype) of the genus *Actinoptychus* described in Guiry and Guiry (2010) as "Cells discoid, solitary. Very common in neritic collections, probably mainly a component of the assemblage lying loose or attached to other algae on coastal sediments. Plastids several, irregular plates. Many fossil species. Valves sectored (6 in the common *A. senarius* [= *A. undulatus*] but up to 20 in others) so that alternate sectors are elevated or depressed. Central area plain or granulate. Areolae in radiate striae, opening by simple pores to the outside but over much of the surface the silica is corrugated or pitted, delimiting groups of areolae. Internally, uneroded areolae are closed by domed vela ... The valve mantle often has spines, wart-like outgrowths, siliceous ridges, etc., and the edge is produced into a smooth flange. Copulae plain, split and wide." *Actinoptychus splendens* is found in warm waters in the sublittoral zone. Synonyms include *Actinosphaenia splendens* Shadbolt 1854, *Actinoptychus quatuordenarius* Ehrenberg 1854, and *Actinoptychus halionyx* Grunow 1870.

Amphora spp. Ehrenberg ex Kützing (Hein et al. 2008) is a cosmopolitan genus composed of 1105 species (and infraspecific) names found in the Guiry and Guiry

(2010) database at present, of which 239 have been flagged as currently accepted taxonomically. Valves are pennate (typically biraphed).

Anomoeoneis sculpta (Ehrenberg) Cleve 1895 (Metzeltin and Lange-Bertalot 2007) is a pennate type preferring halophilic to mesohaline and alkaline conditions. The species has been identified by a number of researchers in Europe and, more recently, in Cuba by Foged 1984. Synonyms include *Navicula sculpta* Ehrenberg 1854 and *Navicula tumens* W. Smith 1853.

Anomoeoneis spp. (Metzeltin and Lange-Bertalot 2007) is genus first described by Pfitzer 1981. Based on data from the Guiry and Guiry (2010) database, the genus comprises 132 species (and infraspecific types) at present, of which 10 have been categorized as currently accepted taxonomically.

Anomoeoneis sphaerophora (Kutzing) Pfitz (Foged 1984) is a pennate type preferring halophilic, alkaline conditions. The species is cosmopolitan and has been identified by a number of researchers in Europe and the Americas. No other synonyms exist, according to Guiry and Guiry (2010).

Aulacodiscus grevilleanus (Greville 1968) is a rare type described by Greville (1968, p. 109) as "Very large. Disc with numerous (about 10) submarginal processes, and circular umbilicus; compartments between the furrows covered with diagonal, intersecting rows of little cushion-like warts, rough with elongated and coral-like granules." The type is not found in the Guiry and Guiry (2010) database. However, Greville identifies it as preferring littoral habitats. Other examples have been found in Seville, Spain, suggesting that the type also prefers warmer waters. Only two examples of this type were identified from Laguna Saladilla slides.

Aulacoseira distans var. *lirata* (Ehrenberg) Simonsen 1979 (Metzeltin and Lange-Bertalot 2007). Records found from both Northern Europe and the North America. Species is cosmopolitan preferring freshwater where cells are planktonic. No other synonyms exists, although it should be noted that, according to Guiry and Guiry (2010), Simonsen (1979) resurrected the long disused name *Aulacosira* (*sic*) and the common species *distans* from the now disused genus *Melosira*.

Aulacoseira granulata (Ehrenberg) Simonsen 1979 (Metzeltin and Lange-Bertalot 2007). As with *Aulacoseira distans* var. *lirata*, the cosmopolitan planktonic species is found in freshwater. Synonyms include *Gaillonella granulata* Ehrenberg 1843, *Melosira granulata* (Ehrenberg) Ralfs 1861, *Melosira punctata* var. *granulata* (Ehrenberg) Cleve & Möller 1879, *Lysigonium granulatum* (Ehrenberg) Kuntze 1891, *Orthosira granulata* (Ehrenberg) Schonfeldt 1907, and *Melosira polymorpha* subsp. *granulata* (Ehrenberg) H. Bethge 1925.

Aulacoseira spp. Thwaites 1848 (Metzeltin and Lange-Bertalot 2007) is a cosmopolitan freshwater genus with a centric form. Guiry and Guiry (2010) list 79 species (and infraspecific), of which 40 have been flagged as currently accepted taxonomically.

Auliscus spp. Ehrenberg 1843 (Navarro 1982) is a somewhat rare centric type that prefers warm waters. It has been found in the sublittoral–littoral zone in the tropics. Guiry and Guiry (2010) list 251 species (and infraspecific) names, of which 5 have been flagged as currently accepted taxonomically.

Biddulphia regina W. Smith 1856 (Foged 1984) is a polyhalobe that has been found in the Americas and Europe (most notably Britain). Navarro (1997) lists the species as present in samples from the Caribbean Sea. No synonyms are listed.

Brachysira spp. Kützing, 1836 (Hein et al. 2008) is a pennate type that is described by Hein et al. (2008) as preferring sandy habitat. Guiry and Guiry (2010) list 109 species (and infraspecific) names in the database, of which 90 have been flagged as currently accepted taxonomically.

Caloneis formosa (Gregory) Cleve 1894 (Foged 1984) has been found in Europe and the Caribbean. Foged (1984) lists the species as "fairly common" in Cuba. The species is found in mesohaline habitats. *Caloneis formosa* is considered a synonym for *Caloneis westii* (W. Smith) Hendey.

Caloneis spp. P. Cleve 1894 (Foged 1984) is described in Guiry and Guiry (2010) as "Valves usually linear-lanceolate to elliptical, sometimes with capitate or rostrate poles and sometimes with undulate margins. Valve face flat or curving smoothly into relatively deep mantles. Axial and central areas variable in shape... *Caloneis* has been reported from fresh, brackish, and marine waters. Because the structure of *Caloneis* is so similar to that of *Pinnularia*, some researchers (e. g., Round and others, 1990) have included *Caloneis* within *Pinnularia*. Traditionally, the genera have been separated by the shape of their alveoli. The alveoli of *Caloneis* are usually thinner and denser than those of *Pinnularia*." 250 species (and infraspecific) names are listed in Guiry and Guiry (2010). Only 49 have been flagged as currently accepted taxonomically.

Campylodiscus hibernicus Ehrenberg 1845 (source unknown) is a freshwater type that has been found all over Europe, including the Canary Islands. Synonyms include *Campylodiscus noricus* var. *hibernica* (Ehrenberg) Grunow 1862 and *Campylodiscus noricus* var. *hibernicus* (Ehrenberg) Grunow 1862.

Campylodiscus daemelianus Grunow 1897 (Navarro 1982) is a rare type found in both the Caribbean and Pacific Islands. This type is found in sublittoral and littoral zones where there is warm water. No synonyms are listed in Guiry and Guiry (2010) or Navarro (1982).

Cocconeis distantula M.H.Giffen 1967 (Hein et al. 2008) has been identified in the Bahamas in habitats that include sand, rock, or stromatolites. No synonyms are listed in Guiry and Guiry (2010) or Hein et al. (2008).

Cocconeis discrepans A.W.F. Schmidt 1874 (Hein et al. 2008) has been found in marine environments where there is sand and/or *Halimeda* (macroalgae). Hein et al. (2008) describe it as an “infrequent” type. No synonyms are listed in Guiry and Guiry (2010) or Hein et al. (2008).

Cocconeis placentula var. *euglypta* (Ehrenberg) Grunow 1884 (Hein et al. 2008) is a cosmopolitan species. Hein et al. (2008) has identified the species in habitats such as plankton, stromatolites, rock, and amongst macroalgae. Synonyms include *Cocconeis euglypta* Ehrenberg 1854, *Cocconeis lineata* var. *euglypta* (Ehrenberg) Grunow 1880, *Cocconeis lineata* var. *euglypta* (Ehrenberg) Grunow 1880, *Cocconeis placentula* var. *euglypta* (Ehrenberg) Cleve 1895, and *Cocconeis placentula* cf. *euglypta* (Ehrenberg) Hustedt 1957.

Cocconeis scutellum var. *parva* (Grunow in Van Heurck) Cleve 1895 (Hein et al. 2008) is a cosmopolitan species. Hein et al. (2008) has identified the species in habitats such as plankton, sand, rock, hardground, and amongst macroalgae. No synonyms are listed in Guiry and Guiry (2010) or Hein et al. (2008).

Cocconeis spp. Ehrenberg 1837 (Hein et al. 2008) is a cosmopolitan genus of which Guiry and Guiry (2010) list 749 species (and infraspecific) names, of which 76 have been flagged as currently taxonomically accepted.

Cocconeis woodii Reyes 1970 (Navarro 1982) is a frequently found species that prefers cold water. Navarro (1982) has identified the species in sublittoral, littoral, and supralittoral zones. No synonyms are listed in Guiry and Guiry (2010) or Navarro (1982).

Coscinodiscus hauckii Grunow 1881 (Hein et al. 2008) is an infrequent type that has been identified in the Bahamas in environments that are rocky or have stromatolites. The name is considered a synonym for *Ehrenbergiulva hauckii* (Grunow).

Coscinodiscus radiatus Ehrenberg 1840 (Foged 1984) is a marine species (polyhalobe) that has a global distribution that includes Antarctica, Canary Islands, Romania and Cuba. The name is synonymous with *Coscinodiscus borealis* Ehrenberg 1862.

Coscinodiscus spp. Ehrenberg 1839 (Foged 1984) is a free floating, centric type found in marine conditions, typically in the phytoplankton. Guiry and Guiry (2010) list 1115 species (and infraspecific) names. 55 of those names have been flagged as taxonomically acceptable.

Cyclotella meneghiniana Kützing 1844 (Foged 1984) is a centric species that is listed in Foged (1984) as a “fairly common” alkaliphile. Guiry and Guiry (2010) list *Cyclotella meneghiniana* as a freshwater species, however Foged (1984) lists it as a halophile. Foged (1984) also found this species in Cuban sites that he classified as slightly brackish. No synonyms are listed in Guiry and Guiry (2010) or Foged (1982).

Cyclotella spp. (Kützing) Brébisson 1838 (Foged 1984) is a planktonic centric type that is found mainly in freshwater, although a few species do exist in shallow coastal waters where they may have evolved from species living in brackish conditions. Guiry and Guiry (2010) list 228 species (and infraspecific) names, 106 of which have been flagged as currently accepted taxonomy.

Cyclotella striata (Kützing) Grunow 1880 (Foged 1984) has been found in Europe, North America, Caribbean, and Pacific Islands. Foged (1984) describes the species as mesohalobe to polyhalobe. No synonyms are listed in Guiry and Guiry (2010) or Foged (1982). The name may be considered synonymous with *Coscinodiscus striatus* Kützing 1844.

Cyclotella stylorum Brightwell (Navarro 1982) is found throughout the year in sublittoral to supralittoral zones. It has been found in brackish-marine environments in Florida, USA and Australia and New Zealand. No synonyms are listed in Guiry and Guiry (2010) or Navarro (1982).

Cymbella spp. C. Agardh 1830 (Navarro 1982, Foged 1984, Metzeltin and Lange-Bertalot 2007) is a frequently occurring pennate type. It is found in both warm and cold waters and has a global distribution. Foged (1984) lists all examples found in Cuba as oligohalobes (preferring brackish conditions). Navarro (1982) only states that it is found in Florida in sublittoral conditions. Metzeltin and Lange-Bertalot (2007) do not specify the habitat of the species found in South America. Guiry and Guiry (2010) list 1354 species (and infraspecific) names, 220 of which have been flagged as taxonomically acceptable.

Denticula spp. Kützing 1844 (Navarro 1982) is found in both marine and freshwater.

Navarro (1982) rarely found examples of the genus in Florida. The species found by Navarro (1982) all shared a preference for warm waters and sublittoral to supralittoral conditions. Guiry and Guiry (2010) list 137 species (and infraspecific) names, of which 17 have been flagged as currently accepted taxonomically.

Diademsis spp. Kützing 1844 (Metzeltin and Lange-Bertalot 2007) is a pennate type for which Guiry and Guiry (2010) list 64 species (and infraspecific) names. 35 of these names have been flagged as taxonomically acceptable.

Diploneis bombus (Ehrenberg) Cleve 1894 (Navarro 1982) was identified by Navarro (1982) as a rare species in Florida. It is typically found in the littoral zone in warm waters. Synonyms include *Navicula abnormis* Castracane 1886, *Pinnularia bombus* Ehrenberg 1844, and *Navicula bombus* (Ehrenberg) Kützing 1849.

Diploneis crabro Ehrenberg 1844 (Hein et al. 2008) is found in algal mats in the Bahamas. It has also been found in Australia, Spain and Britain. The name is synonymous with *Navicula crabro* Kützing 1849.

Diploneis divergens (A. Schmidt) Cleve 1894 (Hein et al. 2008) was found in the Bahamas by Hein et al. (2008). They describe the species' habitats as including either stromatolites, sand, or algal mats. Synonyms include *Navicula divergens* A.Schmidt 1875 and *Navicula pfitzeriana* O'Meara 1876.

Diploneis interrupta var. *caffra* M.H.Giffen 1970 (Navarro 1982) was first discovered in North America by Navarro (1982). It appeared frequently in mangrove samples from Florida, occurring mostly in sublittoral and littoral samples. No synonyms are given by Navarro (1982) or Guiry and Guiry (2010).

Diploneis smithii (Brébisson) Cleve 1894 (Navarro 1982) is a cosmopolitan species principally found in warm, brackish waters. Navarro (1982) found it only in the supralittoral zone of Florida mangroves. Synonyms include *Navicula smithii* Brébisson 1856 and *Navicula elliptica* W. Smith 1853.

Diploneis spp. Ehrenberg ex Cleve 1894 (Navarro 1982, Hein et al. 2008) is found in both freshwater and marine conditions. Guiry and Guiry (2010) list 505 species (and infraspecific) names in the database at present, of which 61 have been flagged as currently accepted taxonomically.

Encyonema silesica (source and year unknown) (Haberyan p. comm.) has been found in freshwater in South Eastern Australia (Monash University Centre for Palynology and Palaeoecology 2010). This diatom type is not listed in Guiry and Guiry (2010) or any of the references available in the University of Tennessee Laboratory of Paleoenvironmental Research.

Encyonopsis braunii (Hustedt) Krammer (Metzeltin and Lange-Bertalot 2007) is found in South America. No further information is available. No synonyms were found in Guiry and Guiry (2010) or Metzeltin and Lange-Bertalot (2007).

Entomoneis alata (Ehrenberg) Ehrenberg 1845 (Guiry and Guiry (2010), Haberyan p. comm.) is found in Europe, Australia, and the Canary Islands. Synonyms include *Navicula alata* Ehrenberg 1840, *Amphiprora alata* (Ehrenberg) Kützing 1844, *Amphicampa alata* (Ehrenberg) Rabenhorst 1864, *Amphitropis alata* (Ehrenberg) Rabenhorst 1868, and *Entomoneis alata* (Ehrenberg) Reimer 1975.

Epithemia argus (Ehrenberg) Kützing 1844 (Guiry and Guiry 2010) is a freshwater species found in Europe, Asia, and Australia. Synonyms include *Eunotia ocellata*

Ehrenberg 1840, *Epithemia ocellata* (Ehrenberg) Kützing 1844, *Epithemia argus* var. *ocellata* (Ehrenberg) F. Fricke 1904, *Eunotia argus* Ehrenberg 1843, and *Cystopleura argus* (Ehrenberg) Kuntze 1891.

