A 6000-year record of ecological and hydrological changes from Laguna de la Leche, north coastal Cuba

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Abstract

Laguna de la Leche, north coastal Cuba, is a shallow (≤ 3 m), oligohaline (~ 2.0–4.5‰) coastal lake surrounded by mangroves and cattail stands. A 227-cm core was studied using loss-on-ignition, pollen, calcareous microfossils, and plant macrofossils. From ~ 6200 to ~ 4800 cal yr BP, the area was an oligohaline lake. The period from ~ 4800 to ~ 4200 cal yr BP saw higher water levels and a freshened system; these changes are indicated by an increase in the regional pollen rain, as well as by the presence of charophyte oogonia and an increase in freshwater gastropods (Hydrobiidae). By ~ 4000 cal yr BP, an open mesohaline lagoon had formed; an increase in salt-tolerant foraminifers suggests that water level increase was driven by relative sea level rise. The initiation of Laguna de la Leche correlates with a shift to wetter conditions as indicated in pollen records from the southeastern United States (e.g., Lake Tulane). This synchronicity suggests that sea level rise caused middle Holocene environmental change region-wide. Two other cores sampled from mangrove swamps in the vicinity of Laguna de la Leche indicate that a major expansion of mangroves was underway by ~ 1700 cal yr BP.
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Introduction

Because of their location at the interface between marine and terrestrial environments, coastal ecosystems are complex and dynamic systems. Since the natural and anthropogenic processes that affect coastal environments operate at a range of timescales, understanding how coastal systems will respond to future environmental variability is facilitated by an historical perspective. Furthermore, in order to explain the causes of global-scale environmental changes, additional historical data are needed from the tropics, an area of the world for which there have been few paleoenvironmental studies. With these points in mind, our aim is to study the processes driving millennial-scale ecological and hydrological variability on a tectonically stable tropical coastline. To do

this, we examined sediments recovered from and within the vicinity of the largest natural lake in Cuba, Laguna de la Leche. Located on the north coast of central Cuba, Laguna de la Leche has never been studied paleolimnologically. It was chosen as a study site for our paleoenvironmental investigations because it is large enough to provide an archive of regional environmental changes, and its proximity to the ocean means that it is likely to be sensitive to changes in relative sea level (RSL). In this paper, we present, analyze, and discuss stratigraphic, palynological, calcareous microfossil (foraminiferal, ostracode, gastropod, and charophyte), and plant macrofossil data. Stable isotopes of oxygen, carbon, and strontium were also studied from Laguna de la Leche to identify past salinity fluctuations and to investigate their causes (Peros et al., in press). In addition to our paleoenvironmental objectives, another impetus behind our work is Caribbean prehistory. North-central Cuba has a rich archaeological heritage and is home to one of the largest and best preserved prehistoric settlements in the Caribbean (Pendergast et al., 2001). This paper provides a detailed environmental

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framework to guide ongoing archaeological research in the region (Peros et al., 2006).

Due to a scarcity of sites suitable for paleolimnological investigations, there are comparatively few lacustrine records of late Quaternary environmental changes from the Caribbean (Higuera-Gundy et al., 1999). The longest, continuous record (12,000 ^{14}C yr BP to the present) is from Lake Antoine, Grenada, where pollen data record a shift from a marsh dominated by palm (possibly *Sabal palmetto*) to a lake at approximately 4,000 ^{14}C yr BP (McAndrews and Ramcharan, 2003). At Lake Miragoane, Haiti, Hodell et al. (1991) used the δ^{18}O of fossil ostracode shells to show that the Caribbean became gradually wetter from ~10,000 to 6000 ^{14}C yr BP, followed by generally drier conditions. Higuera-Gundy et al. (1999) also studied fossil pollen from Lake Miragoane and showed that vegetation tracked the climatic changes seen in the isotopic data by shifting from a shrubby, xeric community in the early Holocene to a moist forest in the middle Holocene; in the last millennium the pollen record reflects pre-Columbian (Taino) and European deforestation. In the Bahamas, pollen from a sink-hole records a relatively dry period from 3000 to 1500 ^{14}C yr BP, followed by a period of wetter climate, although two ^{14}C inversions indicate the chronology of the core used in this study may be unreliable (Kjellmark, 1996). Fossil ostracodes from Wallywash Great Pond, Jamaica, show that lake level fluctuated several times during the Late Quaternary, with a high period occurring 125,000–93,000 yr ago, a depositional hiatus from 93,500 to 10,500 yr ago, and stabilization at its present position by ~1000 ^{14}C yr BP (Holmes, 1998). While these studies (and others; e.g., Leyden, 1985) have added to our knowledge of long-term environmental variability in the region, additional research is needed from the Caribbean to test regional and global-scale models of climatic and RSL variability (Ruter et al., 2004; Peltier, 2002). Our work at Laguna de la Leche marks the beginning of a broader research program designed to document and explain the dynamics of long-term environmental–human interactions in the wider Caribbean region. In this paper, we provide the first pollen record for Cuba and generate new paleoenvironmental data that will aid our understanding of contemporary coastal processes in the tropics.

Site description

Laguna de la Leche is located on the north coast of the Province of Ciego de Avila, Cuba (Fig. 1). The coastline consists of an active coral reef, the Archipiélago Sabana-Camagüey, separated from the mainland by a shallow (<2 m) bay, the Bahía de Perros. The bay is hypersaline, with a maximum tidal range of 30 cm. Laguna de la Leche has a surface area of ~67 km^2 and has a maximum depth of 3 m (Borhidi, 1996). Multiple measurements undertaken in June 2003 indicate that its surface salinity ranges from ~2.0 to 4.5‰, with higher values at its northern end. Mean pH of the surface water is 7.6. The surface of Laguna de la Leche is ~50 cm above mean sea level (msl).

North-central Cuba has a winter dry period from November to March, a summer dry period in June and July, and two rainy seasons from April to May and August to October (Borhidi, 1996). Mean annual mean daily temperature and precipitation are 25.8°C and 1150 mm, respectively, and the seasonal mean daily temperature normally varies by only 5°C (Nuevo Atlas Nacional de Cuba, 1989). Precipitation is often less than 50 mm per month during the dry periods and over 180 mm per month during the rainy seasons (Borhidi, 1996; Nuevo Atlas Nacional de Cuba, 1989). Category 3 (or greater) hurricanes pass near the Laguna de la Leche area roughly once every 20 years; the most recent was Hurricane Michelle in November 2001 (National Hurricane Center, 2005).

Most of the elevation of the north coast of central Cuba is below 5 m above msl. However, three salt domes—Punta Alegre, Turiguano, and Cunagua—outcrop in the region. The Turiguano diapir consists of gypsum overlying halite and limestone (Ituralde-Vinent and Roque-Marrero, 1982). All three diapirs pierced the surface by the late Pliocene, but the region appears to have been tectonically stable throughout the Quaternary (Lewis and Draper, 1990; Carew and Mylroie, 1995). Laguna de la Leche ('Milk Lagoon') derives its name from the whitish appearance of its water, apparently due to the abundant calcite and gypsum particles within the basin.