Eunotia astridae C.W. Fontell (source unknown) is found in the Northern hemisphere, as well as Brazil and Venezuela. No synonyms are listed in Guiry and Guiry (2010).

Eunotia spp. Ehrenberg 1837 (Metzeltin and Lange-Bertalot 2007) is a free floating type of pennate. Valves are asymmetrical. Vineyard (1979) states their habitat as freshwater. Guiry and Guiry (2010) list 1479 species (and infraspecific) names. 253 have been flagged as currently accepted taxonomically.

Eunotogramma laeve Grunow 1883 (Navarro 1982) is found in warm water in the sublittoral to littoral zone. No synonyms are listed in Navarro (1982) or Guiry and Guiry (2010).

Fragilaria brevistriata Grunow in van Heurck 1885 (source unknown) is a cosmopolitan species found in freshwater. No synonyms are listed in Guiry and Guiry (2010).

Fragilaria construens (Ehrenberg) Grunow 1862 (Vineyard 1979) is a freshwater species with a global distribution. The name *Fragilaria construens* is considered a synonym for *Staurosira construens* Ehrenberg 1843. Other synonyms include *Staurosira venter* var. *construens* (Ehrenberg) Cleve & Möller 1879, and *Nematoplata construens* (Ehrenberg) Kuntze 1898.

Fragilaria gaillonii (Ehrenberg) Lange-Bertalot (Navarro 1982) is found in warm to temperate waters in the sublittoral zone. Navarro (1982) lists the species as occurring rarely in his Florida mangrove study. No synonyms are listed in Guiry and Guiry (2010) or Navarro (1982).

Fragilaria pinnata Ehrenberg 1843 (source unknown) is listed in Guiry and Guiry (2010) as being found in freshwater environments in Europe, Asia, and Australia. No synonyms are listed.

Fragilaria spp. Lyngbye 1819 (Vineyard 1979) is found in freshwater to marine environments. According to Guiry and Guiry (2010) “The taxonomy of *Fragilaria* is disarray with some authorities splitting the genus into 6 genera, including *Fragilaria* (Williams and Round 1987) and others lumping species of *Synedra* with *Fragilaria* (Lange-Bertalot 1980). See Round and others (1990) or Krammer and Lange-Bertalot (1991) for descriptions of *Fragilaria sensu stricto* and *sensu lato*, respectively.” This uncertainty around the taxonomy is reflected in the large number of species (and infraspecific) names listed in Guiry and Guiry (2010). Guiry and Guiry (2010) currently list 853 species (and infraspecific) names in the database, yet only 72 have been flagged as being currently accepted taxonomically.

Gomphonema dubravicense Pantocsek 1892 (Foged 1984) is a marine species that thrives in oligohaline, alkaline conditions. No other synonyms for the species are listed, although Foged (1984) points out that the species is occasionally mistaken for *Gomphonema ventricosum* and *Gomphonema ornatum*.

Gomphonema spp. Ehrenberg 1932 (Vineyard 1979) is found mostly in freshwater, although marine species also exist. Guiry and Guiry (2010) list 1247 species (and infraspecific) names, from which 224 have been flagged as taxonomically acceptable.

Gyrosigma attenuatum (Kützing) Cleve 1894 (Haberyan p. comm.) is a freshwater species. Synonyms include *Pleurosigma attentuatum* (Kützing) W. Smith and *Frustulia attenuata* Kützing 1834.

Gyrosigma spp. Hassall 1845 (Navarro 1982) is found in both warm and cold waters. The genus is mostly found in freshwater, although Navarro (1982) also found it in brackish waters in Florida. Guiry and Guiry (2010) list 133 species (and infraspecific) names at present. 50 have been flagged as currently accepted taxonomically.

Licomophora spp. Agardh 1827 (Navarro 1982). Navarro (1982) identified four different species belonging to *Licomophora* in the brackish mangrove swamps of Florida. All exhibited a preference for warm waters and were found in the sublittoral to supralittoral zone. Guiry and Guiry (2010) list 38 species (and infraspecific) names, of which 20 have been flagged as currently accepted taxonomically.

Mastogloia spp. Thwaites ex W. Smith (Navarro 1982) is a very common type in the tropics, although it does have a global distribution. Navarro (1982) found *Mastogloia* where waters were warm enough to support it. Vineyard (1979) states that it is mostly found in North America in marine environments, although a few freshwater species also exist. Guiry and Guiry (2010) list 139 species (and infraspecific) names. 43 have been flagged as currently accepted taxonomically.

Navicula pennata A.Schmidt 1876 (Foged 1984) was found Floridian mangroves in both warm and cold waters in the sublittoral to littoral zone. Guiry and Guiry (2010) note that the species has been found in marine environments in Europe and Canary Islands. No synonyms are listed.

Navicula confervacea (Kützing) Grunow (Foged 1984) is an oligohalobe found in the tropics. It is found in circumneutral waters. No synonyms are listed in Guiry and Guiry (2010) or Foged (1984).

Navicula cuspidata (Kutzing) Kutzing 1844 (Foged 1984) is considered a taxonomic synonym for *Craticula cuspidate*. It is cosmopolitan, preferring alkaline conditions.

No other synonyms are listed in Guiry and Guiry (2010) or Foged (1984).

Navicula ergadensis (Gregory) Ralfs 1861 (Foged 1984) is marine species found in the Indian and Atlantic Ocean. Synonyms include *Navicula blanda* A.Schmidt 1874, *Caloneis blanda* (A. Schmidt) Cleve 1894, and *Pinnularia ergadensis* Gregory.

Navicula granulata Bailey 1854 (Navarro 1982) is found in the sublittoral to littoral zone in warm waters. Guiry and Guiry (2010) note that it has also been found in Canada. No other synonyms are listed.

Navicula grimmii Krasske (Foged 1984) is a cosmopolitan oligohalobe that is found in alkaline conditions. No synonyms are listed in Foged (1984) or Guiry and Guiry (2010).

Navicula hungarica Grunow 1860 (Foged 1984) is a cosmopolitan oligohalobe. According to Foged (1984) it has been found in brackish waters, although Guiry and Guiry (2010) list it as a freshwater species. The species is a synonym of *Hippodonta hungarica* (Grunow) Lange-Bertalot, Metzeltin & Witkowski.

Navicula lyra Ehrenberg 1843 (Foged 1984) is a polyhalobe that has been found in the Caribbean as well as Europe and Australia. No other synonyms are listed in Guiry and Guiry (2010) or Foged (1984).

Navicula nummularia Greville 1859 (Foged 1984) is polyhalobe and synonym of *Fallacia nummularia* (Greville) D.G. Mann. No other synonyms are listed in Guiry and Guiry (2010) or Foged (1984).

Navicula placentula (Ehrenberg) Kützing 1844 (source unknown) has a global distribution. It is considered a synonym for *Placoneis placentula* (Ehrenberg) Mereschkowsky.

Navicula spp. Bory de Saint-Vincent 1822 (Navarro 1982, Foged 1984, Metzeltin and Lange-Bertalot 2007) is pennate type found in fresh to marine water. Guiry and Guiry (2010) list 6721 species (and infraspecific) names. 857 have been flagged as currently accepted taxonomically.

Navicula yarrensis Grunow in Schmidt 1876 (Navarro 1982) is found in both marine and freshwater conditions. Navarro (1982) identified the species in both warm and cold waters in the sublittoral to littoral zone.

Naviculadicta spp. Lange-Bertalot & Moser 1994 (Metzeltin and Lange-Bertalot 2007) is a relatively new genus. Metzeltin and Lange-Bertalot (2007) found the type in South America. Guiry and Guiry (2010) list 50 species (and infraspecific) names. 45 of which have been flagged as taxonomically acceptable.

Neidium affine var. *ceylonicum* Reimer 1966 (robert-lavigne.com). No synonyms, type locations, or distributions are listed in Guiry and Guiry (2010).

Neidium spp. (Pfitzer 1871) similar in appearance to *Caloneis*, however it is only found in freshwater environments. Guiry and Guiry (2010) list 206 species (and infraspecific) names, of which 61 have been flagged as currently accepted taxonomically.

Nitzschia frustulum (Kützing) Grunow in Cleve & Grunow 1880 (Navarro 1982) is found in marine and freshwater. It has a global distribution and is commonly found in the Caribbean in the sublittoral to supralittoral zone. Guiry and Guiry (2010) list *Nitzschia austriaca* Hustedt 1959 as a synonym.

Nitzschia granulata Grunow 1880 (Navarro 1982) is a polyhalobe found in warm to temperate waters in the sublittoral zone. The species looks very similar to *Nitzschia punctata*, except ca. 10 µm larger. No synonyms are listed.

Nitzschia lanceolata W. Smith (Navarro 1982) is a polyhalobe found in Europe, Australia, and the Caribbean. Navarro (1982) states that it is found frequently in Floridian mangroves in warm and cold waters in the sublittoral to littoral zone. No synonyms are listed.

Nitzschia marginulata Grunow 1880 (Foged 1984) is a polyhalobe found in warm to temperate waters in the sublittoral to supralittoral zone. It has a global distribution. The name is a synonym for *Tryblionella marginulata* (Grunow) D.G.Mann.

Nitzschia scalaris (Ehrenberg) W. Smith (Foged 1984) is a cosmopolitan mesohalobe to polyhalobe. No synonyms were listed in Guiry and Guiry (2010) or Foged (1984).

Nitzschia spp. Hassall 1845 (Navarro 1982, Foged 1984) is found in marine and freshwater. Guiry and Guiry (2010) list 1024 species (and infraspecific) names in the database at present. 323 have been flagged as currently accepted taxonomically.

Orthoseira tropica (Krasske) (Metzeltin and Lange-Bertalot 2007) is a synonym of *Orthoseira roeseana* var. *tropica* (Krasske) Lange-Bertalot & Willmann. No further information is listed in Guiry and Guiry (2010).

Pinnularia acrosphaeria W. Smith 1853 (Metzeltin and Lange-Bertalot 2007) is a freshwater species that has a global distribution. Synonyms include *Pinnularia acrosphaeria* Rabenhorst 1853.

Pinnularia borealis var. *islandica* Krammer 2000 (Metzeltin and Lange-Bertalot 2007) has been found in Iceland and throughout South and Central America. Guiry and

Guiry (2010) state that it is a “freshwater/terrestrial” species. No other synonyms are listed.

Pinnularia instabilis (A.Schmidt) D.Metzeltin (Metzeltin and Lange-Bertalot 2007) was found by Metzeltin and Lange-Bertalot (2007) in 11,000 year old sediments from Brazil. Guiry and Guiry (2010) do not list any further information.

Pinnularia spp. Ehrenberg 1843 (Vineyard 1979) is a freshwater species. 2462 species (and infraspecific) are listed in Guiry and Guiry (2010), 412 of which have been flagged as currently accepted taxonomically.

Plagiogramma spp. Greville 1859 (Navarro 1982) is a marine, benthic diatom type. Guiry and Guiry (2010) state “this is a fairly distinctive genus now that several species have been transferred to *Plagiogrammopsis* and *Brockmanniella* by Hasle, von Stosch & Syvertsen (1983), but it is still large. Most of the species listed in VanLandingham require further study.” 19 species (and infraspecific) names are currently listed in the database, from which 15 have been flagged as taxonomically acceptable.

Rhopalodia musculus (Kützing) Otto Müller 1900 (Foged 1984) is a cosmopolitan species that can withstand a range of salinities. Foged (1984) lists the species as a mesohalobe. Synonyms include *Epithemia musculus* Kützing 1844, *Eunotia westermanni* var. *musculus* (Kützing) G.L. Rabenhorst 1847, *Cystopleura musculus* (Kützing) Kuntze 1891, *Rhopalodia gibberula* var. *musculus* (Kützing) Muschler 1908, and *Rhopalodia gibberula* var. *musculus* (Kützing) Cleve-Euler 1952.

Rhopalodia gibba (Ehrenberg) Otto Müller 1895 (Foged 1984) is a cosmopolitan oligohalobe typically found in freshwater. It is alkalibiontic. Synonyms include

Navicula gibba Ehrenberg 1830, *Pinnularia gibba* (Ehrenberg) Ehrenberg 1843
Epithemia gibba (Ehrenberg) Kützing 1844, *Frustulia gibba* (Ehrenberg) Jenner
1845, *Epithemia ventricosa* var. *gibba* (Ehrenberg) J.Schumann 1869, *Cystopleura*
gibba (Ehrenberg) Kuntze 1891, and *Schizonema gibbum* (Ehrenberg) Kuntze 1898.
Rhopalodia operculata (C.Agardh) Håkanasson 1979 (Navarro 1982) is found in warm
waters in the sublittoral to supralittoral zone. Navarro (1982) described them as
“common throughout the year” in Florida mangroves.

Sellaphora pupula (Kützing) Mereschkovsky 1902 (Metzeltin and Lange-Bertalot 2007,
Haberyan p. comm.) was formerly known as *Navicula pupula* Kützing. Guiry and
Guiry (2010) list examples that have been found in Europe, Asia, South America, and
the Hawaiian islands. Other synonyms include *Schizonema pupula* (Kützing) Kuntze
1898.

Sellaphora spp. Mereschkovsky 1902 (Metzeltin and Lange-Bertalot 2007) is a pennate
that was formerly included in *Navicula*. Metzeltin and Lange-Bertalot (2007) list 21
different species in Latin America. Guiry and Guiry (2010) list 88 total species (and
infraspecific) names, 42 of which have been flagged as taxonomically acceptable.

Stauroneis anceps Ehrenberg 1843 (Foged 1984) has a global distribution. It has been
found in both cold and warm waters. It is an oligohalobe, preferring circumneutral
conditions. Guiry and Guiry (2010) list it as a freshwater species. Synonyms include
Schizonema anceps (Ehrenberg) Kuntze 1898, *Navicula anceps* (Ehrenberg) Mann
1907, *Stauroneis anceps* f. *gracilis* (Ehrenberg) Cleve, *Stauroneis amphicephala*
Kützing 1844, *Stauroneis anceps* var. *amphicephala* (Kützing) van Heurck 1880, and
Stauroneis anceps var. *amphicephala* (Kützing) Cleve 1894.

Stauroneis spp. Ehrenberg 1843 (Foged 1984, Metzeltin and Lange-Bertalot 2007) is a cosmopolitan type. It can be found in warm and cold waters. Guiry and Guiry (2010) list 815 species (and infraspecific) names. 123 have been flagged as currently accepted taxonomically.

Surirella spp. Turpin 1828 is (Foged 1984, Metzeltin and Lange-Bertalot 2007) is found globally in warm and cold waters. The type can also be found in marine to freshwater. Guiry and Guiry (2010) list 1214 species (and infraspecific) names in their database. 156 have been flagged as currently accepted taxonomically.

Synedra pulcherrima Hantzsch ex Rabhenhorst (Foged 1984) is a polyhalobe that has been found in Cuba. Guiry and Guiry (2010) do not list any synonyms, distribution information, or habitat preferences.

Tabularia waernii P. Snoeijis 1991 (Hein et al. 2008) has been identified by Hein et al. (2008) in the Bahamas. Hein et al. (2008) termed it an “infrequent” type. Guiry and Guiry (2010) do not list any other synonyms.

Terpsinoë musica Ehrenberg 1843 (Foged 1984) is globally distributed. Foged (1984) described the species as “much debated”. Foged states that he has only ever found it in fast running freshwater. However, it has also been described as euryhaline. Foged (1984) contends that in his experience, any specimens that have been found in coastal waters were the result of being washed out to sea. He contends that freshwater is the preferred species habitat. Guiry and Guiry (2010) do not list any other synonyms.