Present-day vegetation has been documented from our observations, topographic maps, and previous researchers (Borhidi, 1996; Borhidi and Muñiz, 1984). The areas to the northwest and east of Laguna de la Leche consist of large expanses of *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove), and *Conocarpus erectus* (button-wood mangrove); smaller quantities of the succulents *Batis maritima* (saltwort) and *Salicornia perennis* (glasswort); and various grasses, including *Vetiveria zizanioides* (vetivergrass), *Distichlis spicata* (salt grass), and *Spartina alterniflora* (smooth cord grass). Monospecific stands of the sedges *Cladium jamaicense* (saw grass) and *Eleocharis rostellata* (beaked spikerush) fringe the lake in shallow water. *Sabal palmetto* (cabbage palm) also grows in drier areas around the lake within stands of *V. zizanioides* and other grasses and shrubs. To the south and east of Laguna de la Leche is a large, monospecific stand of *Typha domingensis* (southern cattail), although isolated clusters of *R. mangle* grow amid the *T. domingensis* near the Cunagua diapir.

In north-central Cuba, *Rhizophora mangle* tends to grow in areas that are permanently inundated with shallow (~30 cm) saline water; *Conocarpus erectus* in dry conditions, just above high tide; and *Avicennia germinans* in conditions that are transitional between the two. *Batis maritima* and *Salicornia perennis* both grow slightly above high tide in open-canopy areas. *Typha domingensis* normally grows in both fresh and slightly brackish systems on the edges of marshes and ponds (Glenn et al., 1995; Tobe et al., 1998) and in the vicinity of Laguna de la Leche, occupying areas that fluctuate between wet (~10 cm of standing water) and dry conditions, depending on season. The dry upland surrounding Laguna de la Leche consists mostly of sugarcane, banana, and orange plantations, often separated by stands of *Roystonea regia* (royal palm).
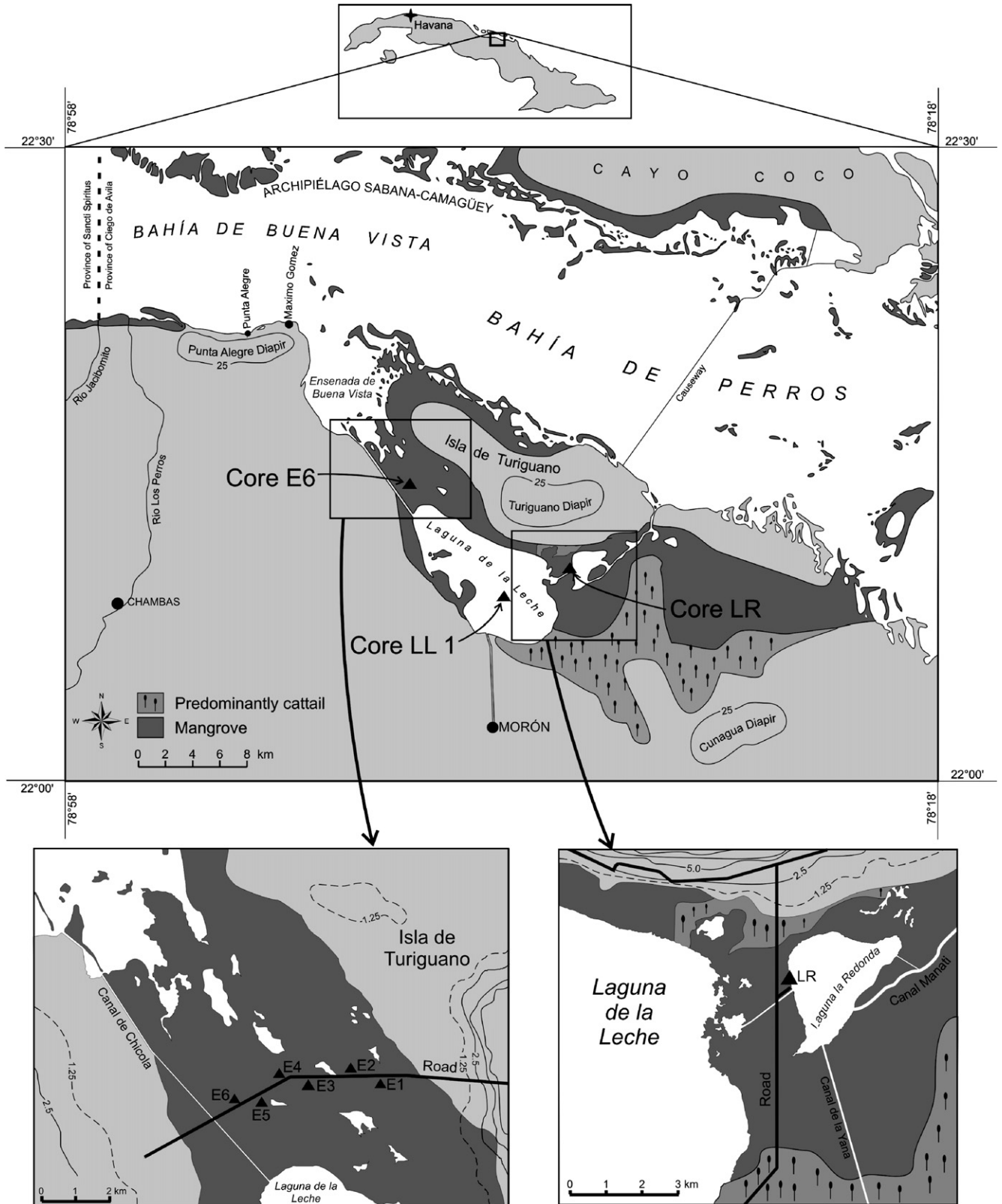
Figure 1. Map of the study region with coring sites indicated. Only the 25-m contours are shown; virtually the entire region is below 5 m. The maximum elevations of the diapirs are Punta Alegre, 138 m; Turiguano, 105 m; Cunagua, 315 m. For the bottom two frames, the contour interval is 2.5 m, with the exception of the 1.25-m contour.

Borhidi and Muñiz (1984) suggest that the natural potential vegetation of this area of Cuba would be mesophytic semi-deciduous forest and savanna with stands of *R. regia*. However, the name Ciego de Avila translates as "Avila's dense forest", suggesting that the landscape may have been more heavily forested when the Spanish arrived in the region in the 18th century (D.M. Pendergast, personal communication, 2005). Also, large quantities of wooden archaeological remains from the Los Buchillones site (∼AD 1220 to 1640), near Punta Alegre (Fig. 1), are made of *Guaiacum officinale* (lignum vitae), an evergreen hardwood once common throughout the Caribbean, suggesting that *G. officinale* was common in the region prior to Spanish arrival (Pendergast et al., 2001).