Thalassiosira spp. Cleve 1873 (Foged 1984) is described in Guiry and Guiry (2010) as, “a large genus - descriptions of species (many new) are to be found in the numerous papers of Hasle & Fryxell. Most species (ca. 100) are marine, although up to 12 have

been recorded in freshwaters (Hasle, 1978); of the latter *T. weissflogii* (= *T. fluviatilis*) is probably the best known. There is considerable variation within the genus, which is one of the largest in our collection; we cannot do justice to it in our illustrations.

Makarova (1988) provides a comprehensive account of the genus in seas around Russia.” A total of 203 species (and infraspecific) names are currently listed in Guiry and Guiry (2010), although only 100 have been flagged as taxonomically acceptable.

Trachyneis aspera (Ehrenberg) Cleve 1894 is a marine species (polyhalobe). Synonyms include *Navicula aspera* Ehrenberg 1840, *Stauroneis aspera* (Ehrenberg) Kützing 1844, *Stauroneis achnanthes* (Ehrenberg) Kützing 1844, *Pinnularia aspera* (Ehrenberg) Ehrenberg 1854, *Stauroptera aspera* Ehrenberg 1841, *Stauroneis pulchella* W. Smith 1853, *Navicula stauroneiformis* Leuduger-Fortmorel 1892, and *Navicula aspera* var. *genuina* (Cleve) Fricke 1902.

Trachysphenia spp. P. Petit 1877 (Navarro 1982) was observed in Florida in the sublittoral zone in December in cold water. However, it is not clear whether the type found in Laguna Saladilla is the same species (*Trachysphenia acuminata*) as that observed by Navarro (1982). Guiry and Guiry (2010) currently list 7 species (and infraspecies) names, 5 are flagged as currently acceptable.

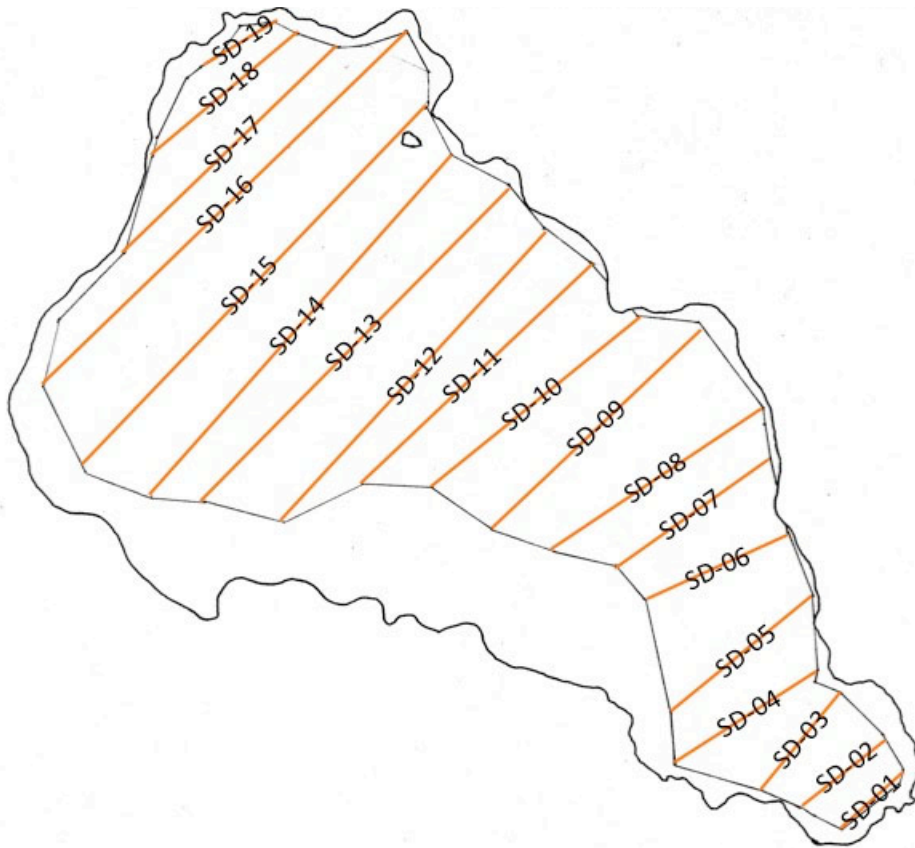
Tropidoneis lepidoptera (Gregory) Cleve 1894 has been found in Europe and South America. Synonyms include *Tropidoneis lepidoptera* var. *mediterranea* Peragallo 1897 and *Amphiprora lepidoptera* Gregory 1857.

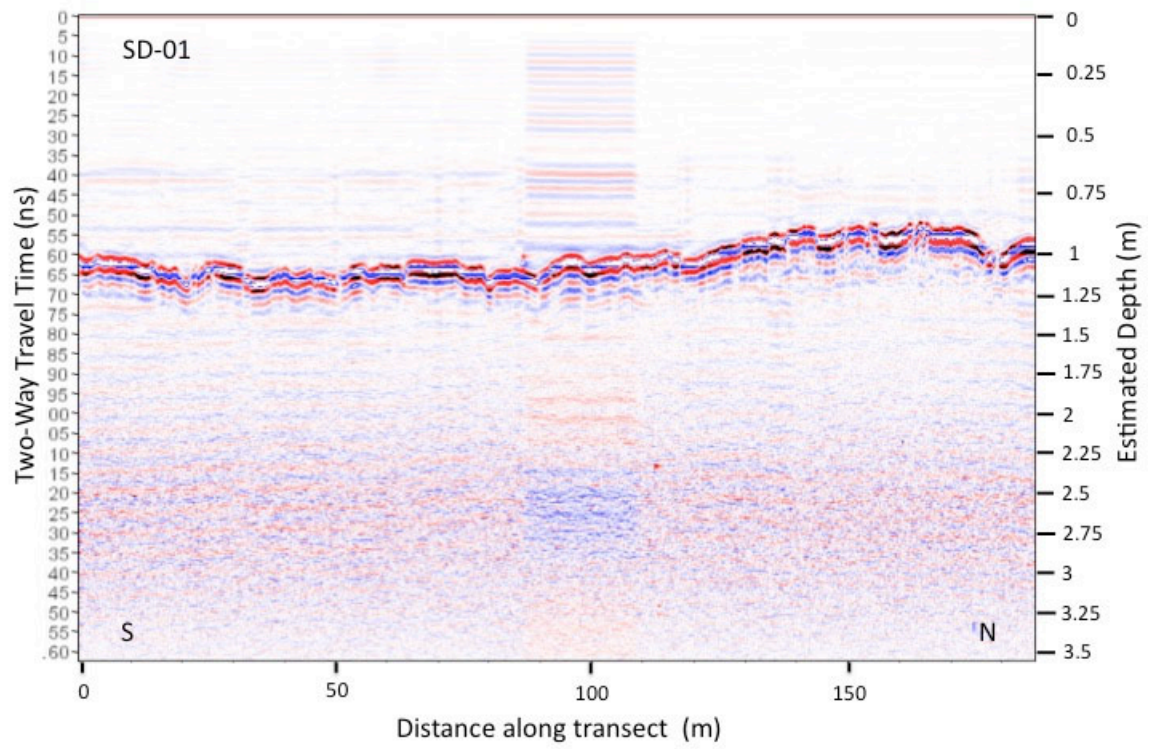
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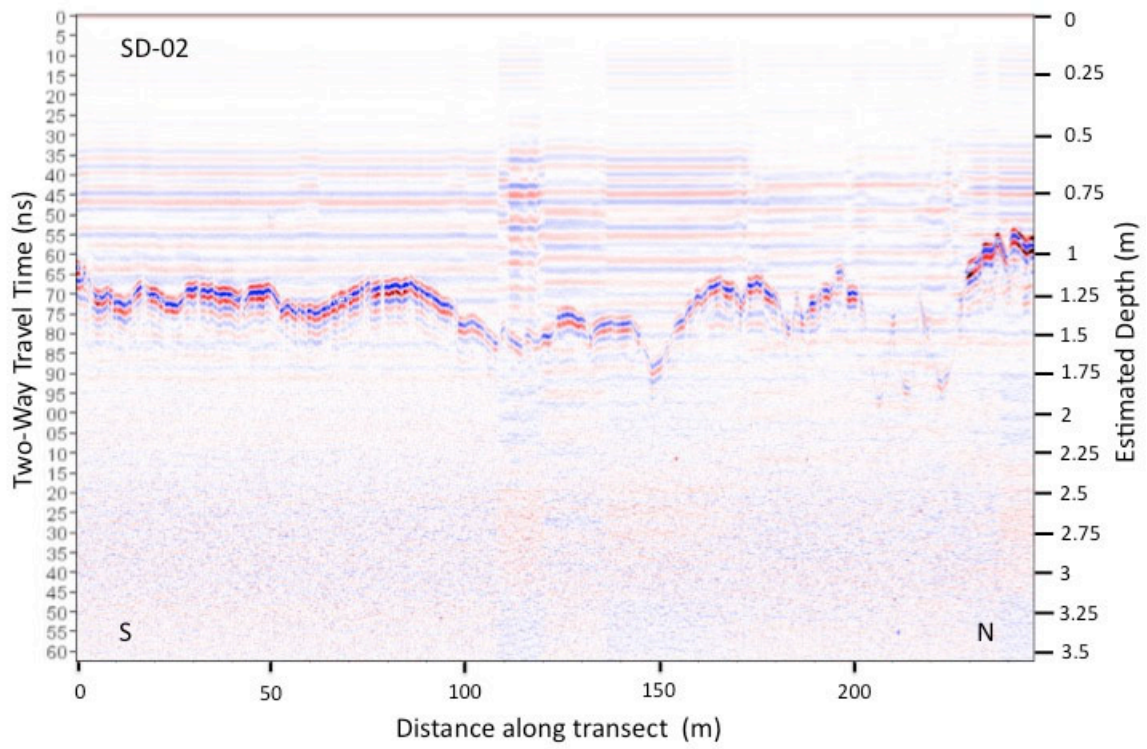
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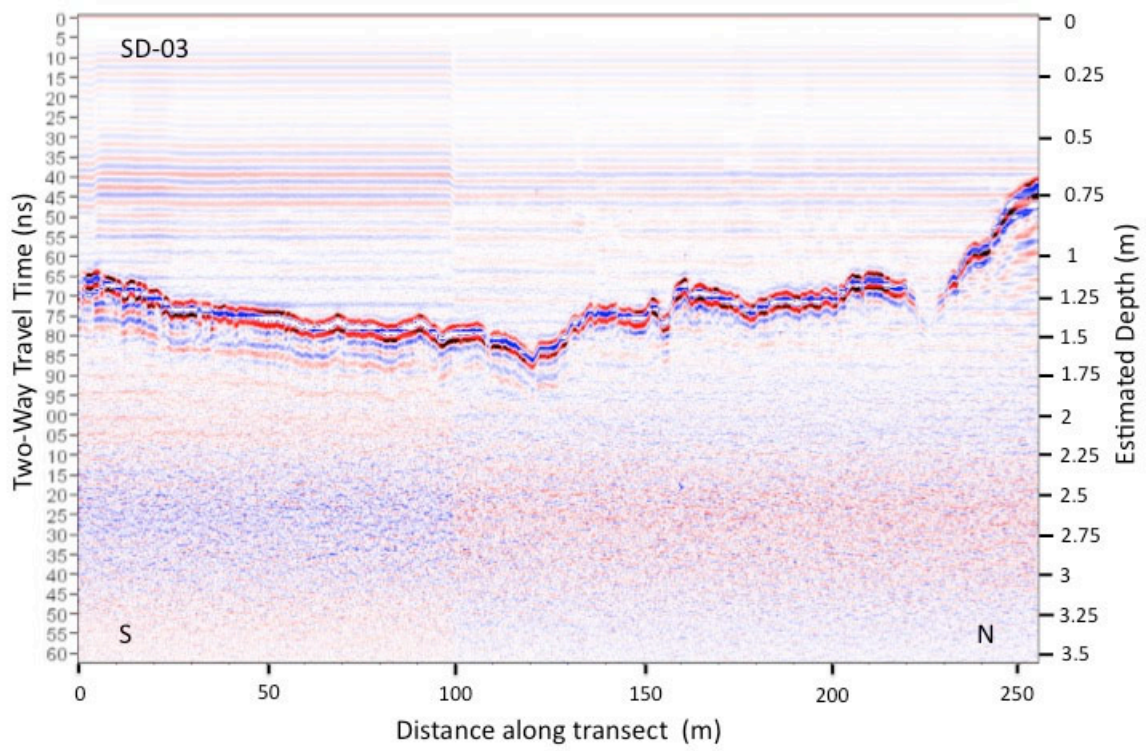
APPENDIX III: LAGUNA SALADILLA GROUND PENETRATING
RADAR PROFILES

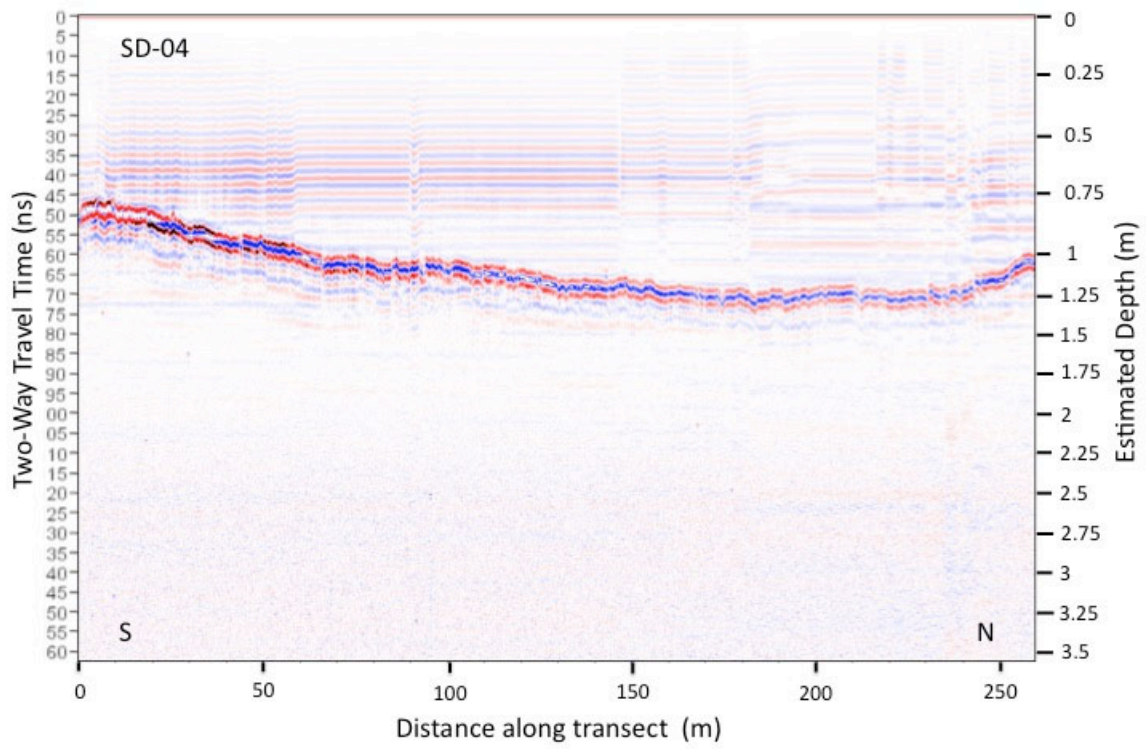
Estimated depth is based on the mean RDP of samples (Chapter 3). A mean RDP value was used to mitigate for lateral variations in subsurface radar-wave velocity.

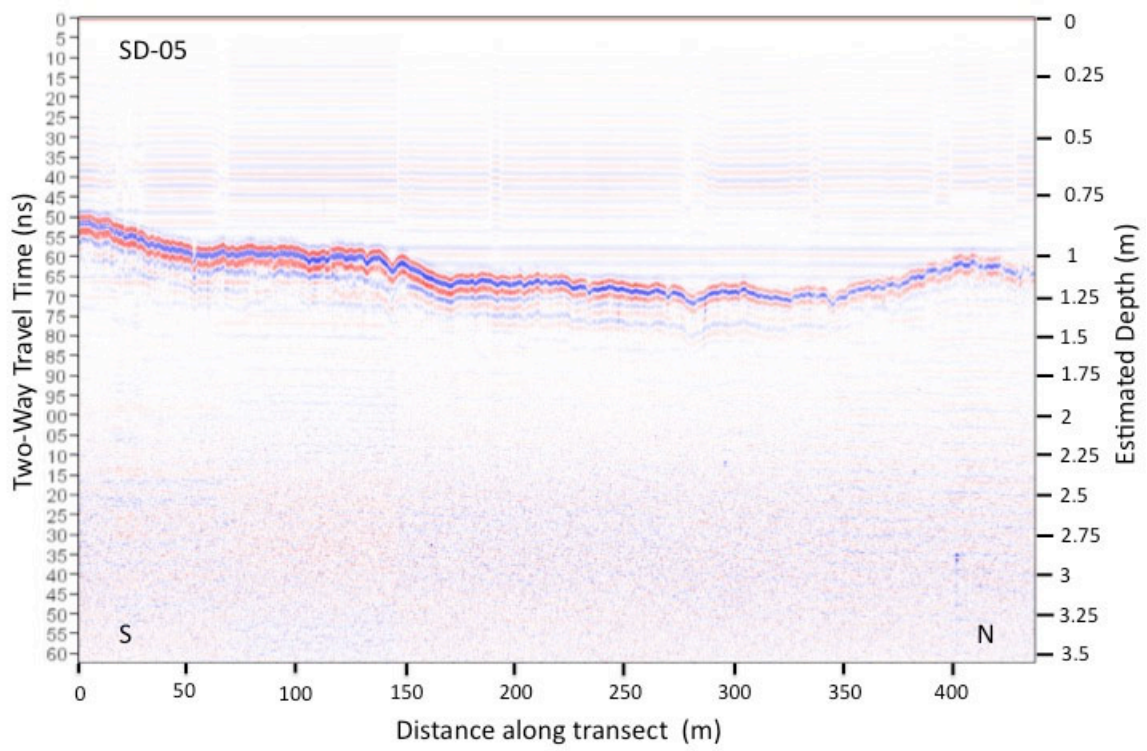


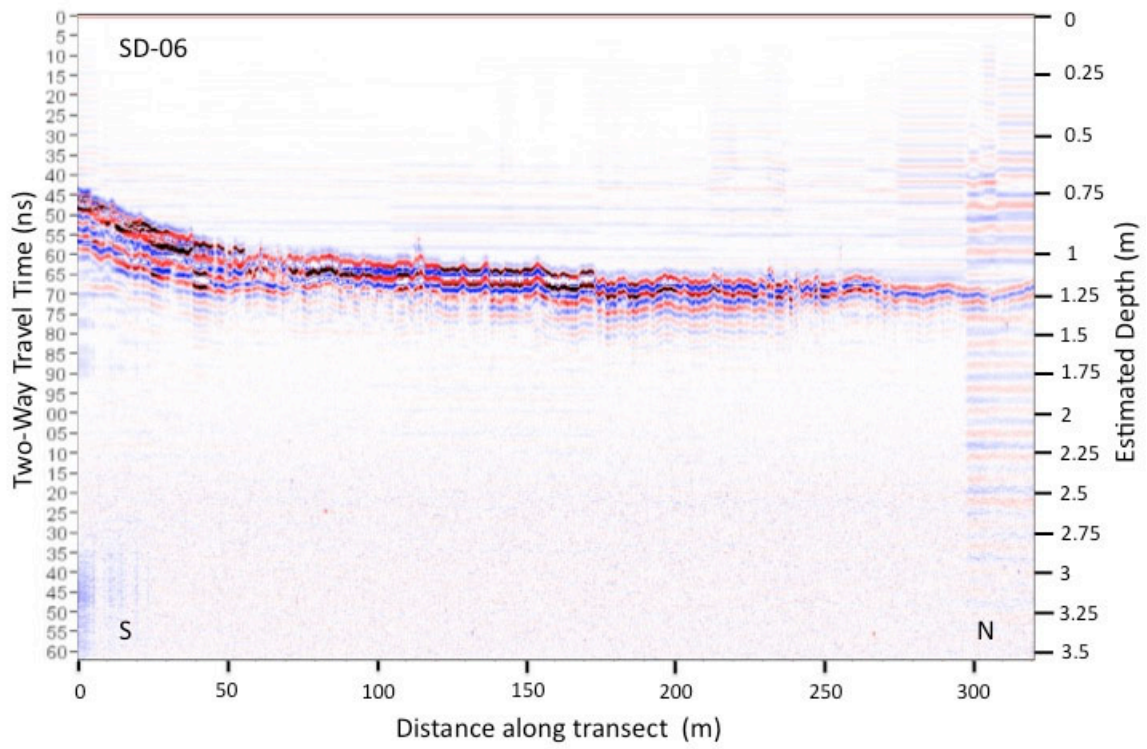


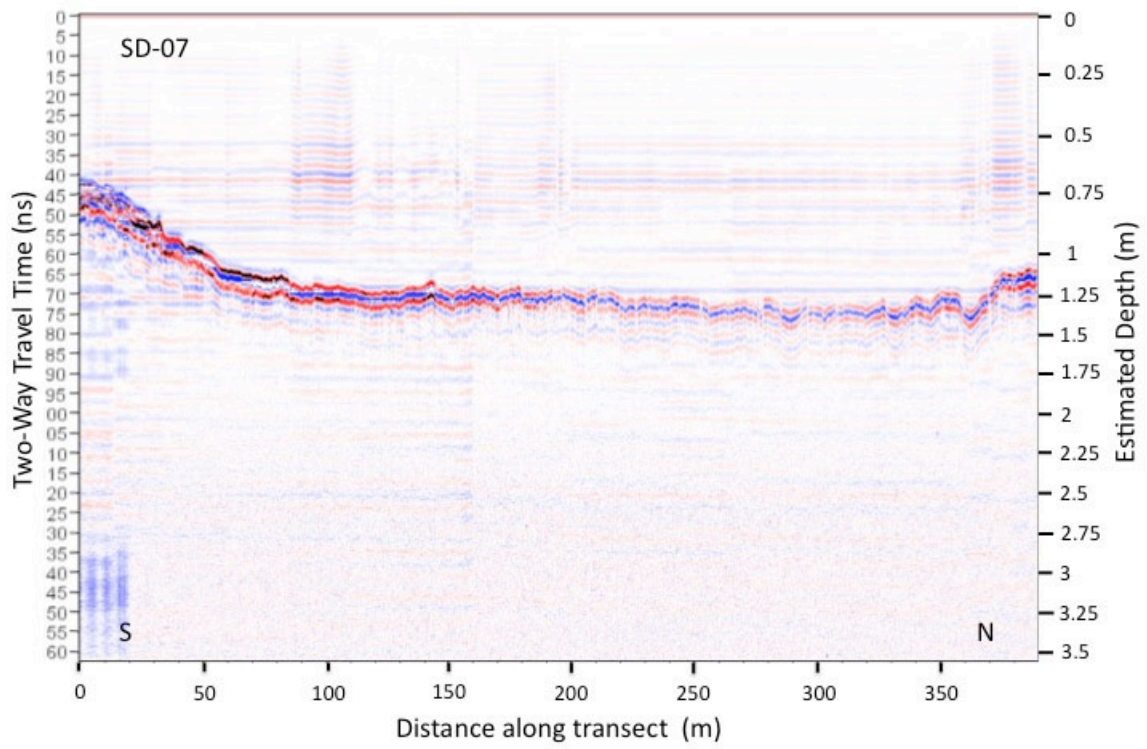


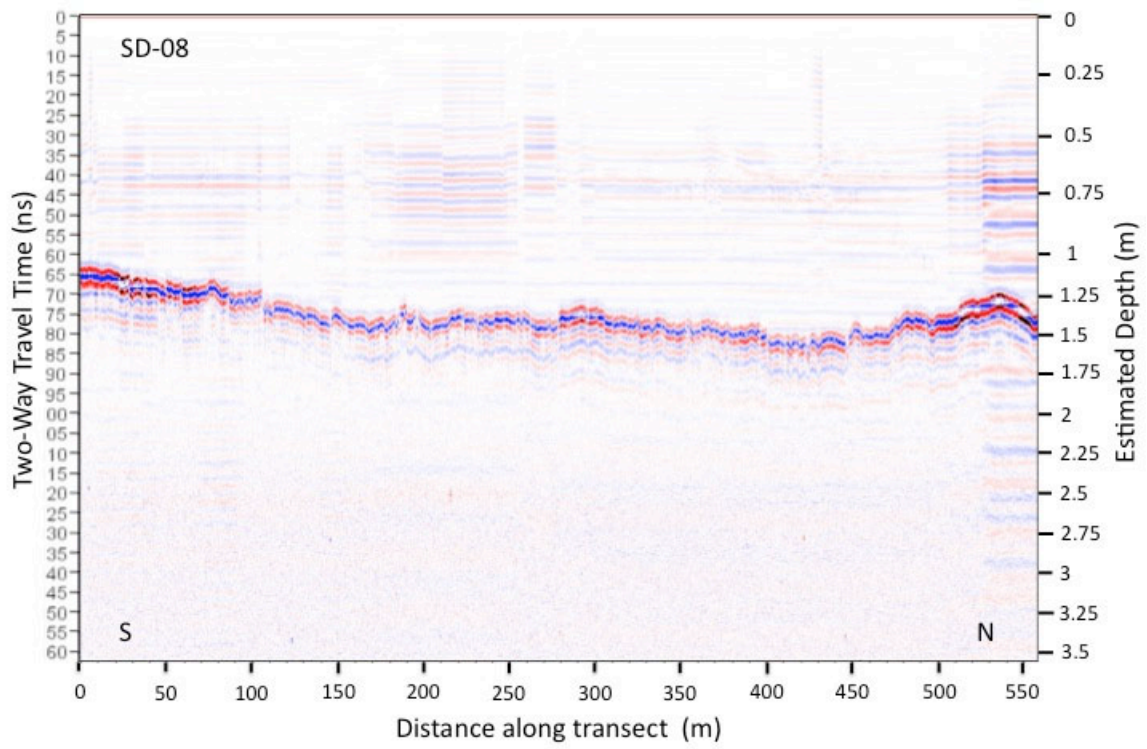


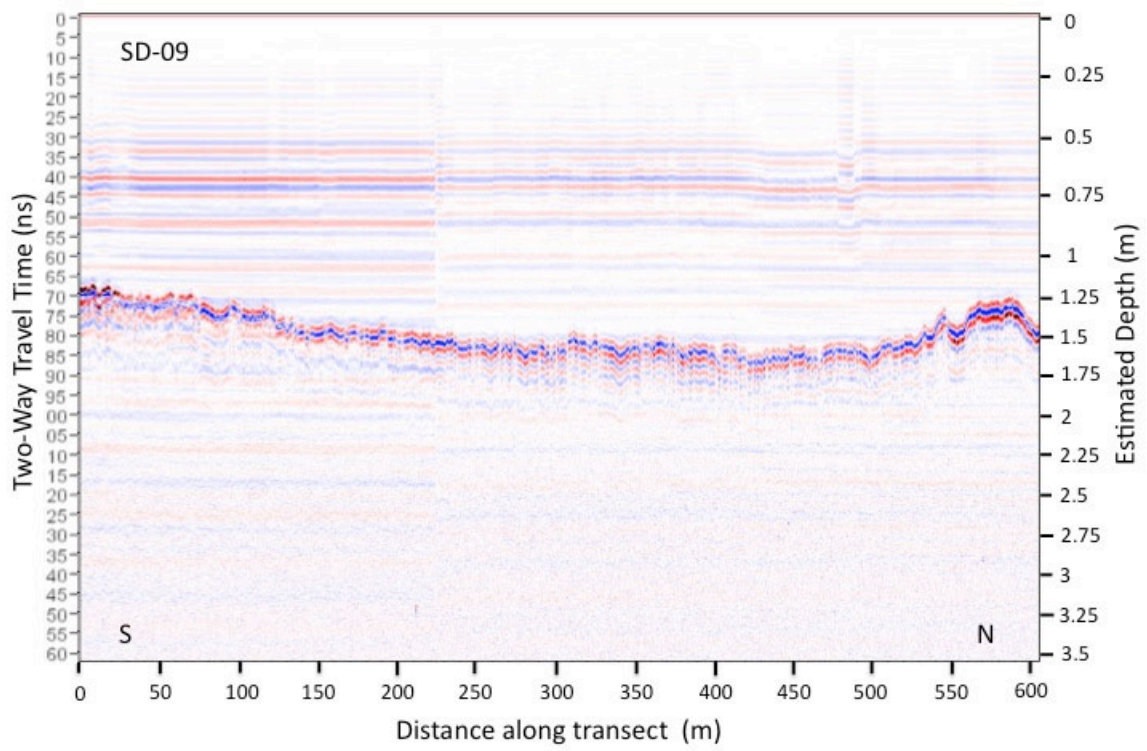


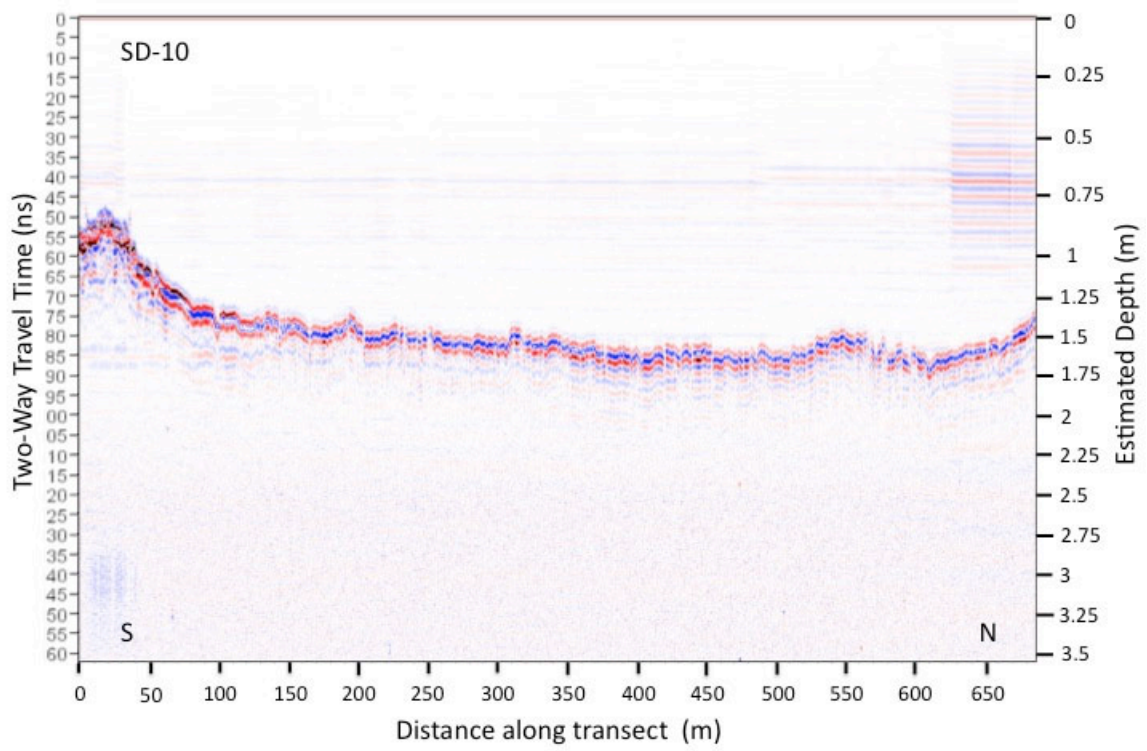


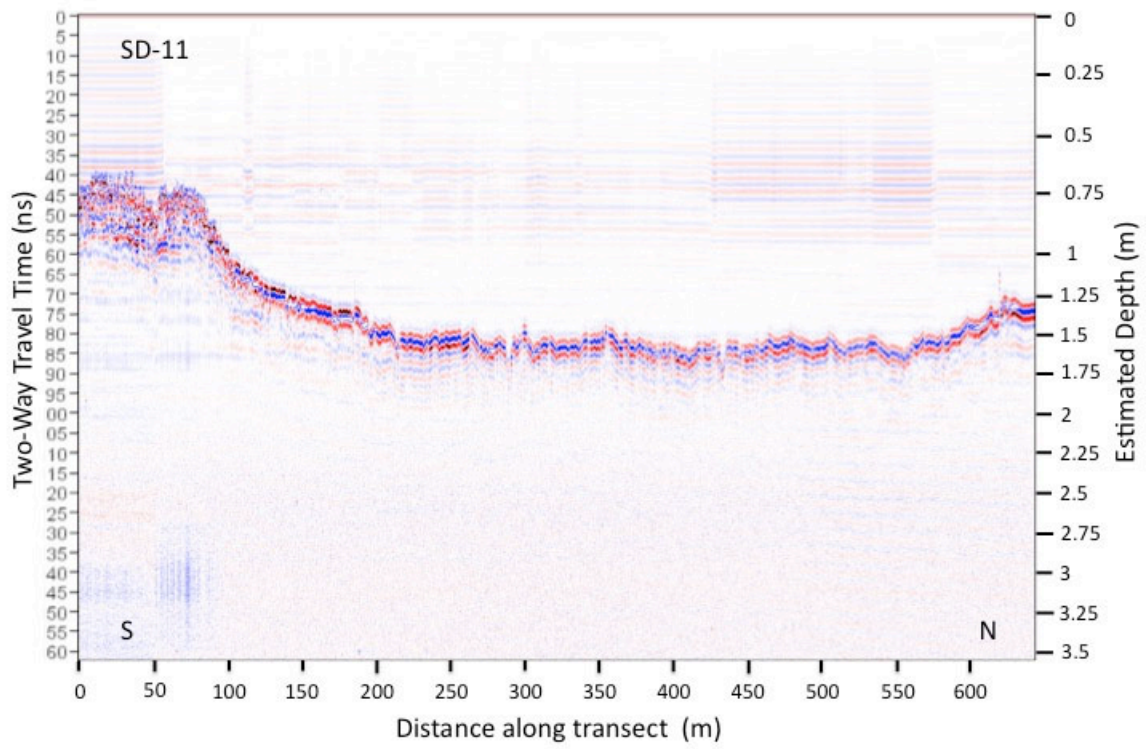


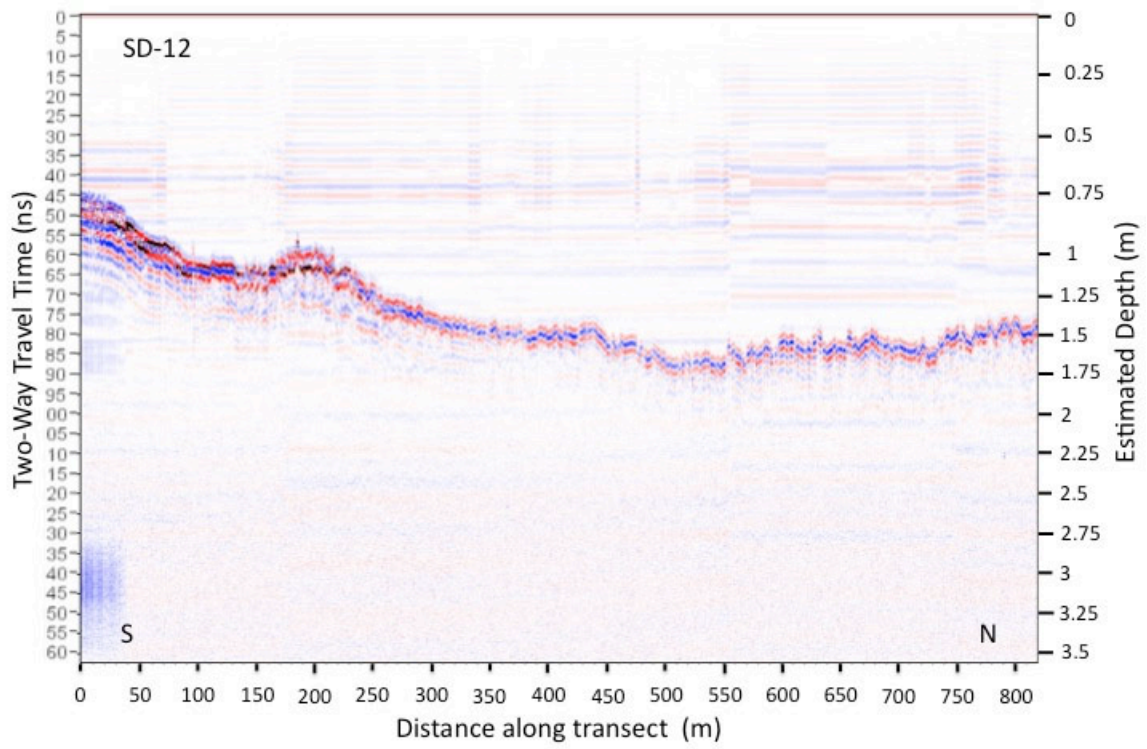


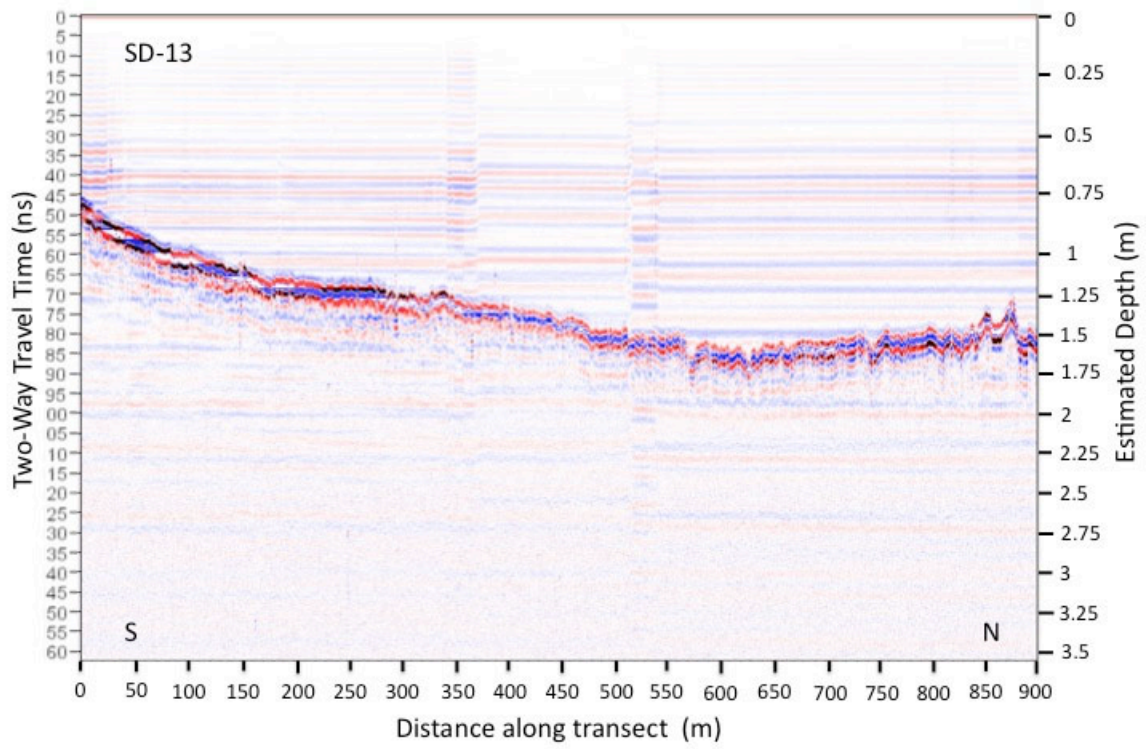


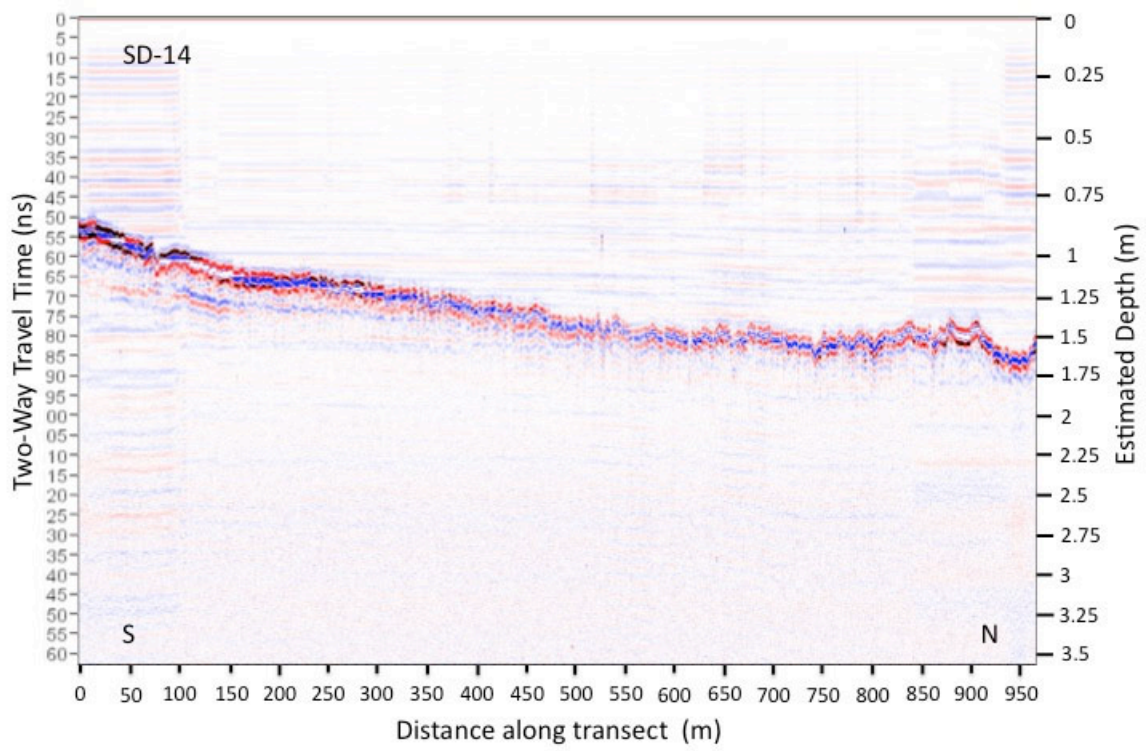


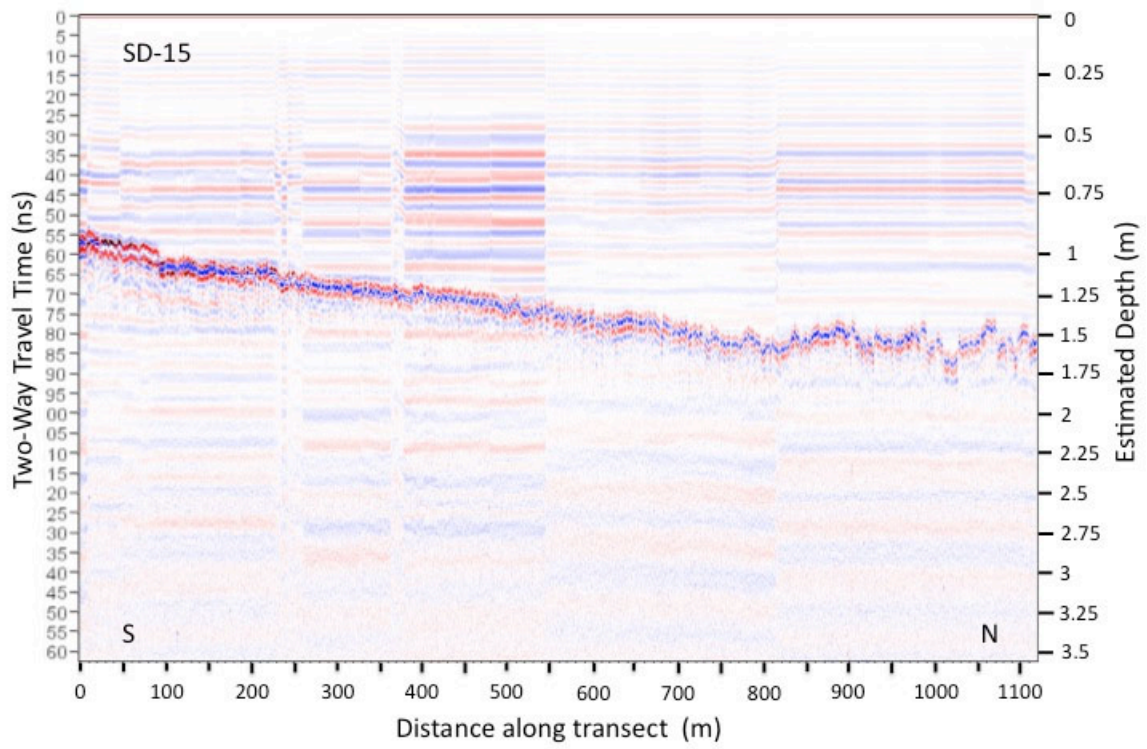


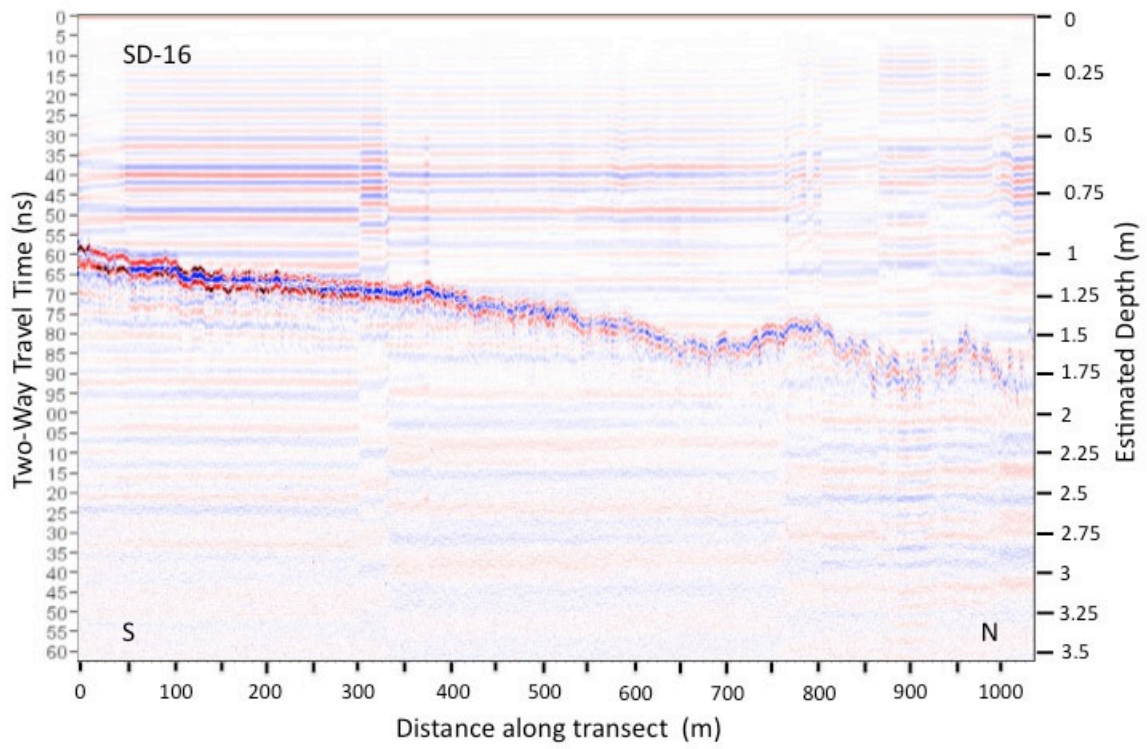


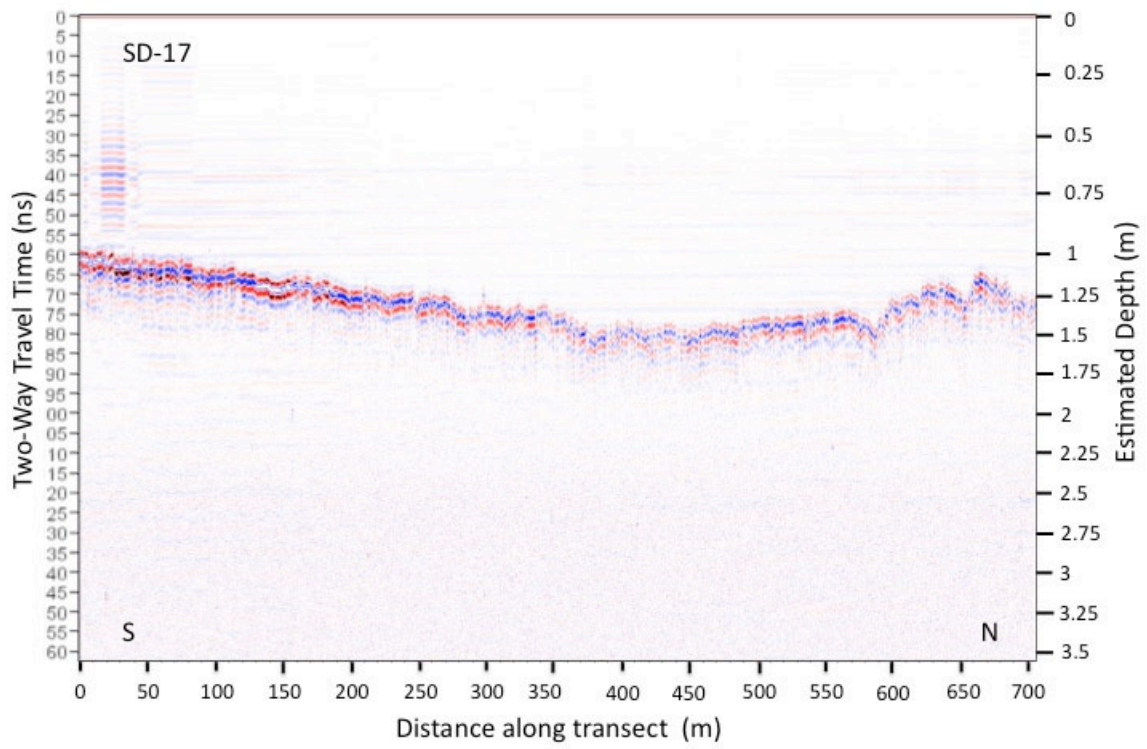


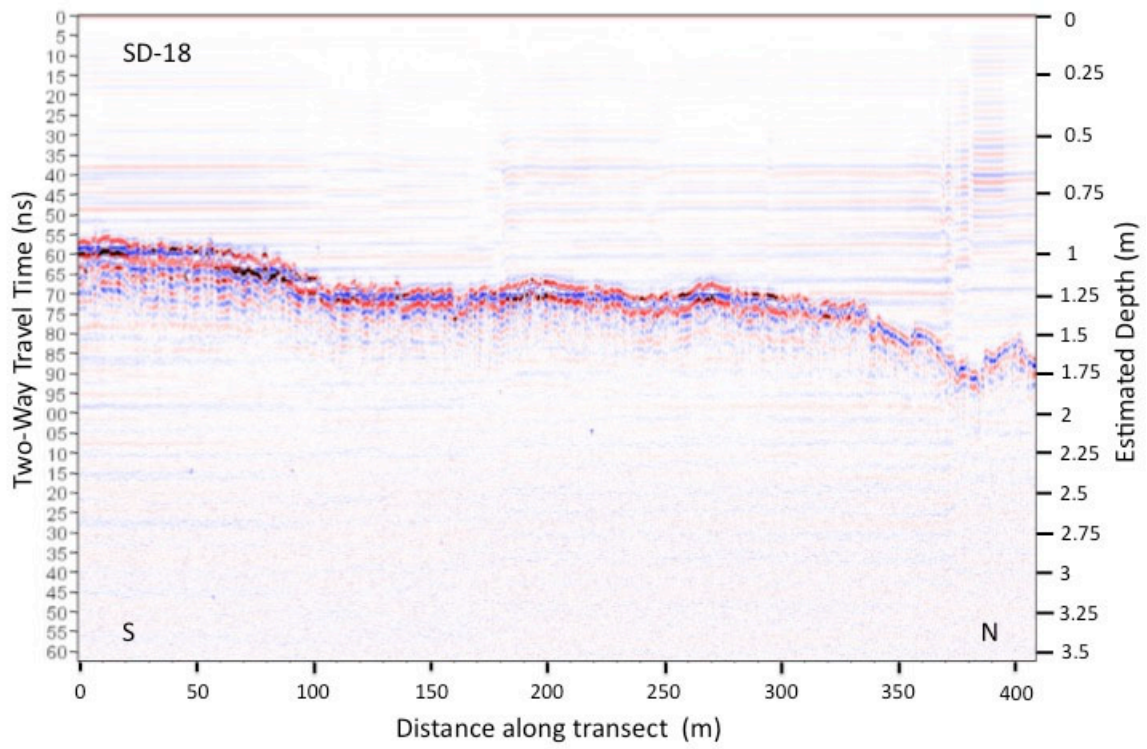


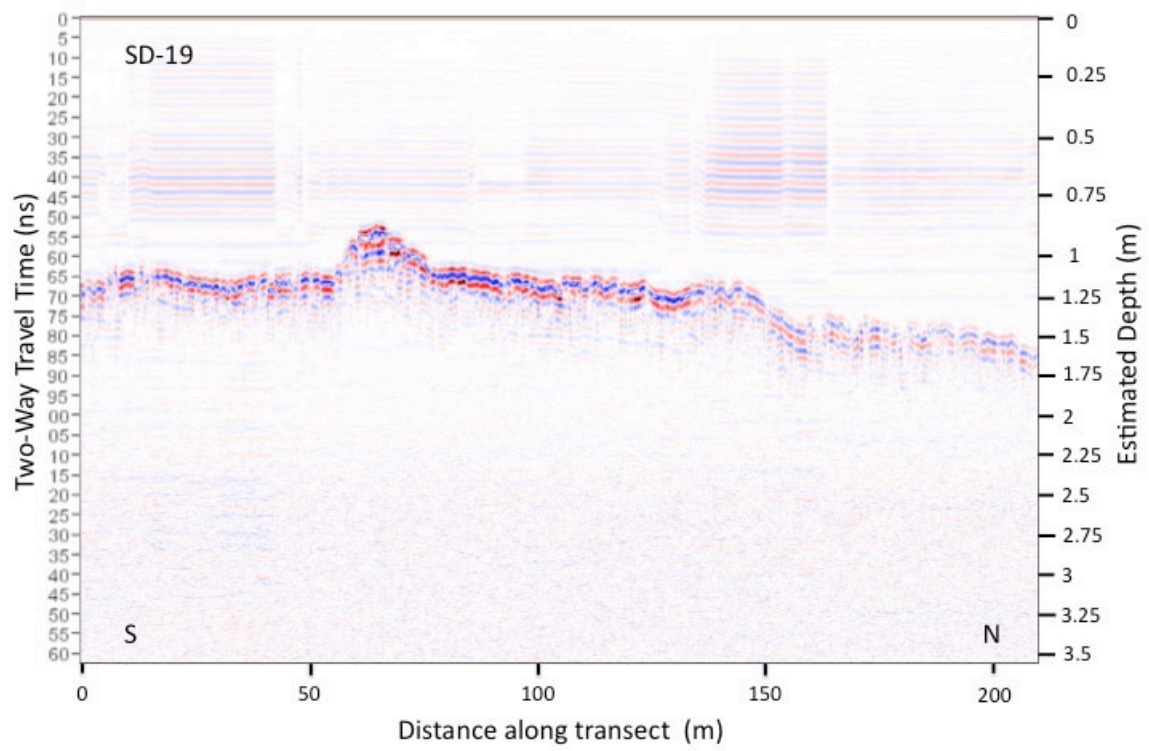


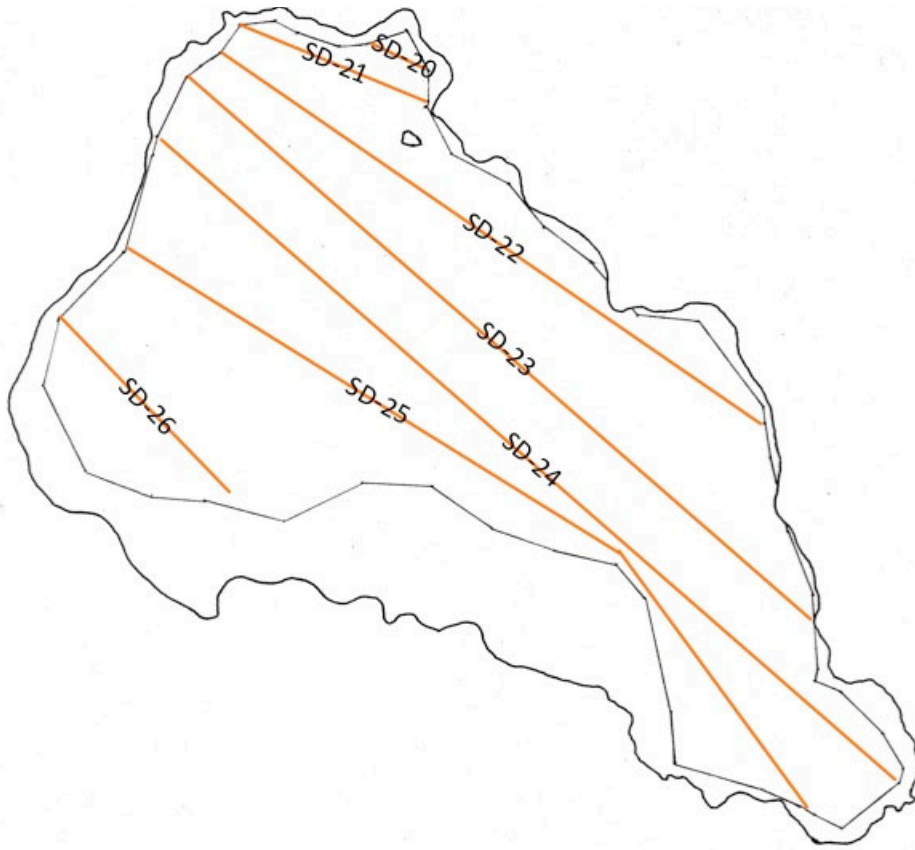


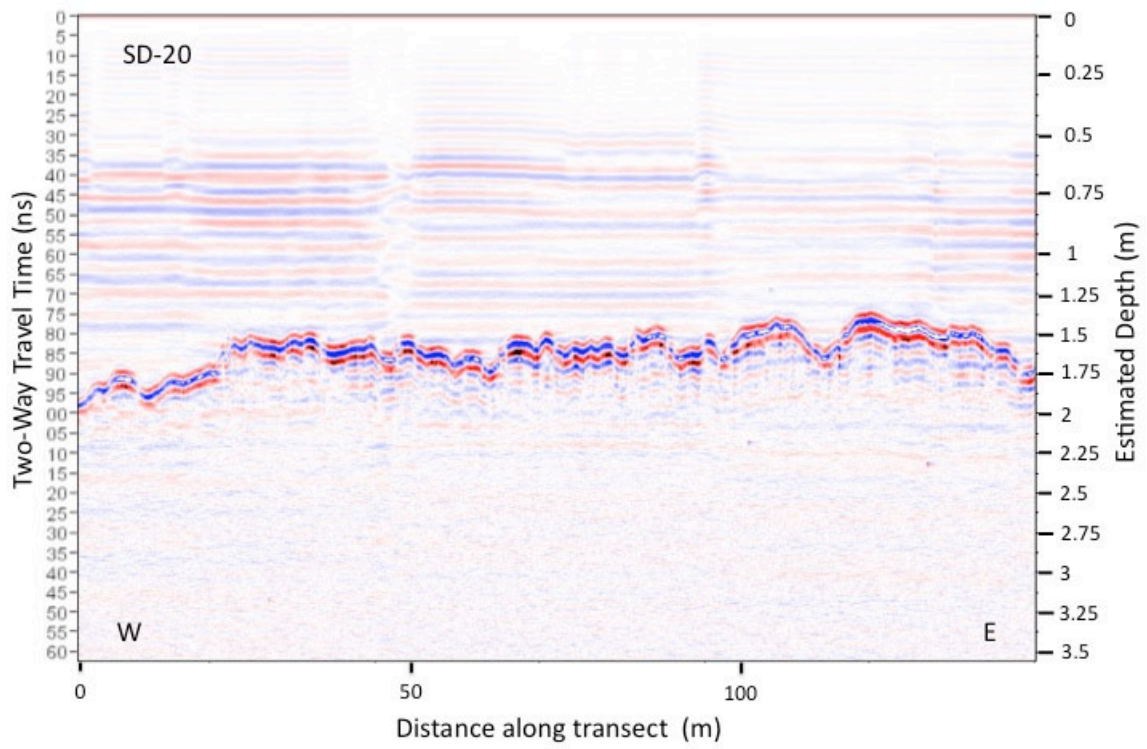


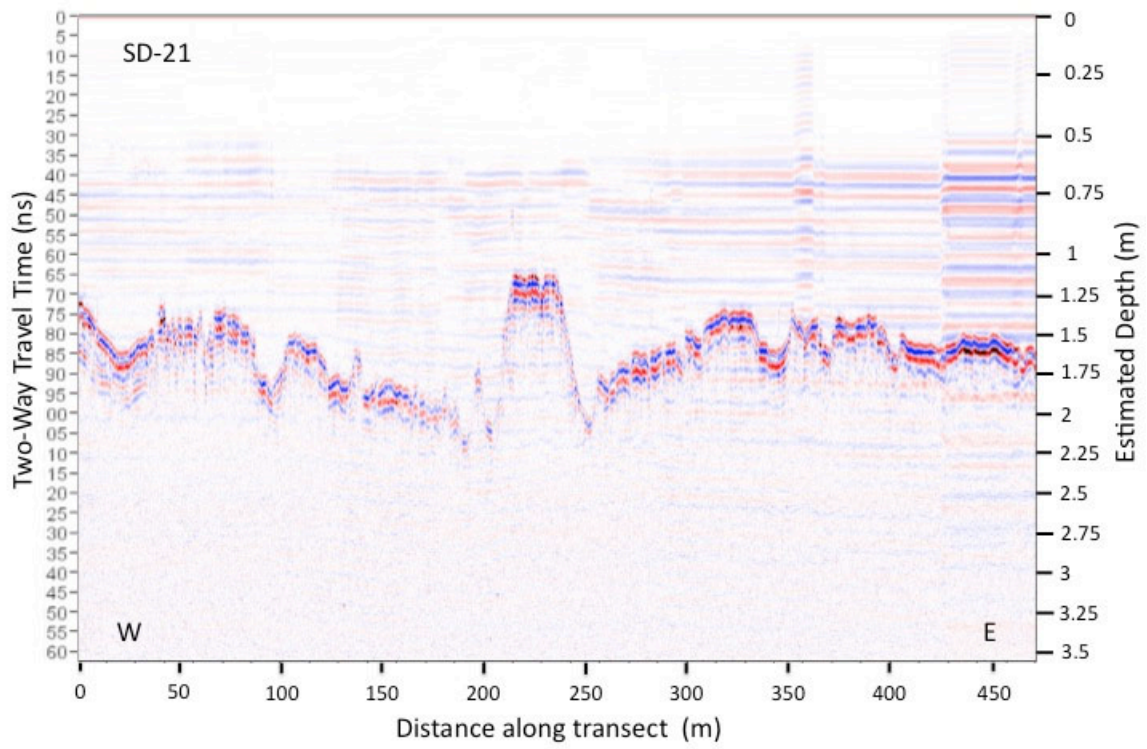


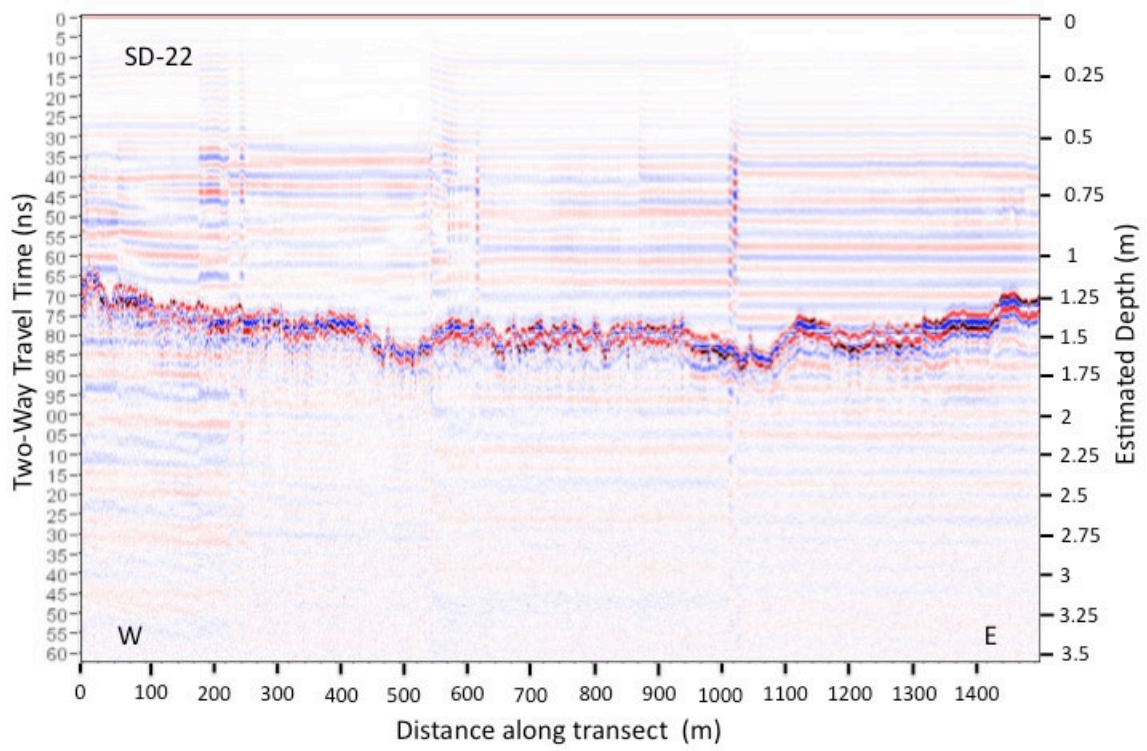


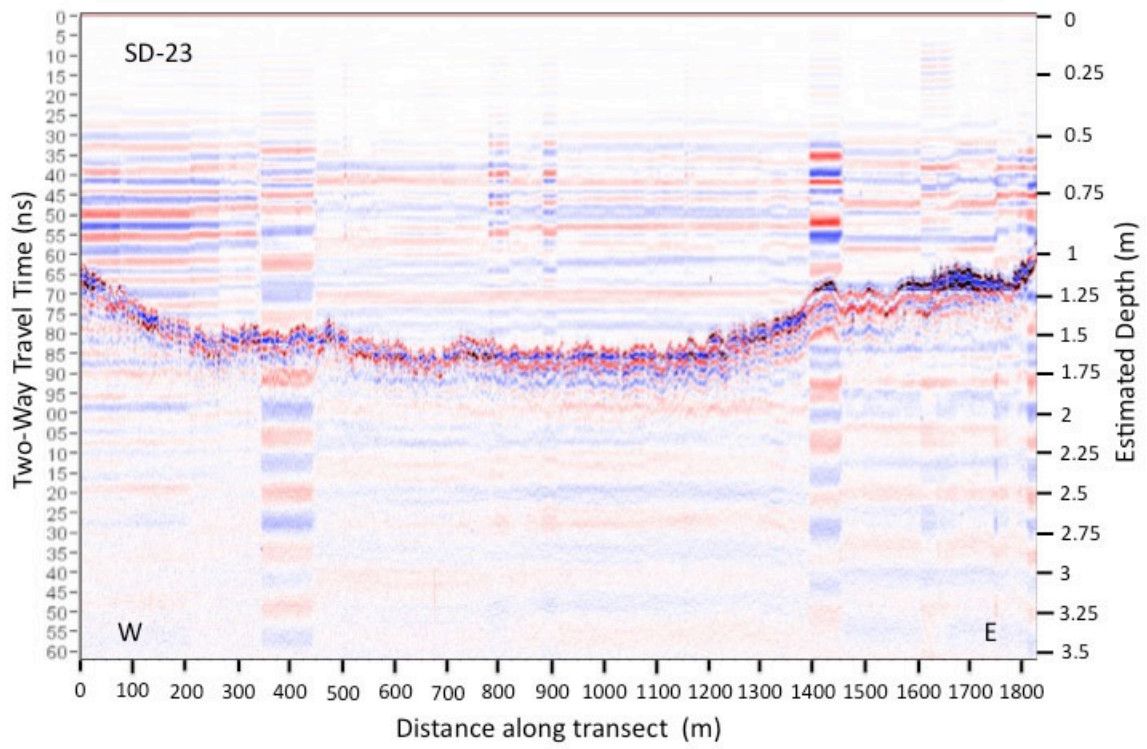


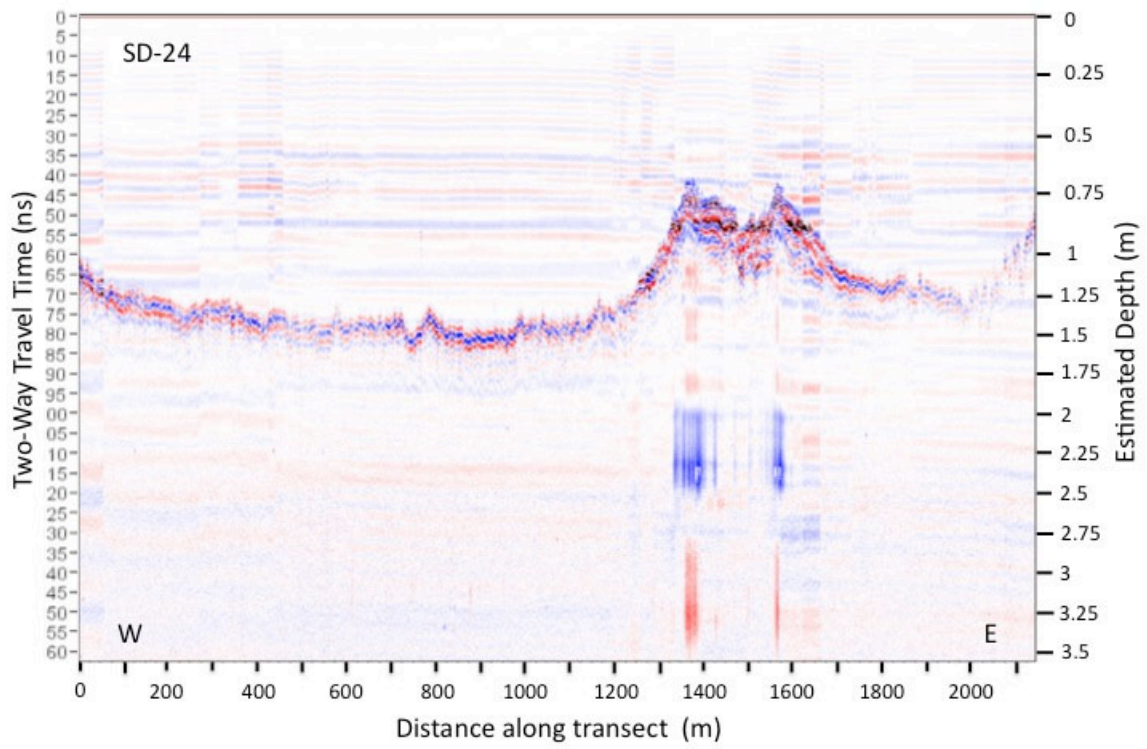


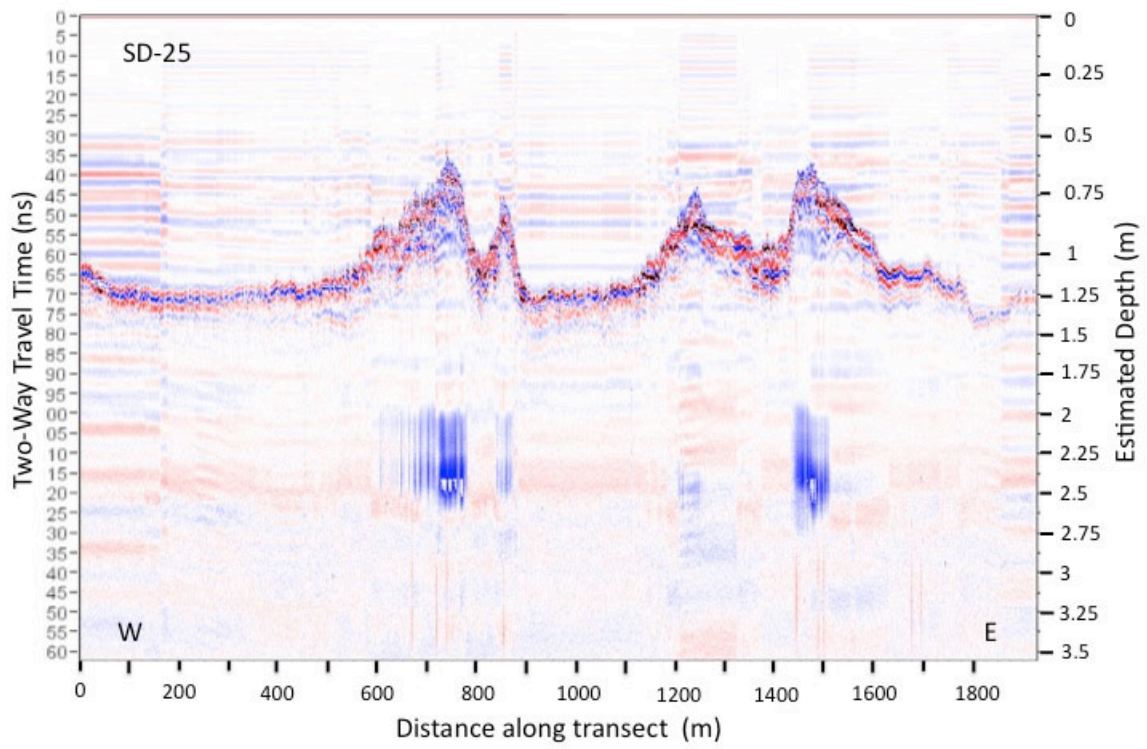


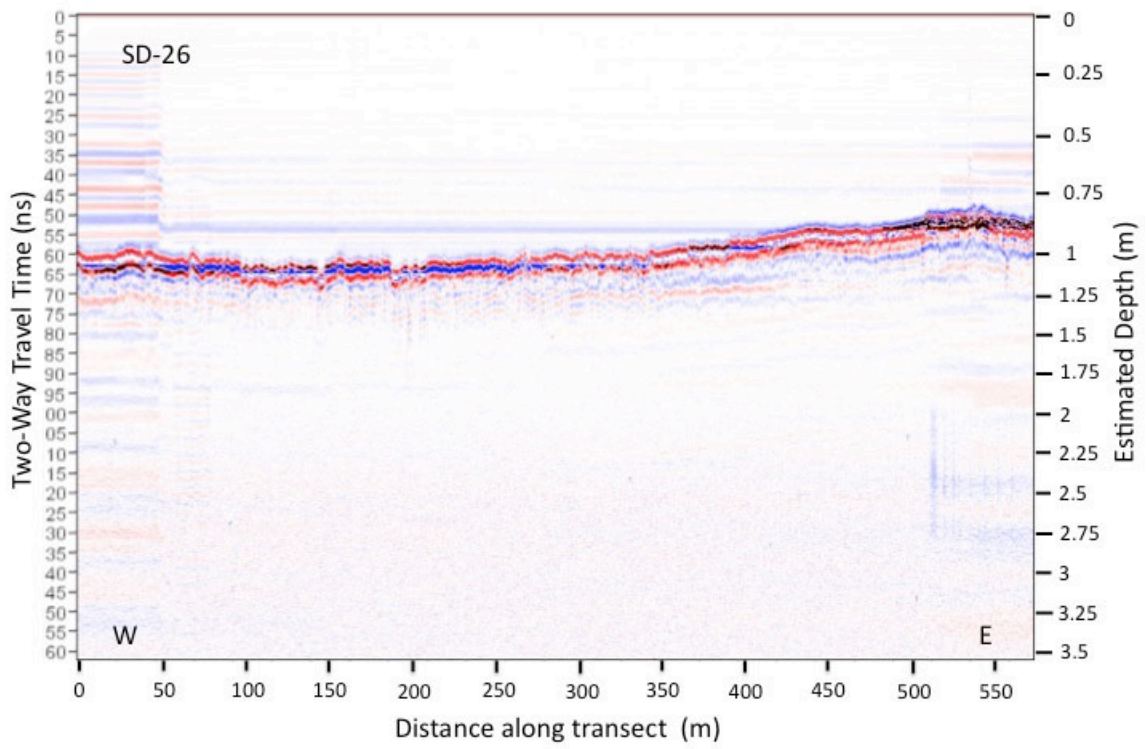




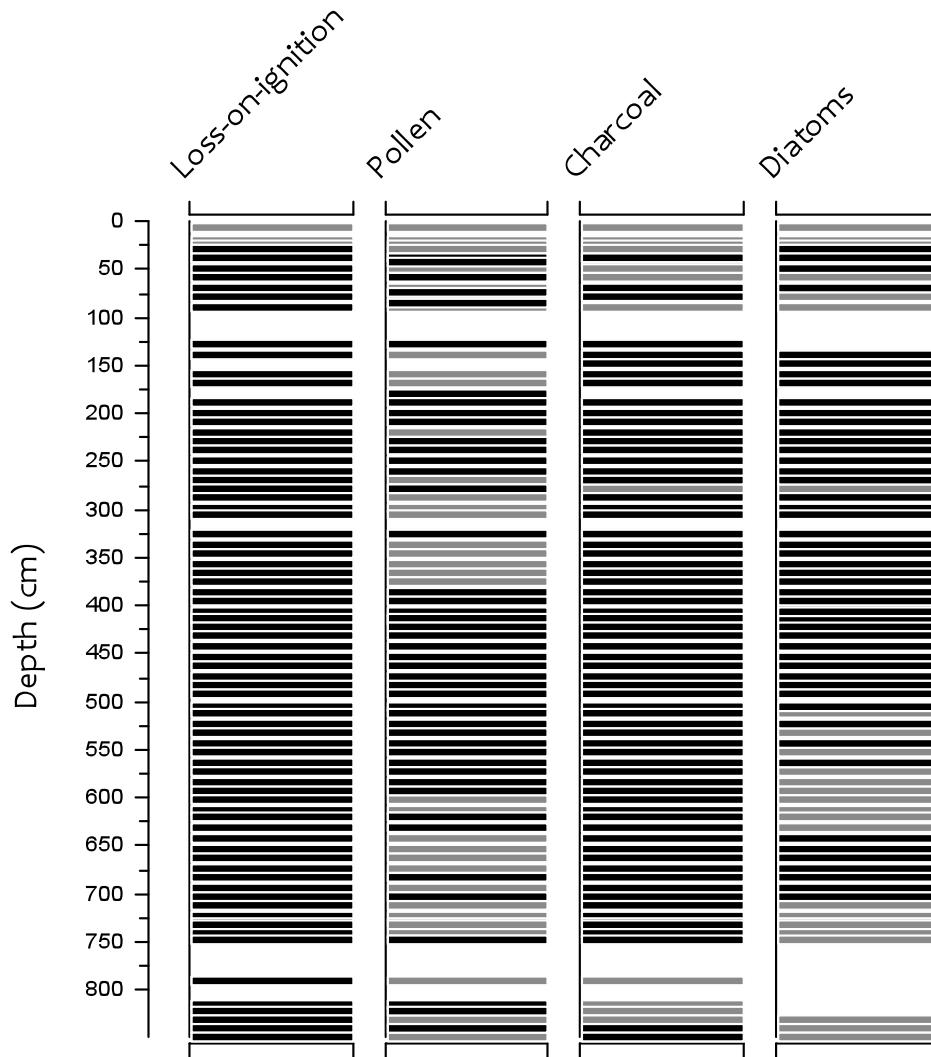




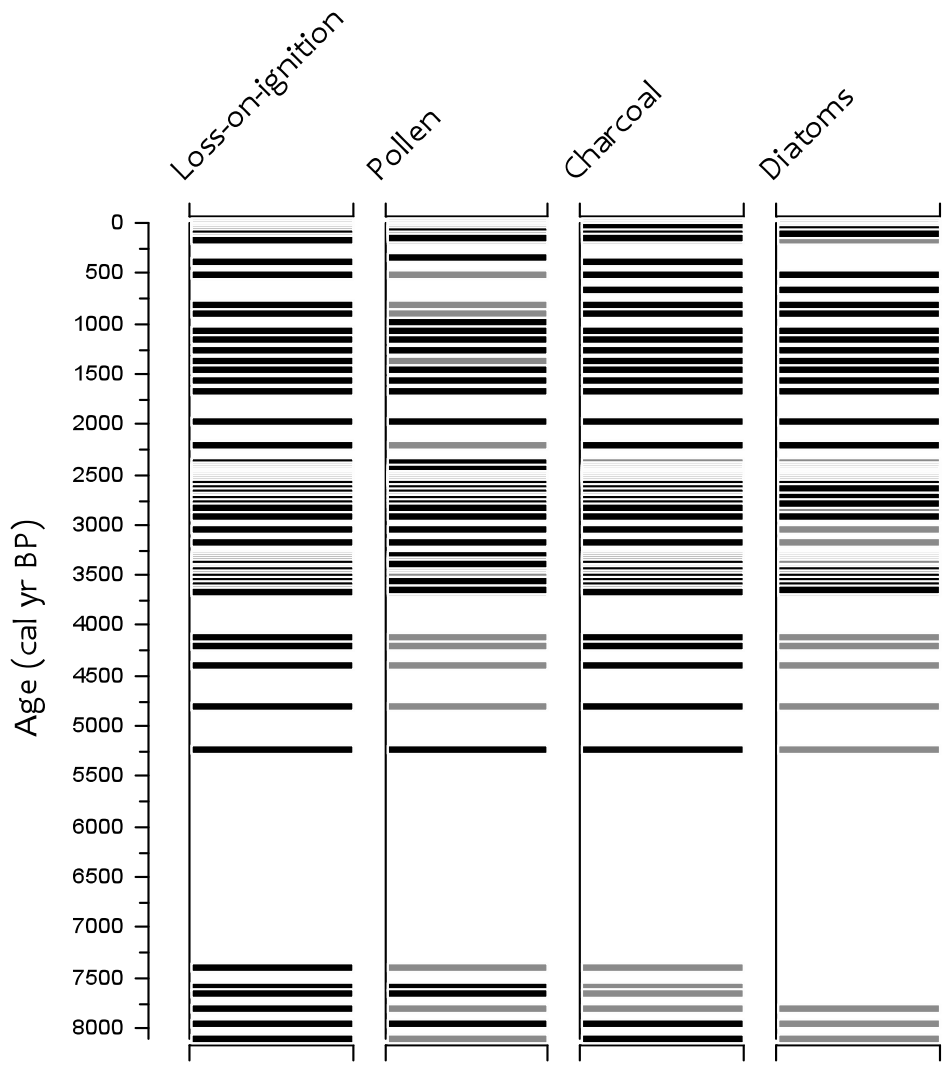




APPENDIX IV: LEVELS SAMPLED IN THE LAGUNA
SALADILLA SEDIMENT CORE



Gray bars represent levels where samples were prepared, but not included in diagrams (mostly because concentrations were too low to count). Black bars represent levels where samples were prepared and counted. Plotted based on depth in the core.



Gray bars represent levels where samples were prepared, but not included in diagrams (mostly because concentrations were too low to count). Black bars represent levels where samples were prepared and counted. Plotted based on age in the core.

Table showing where samples were prepared and counted in the core.