Laguna de la Leche drains into the Bahía de Buena Vista and the Bahía de Perros through two engineered canals: one is 15 m wide and 2 m deep, flows northeast into Laguna la Redonda, and connects to the natural Canal Manatí; the other (Canal de Chicola) is 20 m wide and 3.5 m deep and flows to the northwest. Another artificial canal (Canal de Júcaro) connects Laguna de la Leche to the city of Morón to the south. No natural rivers presently enter or leave the basin.

Methods

Ten cores were sampled for this study using a Livingstone piston sampler: six from the mangrove area northwest of Laguna de la Leche, at roughly evenly spaced intervals north and south of a road (cores E1–E6); one from the edge of Laguna la Redonda (core LR); and three from Laguna de la Leche itself (cores LL1–LL3). Of these ten cores, the three longest from each area (cores E6, LR, and LL1) were selected for detailed stratigraphic and paleoecological study; the others were described for their stratigraphy and bulk sediment composition.

Core LL1 (22°12′N, 78°37′W) was lifted from near the center of Laguna de la Leche in 3 m of water (Fig. 1). The site of core E6 (22°16′29″N, 78°42′12″W) was located near the Canal de Chicola (Fig. 1). Core LR (22°12′45″N, 78°34′18″W) was lifted west of Laguna la Redonda (Fig. 1). Refusal depth in each case was determined by impenetrable (coarse or clayey) sediment. The cores were wrapped in polyethylene sheets and sealed in solid containers for transport to Toronto.

In the laboratory, each core was split lengthwise and its colour and texture were described. Approximately 3 cm^3 of sediment was sampled at 10-cm intervals to estimate the proportion of organic matter (OM), calcium carbonate (CaCO$_3$), and silicate material by loss on ignition (LOI) following procedures outlined by Dean (1974) and Heiri et al. (2001). Samples were oven dried overnight at 110°C and combusted for 2 h at 550°C, cooled in a dessicator and weighed; the samples were then combusted at 1000°C for 2 h, cooled in a dessicator, and weighed again. Ignition at 550°C was deemed suitable given the low quantity of clay in each sample (Beaudoin, 2003). The percent weight of CaCO$_3$ was determined by dividing the loss in weight after LOI at 1000°C by 0.44, the proportion of CO$_2$ in CaCO$_3$ (Dean, 1974). Silicates were calculated using the dry weight of the original sample minus the sum of the OM and CaCO$_3$.

Samples for pollen analysis were taken from all three cores at intervals of 3 to 10 cm. Pollen was concentrated by sieving (see Cwynar et al., 1979) and treatment with HCl, KOH, HF, glacial acetic acid, and acetolysis solution. A known number of exotic *Lycopodium* spores were also added to pollen preparations to determine pollen concentration in grains per milliliter, and pollen influx was then calculated by multiplying the pollen concentration by the sediment accumulation rate for each level (Faegri and Iversen, 1989). Pollen identification was made using slide reference material from the Royal Ontario Museum and atlases (Bush and Weng, in press; Colinvaux et al., 1999; Roubik and Moreno, 1991). At least 400 grains were counted per level.

Core LL1 was sampled for calcareous microfossils (foraminifera, ostracodes, gastopods, and charophytes) at intervals of roughly 10 cm and at closer intervals where abrupt changes in lithology occurred. The calcareous microfossils were concentrated by wet sieving and retaining the 2 mm–45 μm fraction; they were then separated from the heavier minerals by floatation with tetrachloroethylene. At least 400 foraminifera and other microfossils were counted per sample. In the case of the ostracodes, articulated carapaces were considered to be a single specimen; disarticulated carapaces were counted although their total was halved so as to not overestimate ostracode abundance. Identifications were made using reference atlases and published articles (Wood, 1967; Jones and Bock, 1971; Buzas et al., 1977; Dix et al., 1999; Thompson, 2004).

Plant macrofossils were also sampled from core LL1 by sieving 1-cm-thick samples through 63 μm mesh and retaining the coarse fraction. Identifications were made with reference to an online atlas (Byrne, 2005) and expert advice (L.A. Newsom, personal communication, 2005).

To generate biostratigraphic zones, stratigraphically constrained cluster analysis was undertaken using the Orlóci's chord distance transformation on CONISS (Constrained Incremental Sum of Squares) (Grimm, 1987; Legendre and Legendre, 1998). Orlóci's chord distance was selected to avoid a circumstance whereby samples that have few species in common appear more similar than other samples sharing more species (Legendre and Legendre, 1998; Finkelstein et al., 2005).

Radiocarbon dates were obtained to provide chronologies for the sediment cores. Peat samples were sent from cores E6 and LR for conventional ^{14}C dating, whereas bulk sediment samples from core LL1 were sent for dating by AMS. In the latter case, bulk organic matter was isolated from the sediment matrix for dating. Calibration of the ^{14}C data was performed with CALIB 5.0.1 (Stuiver and Reimer, 1993) using the intcal04.14c dataset (Reimer et al., 2004). All dates are reported in calibrated years before present (cal yr BP) using the 2σ range.

Results

Core E6 and its stratigraphic setting

The site of core E6, northwest of Laguna de la Leche, is seasonally dry. The vegetation consists of a mixed stand of

Rhizophora mangle and *Conocarpus erectus*. Core E6 is 150 cm long and consists of three facies: a basal unit consisting of clay and small pebbles from 134 to 150 cm; an intermediate unit of organic-rich mud from 102 to 134 cm; and a peat unit from 0 to 102 cm (Fig. 2). The LOI results show that silicates constitute approximately 70% of the dry weight of the sediment from 122 to 150 cm and, with the exception of the uppermost sample, decrease in abundance upcore. Organic matter constitutes ~50–60% of the dry weight of the core from 10 to 90 cm; $CaCO_3$ has values near 30% for the same section. Three bulk ^{14}C dates of 310–510, 1050–1290, and 1530–1810 cal yr BP provide age control (Table 1).

Pollen was identified and counted from 3 to 120 cm (Table 2). The results show that mangrove pollen, mostly *Rhizophora mangle*, is dominant throughout this section, although other taxa, such as Chenopodiaceae, occur at the base. Dry, upland plants, such as *Spondias mombin* (hog plum) and *Bursera simaruba* (birch gum), are present in small quantities throughout the core.

Cores E1–E6 allow for a generalized stratigraphy of the mangrove area to be constructed (Fig. 3). Cores E1–E3 overlie southwestward-dipping limestone, likely tilted due to the upward movement of the Turiguano diapir (Iturralde-Vinent and Roque Marrero, 1982). Core E4 appears to have the same

sand–pebble unit at its base as core E6; limestone was not reached although it likely underlies this unit. Overlying the sand and limestone in cores E3–E6 is a shelly marl with numerous roots of *Thalassia testudinum* (turtle grass), a shallow marine grass. This unit is overlain by grey-brown organic-rich marl which appears in all cores, although in core E5 the unit is whitish-pink with a gelatin-like composition. Mangrove peat of varying thicknesses overlies this marl unit in cores E1–E6. While differences in the elevation of the surface of the marsh may account for some vertical offset among the cores, the data presented in Figure 3 suggest that a shallow channel connected the Ensenada de Buena Vista to Laguna de la Leche prior to peat development at ~1,700 cal yr BP.

Core LR

Core LR, from the mangrove swamp between Laguna de la Leche and Laguna la Redonda (Fig. 1), was sampled from a monospecific stand of dense, tall *Rhizophora mangle* in 10 cm of water. The core is 140 cm long and consists of three facies: a unit of shelly sand from 111 to 140 cm; a unit from 74 to 111 cm consisting of a mixture of marl and peat; and a peat unit from 0 to 74 cm (Fig. 4). The LOI results show that $CaCO_3$ makes up approximately 70% of the dry weight of the core from 80 to
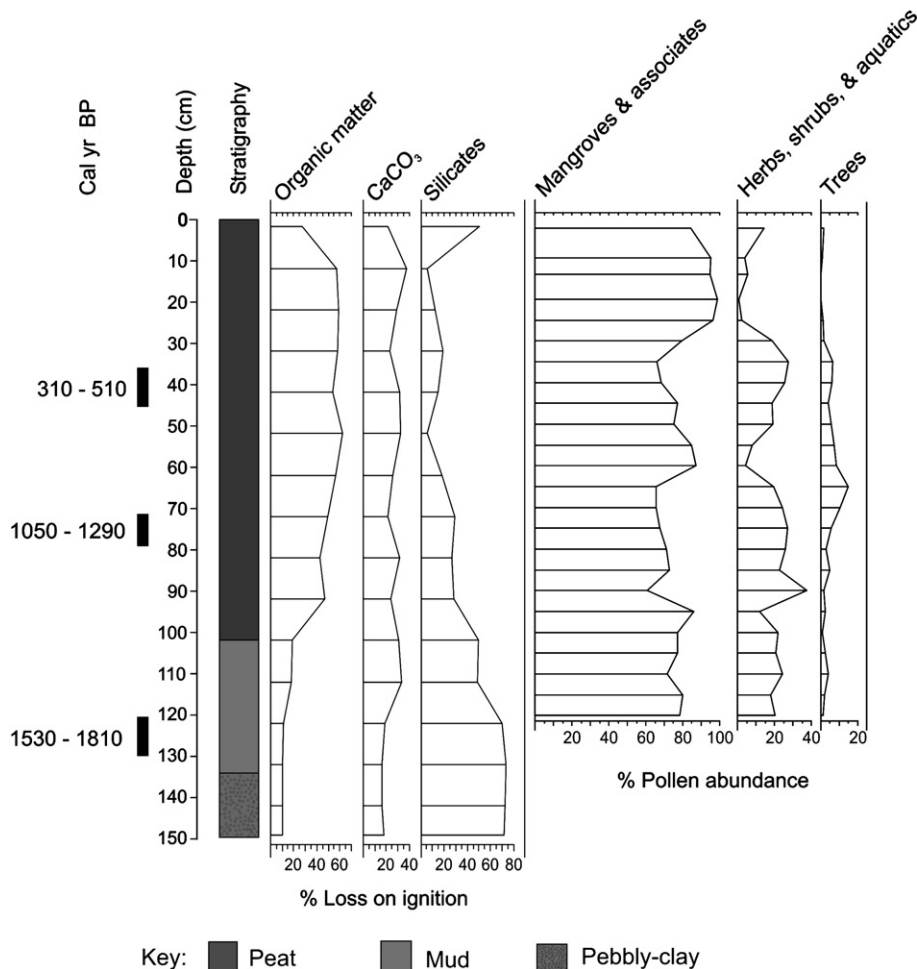

Figure 2. Core stratigraphy, LOI results, and summary percentage pollen diagram of core E6. All taxa are part of the total pollen sum.

Table 1
Radiocarbon dates and calibrated ages for the Laguna de la Leche region (this paper) and Dune Pass Bay Pond core, Bahamas (Dix et al., 1999)

Core	Depth in core (cm)	Conventional radiocarbon age (^{14}C yr BP)	δ^{13}C (‰ VPDB)	Cal yr BP (2σ confidence interval)	Material dated	Laboratory code	Cal yr BP (2σ) corrected for reservoir effect
E6	35–45	380±60	−26.1	310–510	Peat	Beta-209773	
E6	72–79	1230±80	−29.08	1050–1290	Peat	BGS2545	
E6	130–140	1730±60	−28.27	1530–1810	Peat	BGS2307	
LR	22–32	modern	−28.4	modern	Peat	Beta-209774	
LR	64–72	230±70	−24.9	60–460	Peat	Beta-209775	
LR	90–100	920±50	−26.37	650–1030	Peat	BGS2488	
LL1	12–15	2140±60	−19.7	1990–2320	OM	Beta-207504	250–660
LL1	25–29	2770±50	−19.3	2760–2980	OM	SNU04-417	1160–1380
LL1	84–89	4520±60	−15.2	4970–5320	OM	SNU4-272	3370–3720
LL1	109–115	5480±40	−14.7	6200–6320	OM	SNU03-721	4600–4720
LL1	202–208	6970±80	−22.2	7670–7950	OM	SNU03-528	6070–6350
DPBP	3.0–3.5	100	−10.1	modern	Gastropod	GX-20612-AMS	
DPBP	19–20	1880±70		1690–1950	Gastropod	TO-4590	
DPBP	56–57	2180±60	−4.8	2040–2330	Gastropod	GX-20613-AMS	
DPBP	83–84	2640±60	−4.0	2700–2870	Gastropod	GX-20614-AMS	
DPBP	133–134	3080±70		3140–3450	Gastropod	TO-4591	

The term "OM" refers to bulk organic matter. δ^{13}C values were not reported for two of the Bahamian samples.

170 cm. Organic matter constitutes 75–80% of the core from 0 to 70 cm. Three peat samples were dated; the uppermost sample (22–32 cm) had more ^{14}C than the reference standard, suggesting that the material analyzed was part of a system respiring carbon after thermonuclear bomb testing began in the 1950s and is thus essentially modern (D. Hood, personal communication, 2005). The other two dates are 60–460 and 650–1030 cal yr BP, respectively (Table 1).

Pollen was identified and counted from 110 cm to the surface (Table 2). Mangrove pollen occurs throughout the core, although increases in abundance around 75 cm from ∼50% to ∼90% of the total pollen sum. Upland plants such as *Triumfetta semitriloba* (burweed) are present in modest quantities from the base of the core to 75 cm.