X = Not sampled

○ = Sampled, but not included in diagrams (mostly because concentrations were too low to count)

● = Sampled and counted

Lab code	Depth (cm)	Estimated age (cal yr BP) ⁱ	Loss-on-ignition	Pollen	Charcoal	Diatoms
MWI 6-8	7	-34	○	○	○	○
MWI 20-22	21	0	○	○	○	○
MWI 24-26	25	10	○	○	○	○
206-306/10	29	20	●	○	○	●
MWI 38-40	31	25	○	○	○	○
MWI 38-40	39	44	○	●	○	○
206-306/20	39	44	●	○	●	●
MWI 42-44	43	54	○	●	○	○
206-306/30	49	69	●	○	○	●
206-306/40	59	93	●	●	○	○
206-306/50	69	118	●	○	●	●
206-306/56	75	132	X	●	X	X
206-306/60	79	142	●	○	●	○
206-306/66	85	157	X	●	X	X
206-306/70	89	169	●	○	○	○
306-406/8	127	353	X	●	X	X
306-406/10	129	381	●	X	○	X
306-406/20	139	523	●	○	●	●
306-406/30	149	665	X	X	○	●
306-406/40	159	807	●	○	●	●
306-406/50	169	904	●	○	●	●
306-406/60	179	990	X	●	X	X
306-406/70	189	1077	●	●	●	●
306-406/80	199	1163	●	●	●	●
306-406/90	209	1265	●	●	●	●
306-406/100	219	1366	●	○	●	●
406-506/10	229	1468	●	●	●	●
406-506/20	239	1569	●	●	●	●
406-506/30	249	1671	●	●	●	●
406-506/42	261	1980	●	●	●	●

406-506/50	269	2211	●	○	●	●
406-506/60	279	2380	●	●	○	○
406-506/69	288	2428	●	○	●	●
406-506/80	299	2435	●	○	●	●
406-506/86	305	2440	●	○	●	●
503-603/10	326	2454	●	●	●	●
503-603/20	336	2462	●	○	●	●
503-603/30	346	2469	●	○	●	●
503-603/40	356	2477	●	○	●	●
503-603/50	366	2484	●	○	●	●
503-603/60	376	2492	●	○	●	●
503-603/70	386	2499	●	●	●	●
503-603/80	396	2507	●	●	●	●
520-620/70	403	2512	X	X	X	○
503-603/90	406	2514	●	●	●	●
520-620/80	413	2520	●	●	●	○
503-603/100	416	2523	●	●	●	●
520-620/90	423	2531	●	●	●	●
520-620/98	431	2539	●	●	●	●
620-720/10	443	2552	●	●	●	●
620-720/20	453	2562	●	●	●	●
620-720/30	463	2572	●	●	●	●
620-720/40	473	2583	●	●	●	●
620-720/50	483	2593	●	●	●	●
620-720/60	493	2604	●	●	●	●
620-720/72	505	2645	●	●	●	●
620-720/80	513	2677	●	●	●	○
620-720/90	523	2716	●	●	●	●
620-720/99	532	2752	●	●	●	○
720-820/10	543	2795	●	●	●	●
720-820/20	553	2834	●	●	●	○
720-820/30	563	2927	●	●	●	●
720-820/40	573	3056	●	●	●	○
720-820/50	583	3184	●	●	●	○
720-820/60	593	3303	●	●	●	○
720-820/70	603	3328	●	○	●	○
720-820/80	613	3353	●	○	●	○
720-820/88	621	3373	●	●	●	○
720-820/98	631	3398	●	●	●	○
820-920/10	643	3428	●	○	●	●
820-920/20	653	3453	●	○	●	●
820-920/30	663	3490	●	○	●	●
820-920/40	673	3528	●	○	●	●

820–920/50	683	3566	●	●	●	●
820–920/60	693	3604	●	○	●	●
820–920/70	703	3639	●	●	●	●
820–920/80	713	3673	●	○	●	○
820–920/90	723	4119	●	○	●	○
820–920/96	729	4213	●	○	●	○
838–938/82	733	4388	●	○	●	○
838–938/90	741	4811	●	○	●	○
838–938/98	749	5235	●	●	●	○
938–1038/39	790	7405	●	○	○	X
938–1038/64	815	7602	●	●	○	X
938–1038/70	821	7650	●	●	○	X
938–1038/80	831	7809	●	○	○	○
938–1038/90	841	7967	●	●	●	○
938–1038/98	849	8108 ⁱⁱ	●	○	●	○

ⁱInterpolated ages based on weighted mean ages listed in Table 4.1.

ⁱⁱExtrapolated age based on basal date β 160460.

APPENDIX V: SHELL DATA

This list of shell and other carbonaceous remains encountered in the Saladilla sediment samples is based on work by Ken Orvis (Orvis, unpublished data). Bold numbers represent contemporaneous shell remains. Italicized numbers are contemporaneous and remobilized remains. Numbers without any emphasis are remobilized Pleistocene fossils.

	Depth (cm)																		
	837	836	826	817	811	806	801	796	792	786	781	776	771	766	760	737	731	720	665
<i>Andara chemnitzii</i>															1				
<i>Anadara ovalis</i>															1				
<i>Atys riiseana</i>								1											