Core LL1

Lithology and chronology

Core LL1, from the centre of Laguna de la Leche, is 227 cm long (Fig. 5). It consists of three facies: a greenish-grey unit from 217 to 227 cm consisting of small pebbles in a clayey-silt matrix, grey mud from 97 to 217 cm, and shell-rich marl from 0 to 97 cm. The unit from 97 to 217 cm has two 1-cm-thick layers at 123–124 cm and 116–117 cm that are dominated by ∼3-mm-long gastropods. The LOI results indicate that organic matter varies from 5 to 12% within the core and is greatest from 110 to 200 cm. Calcium carbonate is lowest in the basal unit (∼20%), it increases to around 60% in the overlying unit and constitutes 80–90% of the unit from 0 to 97 cm. Silicates compose more than 80% of the unit from 217 to 227 cm and decrease to less than 15% in the upper meter of the core.

Five ^{14}C dates on core LL1 provide age control. A linear age–depth trend of 0.24 mm·yr^{-1} is apparent from the top of the core to 112 cm, whereas a single date centered at 202 cm indicates that the mean sedimentation rate below 112 cm was 0.6 mm·yr^{-1} (Fig. 5; Table 1). Of note is a 1600-yr offset when

the age–depth model is extrapolated to 0 cm, suggesting that the dates have been influenced by a reservoir effect (i.e. age offset caused by the incorporation of ^{14}C-deficient carbon) (MacDonald et al., 1987). This claim is supported by several lines of evidence. First, numerous macrofossils of several aquatic plants (e.g., *Najas*) have been found throughout the core (Fig. 7). These plants normally assimilate bicarbonate from the water in which they grow (Olsson and Kaup, 2001). Because the bulk organic matter submitted for dating produced δ^{13}C values (Table 1) typical of those associated with submerged aquatic plants (Farquhar et al., 1989), it is likely that detritus from these plants was measured for the ^{14}C analysis. Second, four ^{14}C-dated gastropods from a core taken from Dune Pass Bay Pond, Bahamas, show an almost identical age offset, which has been attributed to a reservoir effect in that geologically similar area (Dix et al., 1999). Third, the limestone rocks surrounding Laguna de la Leche would provide a significant source of ^{14}C-deficient carbon. In order to account for the apparent reservoir effect at Laguna de la Leche, we subtracted 1600 yr from each calibrated ^{14}C date. A uniform correction for each date is appropriate because, as will be shown, the initiation of the Laguna de la Leche wetland correlates to a major environmental shift in Florida when a systematic correction of 1600 yr is applied.

Calcareous microfossils

Well-preserved calcareous microfossils occur in core LL1 from 0 to 215 cm and are particularly abundant from 0 to 97 cm. The assemblage includes at least eleven foraminifera, the oospores of a charophyte, and several ostracode and gastropod taxa (Fig. 6). A stratigraphically-constrained cluster analysis of the foraminiferal data defines two main zones. Zone 1, from 83 to 215 cm, can be divided into two subzones, 1a and 1b. Subzone 1a consists of the euryhaline foraminifer *A. beccarii* and sympathetically fluctuating quantities of ostracodes and gastropods. The foraminifera in subzone 1b also consist of *A. beccarii*, but the ostracodes and gastropods abruptly increase in

Table 2
List of pollen types identified in cores E6, LR, and LL1

Plant	E6	LR	LL1
Mangroves and associates			
Rhizophora mangle	X	X	X
Avicennia germinans	X	X	X
Conocarpus erectus	X	X	X
Acrostichum aureum	X	X	X
Hippomane mancinella	X		
Aquatics			
Cyperaceae	X	X	X
Nymphaea	X	X	X
Poaceae	X	X	X
Potamogeton	X		X
Ruppia maritima			X
Typha domingensis	X	X	X
Herbs and shrubs			
Acalypha			X
Adiantum	X	X	
Arrabidaea	X	X	X
Asteraceae	X	X	X
Batis maritima	X	X	X
Bauhinia		X	
Begonia			X
Cayaponia	X	X	X
Chenopodiaceae	X	X	X
Euphorbiaceae	X	X	
Polypodiaceae (monolete)	X	X	X
Polypodiaceae (trilete)			X
Selaginella			X
Triumfetta semitriloba	X	X	X
Upland trees			
Alnus	X		X
Anacardiaceae	X		X
Arecaceae			X
Bursera simaruba	X	X	X
Caesalpinioideae			X
Celtis	X		X
Ficus	X		
Meliaceae			X
Moraceae	X	X	X
Pinus caribaea	X	X	X
Protium	X	X	X
Pouteria			X
Rubiaceae			X
Spondias mombin	X	X	X
Tabebuia			X
Tapirira		X	X
Tilia	X		X
Ulmus	X	X	X

abundance at the subzone 1a–1b boundary, and then decrease in quantity as they approach zone 2. In addition, oogonia of the charophyte *Chara canescens f. hitsuta* or *C. fibrosa* occur in subzone 1b and have a maximum abundance that slightly lags the ostracode and gastropod peaks (García, 1994; Wood, 1967). In both subzones 1a and 1b, the gastropods all belong to the fresh/brackish-water family Hydrobiidae and may include *Heleobops* spp. and *Littoridinops* spp. (Thompson, 2004), whereas the ostracodes are all Podocopida and include the euryhaline *Cyprideis edentate* and *Perissocytheridea*

cribrosa and the freshwater *Physocypria* spp. and *Cypridopsis vidua*, and likely other taxa (Maddocks, personal communication, 2005). The presence of *A. beccarii* in association with these ostracodes, gastropods, and charophyte oogonia suggests that throughout subzone 1a salinity conditions were oligohaline (<5‰), and that a freshening occurred in subzone 1b.

Zone 2, from 0 to 83 cm, is characterized by an increase in foraminiferal diversity, particularly the concurrent appearance of *Elphidium* spp. and the miliolid *Triloculina oblonga*. Small quantities of *Quinqueloculina* spp., *T. bermudezi*, *T. oblonga* and *T. rotunda* also occur. A slight decrease in *T. oblonga* occurs at both 15 cm and 19 cm. *Ammonia–Triloculina* assemblages have been identified in Holocene sediments from western Cuba (Alvarez García and Borro García, 1979a,b) and elsewhere in the Caribbean, such as Lee Stocking Island, Bahamas (Dix et al., 1999), and Barbuda (Brasier, 1975). These assemblages are indicative of higher salinities than appear to have occurred in zone 1, consistent with the virtual absence of the ostracodes, gastropods, and charophyte oogonia from zone 2 (Dix, et al., 1999; Murray, 1991). While the euryhaline nature of *Ammonia beccarii*, *Elphidium* spp., and *T. oblonga* makes it difficult to provide a more precise estimate of the salinity of zone 2, the proportions of these taxa are suggestive of a mesohaline (5–18‰) system (Murray, 1991).