<i>Cerithium algicola</i>																	1		
<i>Chione cancellata</i>										1					1				
<i>Corbula aequivalvis</i>								1					2		1	1	1		
<i>Corbula cf. contracta</i>	1	1		3			3	4		1	2	1	4		3	1		1	
<i>Crassinella guadalupensis</i>					1		1												
<i>Diodora cf. arcuata</i>										1									
<i>Macoma sp.</i>				1															1
<i>Tellina cf. aequistriata</i>				1															
<i>Trachycardium cf. magnum</i>															1		1		
<i>Turbonilla abrupta</i>	2						1					1							
<i>Brachidontes recurvus</i>								1				1							
<i>Ostrea cf. frons</i>	2																		
<i>Codakia orbiculata</i>		1																	
<i>Solen obliquus</i>								1											
<i>Lucapinella cf. limatula</i>										1					1				
Coral fragment	1			1		1	1								1		1		
Indeterminate mollusk fragment	1		1	1	1	1	1	1	1	1	1	1		1	1		1		

Key:

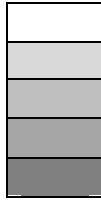
Shallow water, marine

Intertidal

Unknown

Mid depth marine (10–150 m)

Low tide, high energy shores



VITA

Maria Caffrey was born in London, United Kingdom in 1981. She earned her Bachelor of Science (Hons) degree in geography from the University of Plymouth in Devon, United Kingdom in 2004. She was first introduced to paleoenvironmental research by Dr. C. Neil Roberts, who taught her diatom ecology. She was later introduced to palynology while studying as an exchange student at the University of Denver. For her undergraduate thesis research, she used both proxies together with loss-on-ignition analysis to study the paleoecological effects of the Younger Dryas on Grand Mesa, Colorado.