Pollen

Pollen was identified from 5 to 210 cm. In general, pollen preservation is good, although Poaceae grains tend to be folded or torn. Thirty-eight pollen taxa (Table 2) were identified and two primary pollen zones were defined on the basis of the stratigraphically-constrained cluster analysis results and visual inspection of the data (Fig. 7). Zone 1, from 97 to 210 cm, consists of two subzones, 1a and 1b. Subzone 1a is from 122 to 210 cm and is characterized by high percentages of Chenopodiaceae, Asteraceae (Aster family), and *Typha domingensis*. Based on pollen size and morphology, as well as its presence in the region today, most of the Chenopodiaceae pollen is probably from the plant *Salicornia perennis*. Smaller percentages of the ferns *Acrostichum aureum* (mangrove fern) and *Adiantum* spp. (maidenhair fern), and the succulent *Batis maritima* are also present, along with Poaceae and *Cayaponia* spp. (melonleaf)—an herbaceous vine found alongside streams and in swamps (Tobe et al., 1998). Pollen influx fluctuates throughout this subzone and abruptly increases at 125 cm. Based on the nature of the taxa and the relatively high influx of pollen in this portion of the core, the pollen assemblage in subzone 1a appears to have had a predominantly local origin.

Subzone 1b, from 97 to 122, is similar to subzone 1a, although it is characterized by a decrease in *Acrostichum aureum* and Chenopodiaceae; and an increase in *Typha domingensis* (which is at its highest abundance in the core), Euphorbiaceae (spurge family), and Moraceae. The pollen influx in the core is at its highest in subzone 1b; the fresher water conditions, as recorded in the calcareous microfossils, may have increased plant density and hence pollen rain.
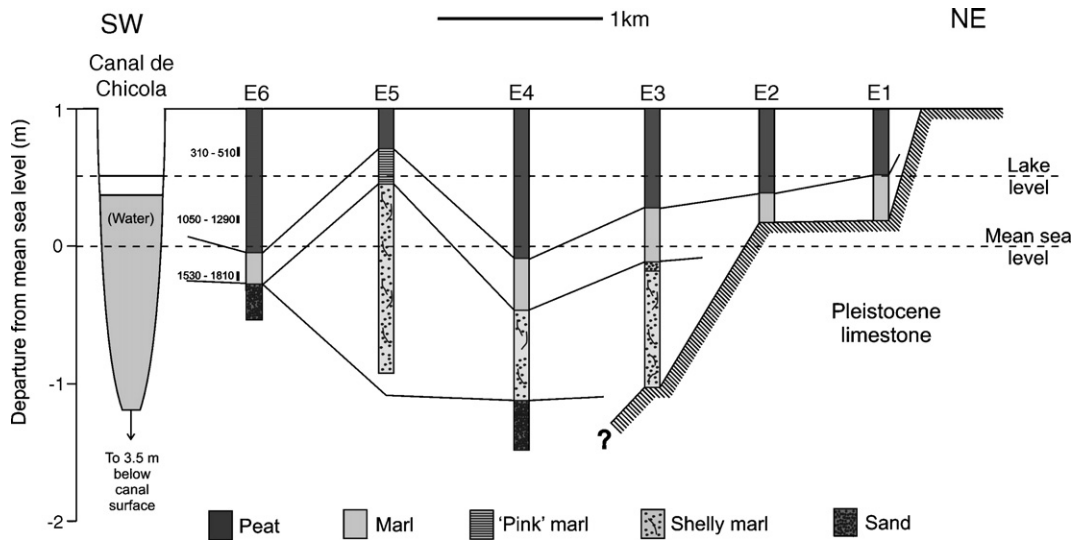
Figure 3. Stratigraphy of mangrove area northwest of Laguna de la Leche (Fig. 2). Vertical exaggeration is 150×. Calibrated (2σ) radiocarbon dates are reported for core E6.
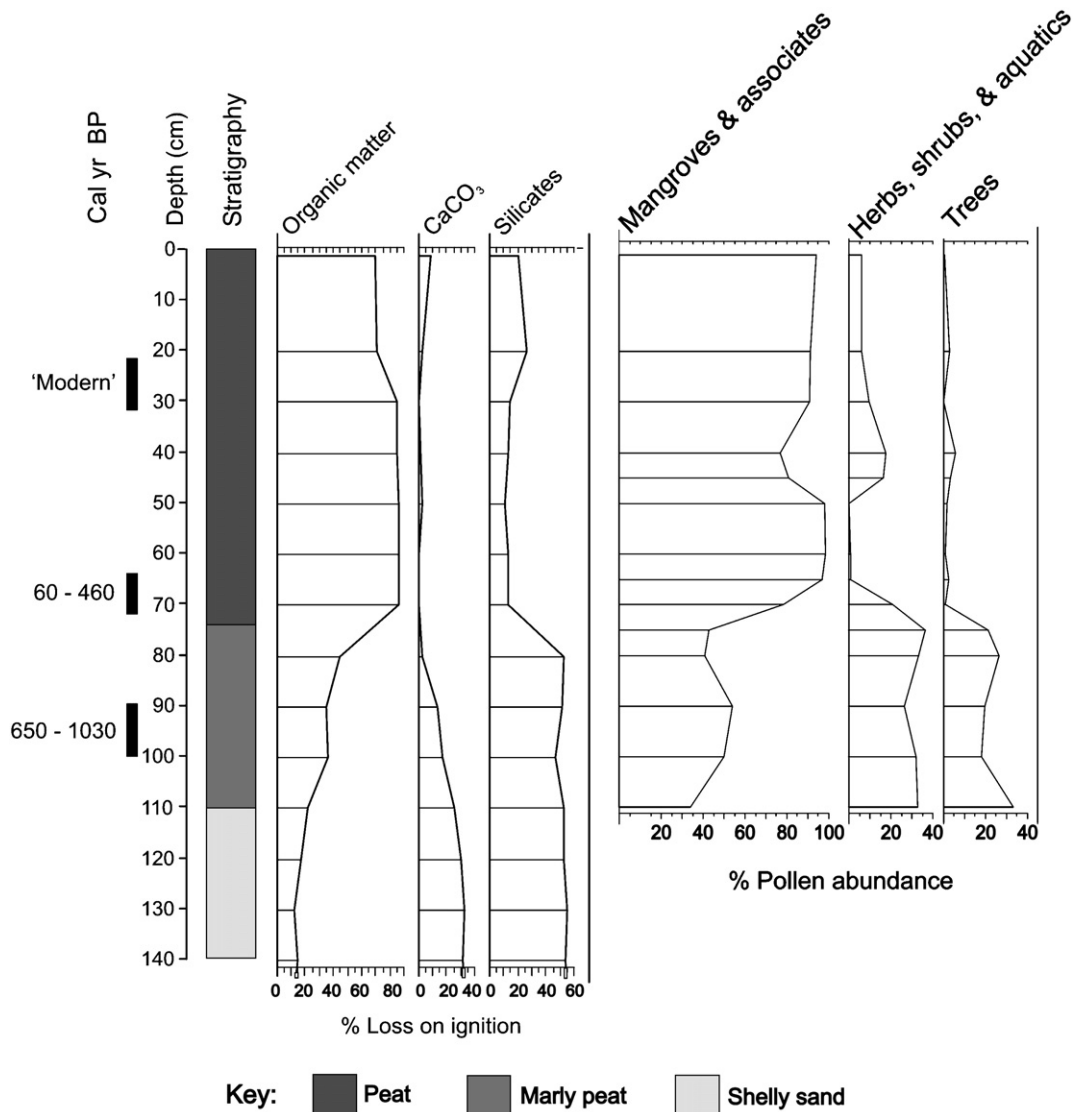

Figure 4. Core stratigraphy, LOI results, and summary percentage pollen diagram for core LR. All taxa are part of the total pollen sum.
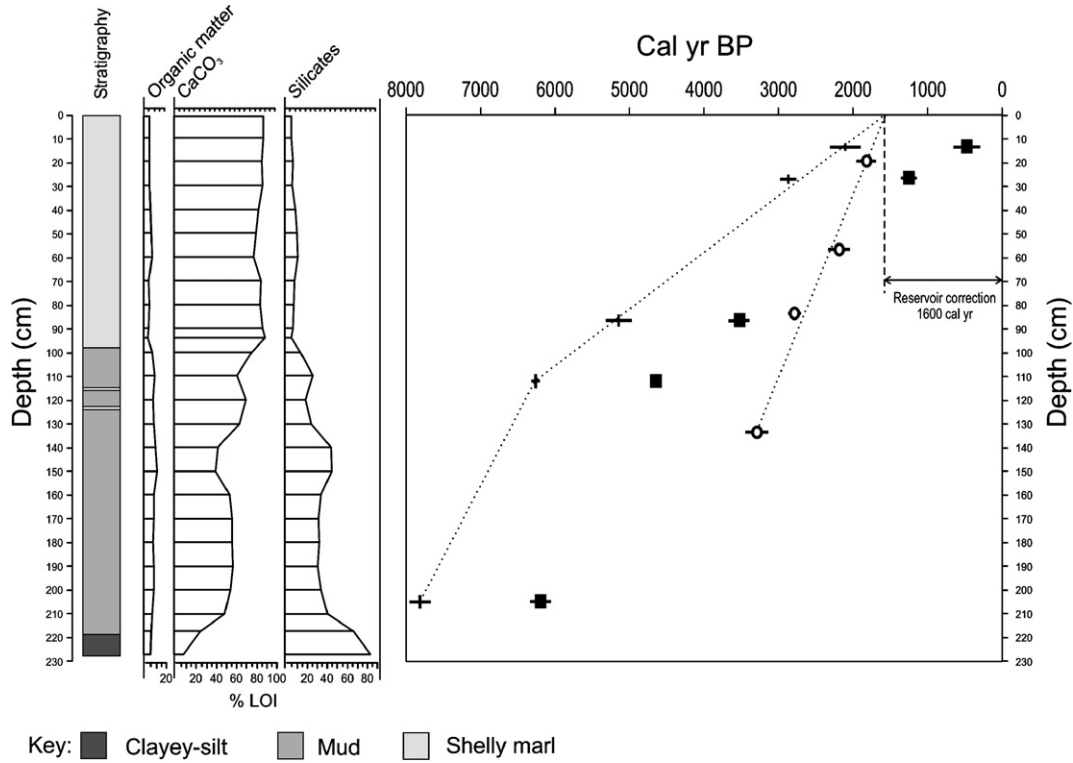
Figure 5. Core stratigraphy, LOI, and radiocarbon data from core LL1, Laguna de la Leche. The crosses are uncorrected; calibrated radiocarbon dates in yr BP (the vertical shafts refer to the thickness of each sample used for dating). The black boxes represent the same samples corrected for a reservoir error of 1600-year. The open circles are radiocarbon data from Dune Pass Bay Pond, Bahamas (Dix et al., 1999). In all cases the horizontal bars are equivalent to the 2σ error range. Note that the best-fit lines for the Cuban and Bahamian data converge at 1600 cal yr BP.
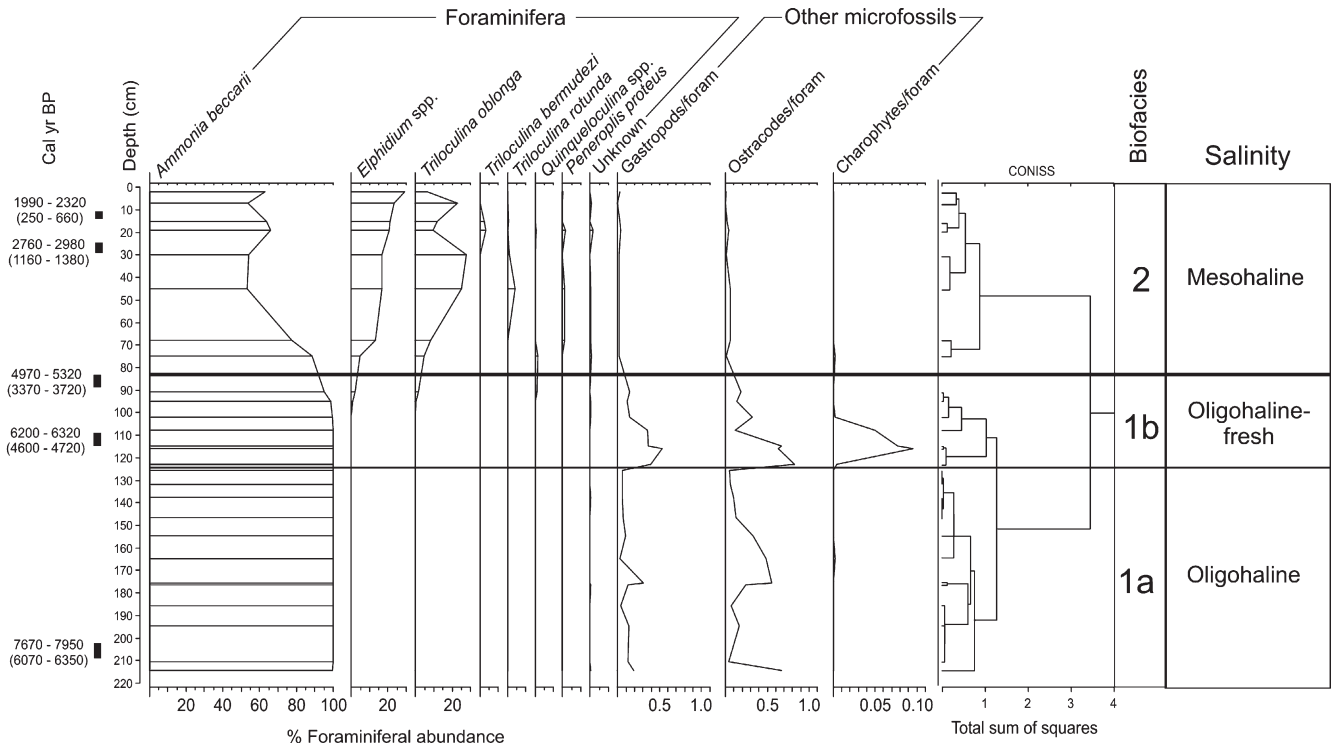
Figure 6. Calcareous microfossil results, core LL1. Calibrated radiocarbon ages are presented adjacent to the depth scale; reservoir-corrected ages are in brackets. Foraminifera are plotted as percent of the total sum; gastropods, ostracodes, and charophytes are plotted as the proportion of each group in relation to the total foraminifera counted. Note the change of scale for the charophytes.
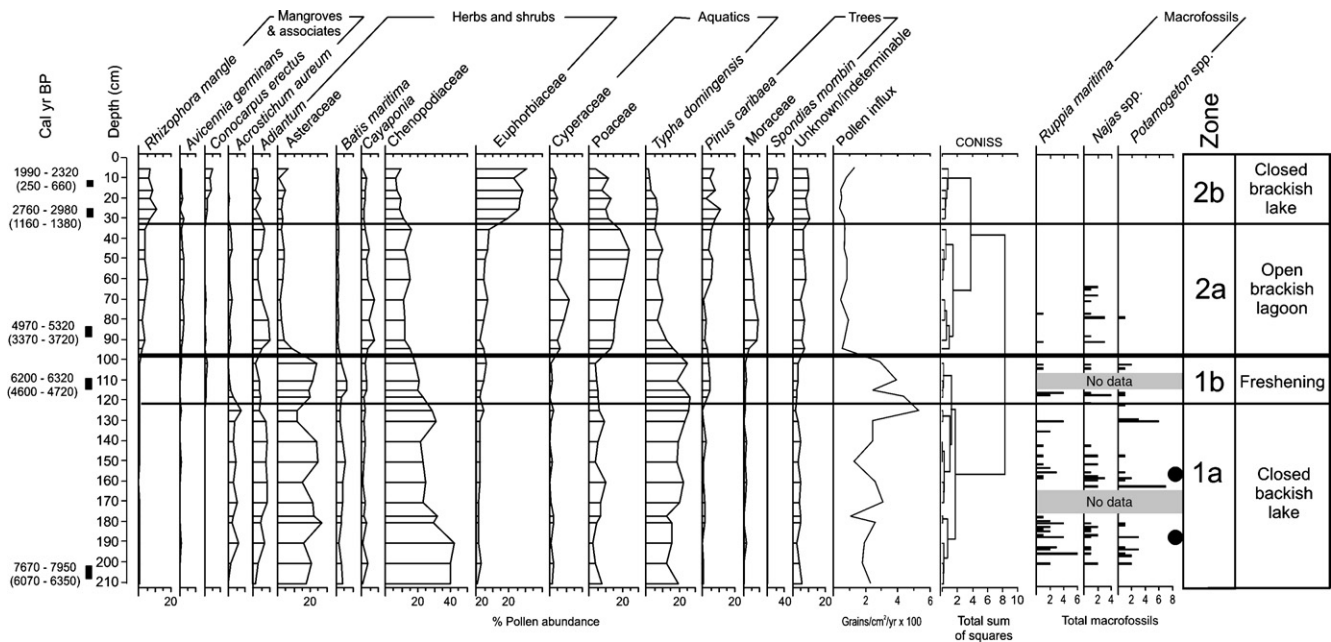
Figure 7. Diagram of pollen and plant macrofossils from core LL1, Laguna de la Leche. Calibrated radiocarbon ages are presented adjacent to the depth scale; reservoir-corrected ages are in brackets. Pollen data are represented by interpolated depth bars. All pollen taxa are part of the total pollen sum, although rare taxa are excluded from the pollen diagram. Plant macrofossils are illustrated with solid bars and are quantified using absolute numbers of macrofossils per level. The grey bars represent portions of the core that were completely used for other proxy indicators before plant macrofossil analysis had begun. The black circles mark the locations of fish spines. The zonation, guided by the constrained cluster analysis, was based on the pollen data.