In 2007, Maria received her Master of Arts degree in geography from the University of Denver. Her thesis research examined paleoclimate in highland Guatemala as reconstructed from pollen, charcoal, and sediment geochemistry at Miquil Meadow, Guatemala. It was through this research, under the guidance of Dr. Matthew Taylor, that she was introduced to tropical paleoecology and paleoclimatology.

Maria has used paleoenvironmental proxies in a number of other research projects during her undergraduate and graduate career, such as identifying the spread of invasive species from surface pollen samples collected across Sonora and Baja California, Mexico; reconstructing the last 7000 yrs of vegetation and fire in Bear Lake, Colorado; developing a new heavy liquid technique to separate pollen from sediments using lithium heteropolytungstate; extracting dinoflagellates from carbonaceous sediments; and identifying ancient tobacco pollen from residues in archaeological pipes. In recognition

of her extensive graduate research involving pollen, Maria was awarded a scholarship from the AASP — The Palynological Society in 2009.

For her Ph.D. dissertation at the University of Tennessee, Maria undertook a study of the paleoenvironment of Laguna Saladilla, Dominican Republic, to reconstruct changes in Caribbean climate during the Holocene. As part of her research she travelled to Puerto Rico and across the Dominican Republic. In the future she hopes to expand her paleoenvironmental research in the Caribbean and Central America to further our understanding of how aquatic as well as terrestrial communities and environments responded to changes in climate in the past. She aims to use her expertise in paleoenvironmental change to assist in predicting the impacts of future climate change in Latin America.