Furthermore, the abundance of *T. domingensis* pollen throughout zone 1 is consistent with the oligohaline salinity values inferred from the calcareous microfossil data, since the growth of *T. domingensis* is negligible in salinities exceeding ∼6‰ (Glenn et al., 1995).

Zone 2 is from 0 to 97 cm and consists of two subzones, 2a and 2b. Zone 2a, from 33 to 97 cm, is typified by a more diverse assemblage compared to zone 1 and includes the appearance of mangrove pollen (*Rhizophora mangle* and *Avicennia germinans*), and increases in *Acrostichum aureum*; Cyperaceae, most of which appears to be *Cladium jamaicense*; Poaceae; *Cayaponia* spp.; and *Pinus caribaea* (Caribbean pine). This subzone is also characterized by decreases in Asteraceae, *Typha domingensis*, and *Batis maritima*.

Subzone 2b is from 0 to 33 cm and is primarily defined by a substantial increase in Euphorbiaceae. The tricolporate, reticulate, and subprolate pollen is tentatively identified as *Chamaesyce*, a herb common in the Caribbean and south Florida that grows in dry, sandy soil in saline coastal areas (Tobe et al., 1998). In addition to the rise in Euphorbiaceae, subzone 2b also sees an increase in *Rhizophora mangle* and the appearance of the mangrove *Conocarpus erectus* and the anacard *Spondias mombin* (hog plum), a deciduous tree common in upland and coastal areas throughout Central America and the Caribbean. Nonetheless, the much lower pollen influx of zone 2, as well as the preponderance of upland taxa, indicates that the pollen in zone 2 had a predominantly regional origin. Most of the regional pollen probably originated from the area around Laguna de la Leche (e.g., *R. mangle*), with some from farther afield (e.g., *Pinus caribaea*).

Macrofossils

Fossil seeds of the aquatic plants *Potamogeton* (pondweed), *Najas* (water-nymph), and *Ruppia maritima* (widgeon-grass) are common throughout pollen zone 1 (Fig. 7). *Najas* is relatively common from 65 to 94 cm, whereas the other two species only record a presence over this interval. *R. maritima* normally grows within brackish or saline waters, whereas *Potamogeton* and *Najas* both occupy a variety of wetland habitats, including brackish systems, depending on species (Godfrey and Wooten, 1989). Only small quantities of *Potamogeton* and *R. maritima*, and no *Najas* pollen, were identified in the core; this situation is not surprising, however, since these pollen grains have thin exines and are therefore generally poorly preserved in lacustrine sediments (McAndrews et al., 1973; Wodehouse, 1935). Three fish spines (i.e. fin bones) were also identified from pollen zone 1: one at 189 cm (15 mm in length) and two from 157 cm (3 and 6 mm in length), probably representing two individuals. The spines could not be identified beyond the class Osteichthyes (bony fish) (Quitmeyer, personal communication, 2005).

Discussion

Evolution of Laguna de la Leche

Where Laguna de la Leche is situated today appears to have been dry prior to ∼6500 cal yr BP (Fig. 8a). The silicate-rich sediment at the bases of cores LL1 and E6 likely correlate. At the Los Buchillones archaeological site, near the town of Punta Alegre (Fig. 1), geochemical data from eleven
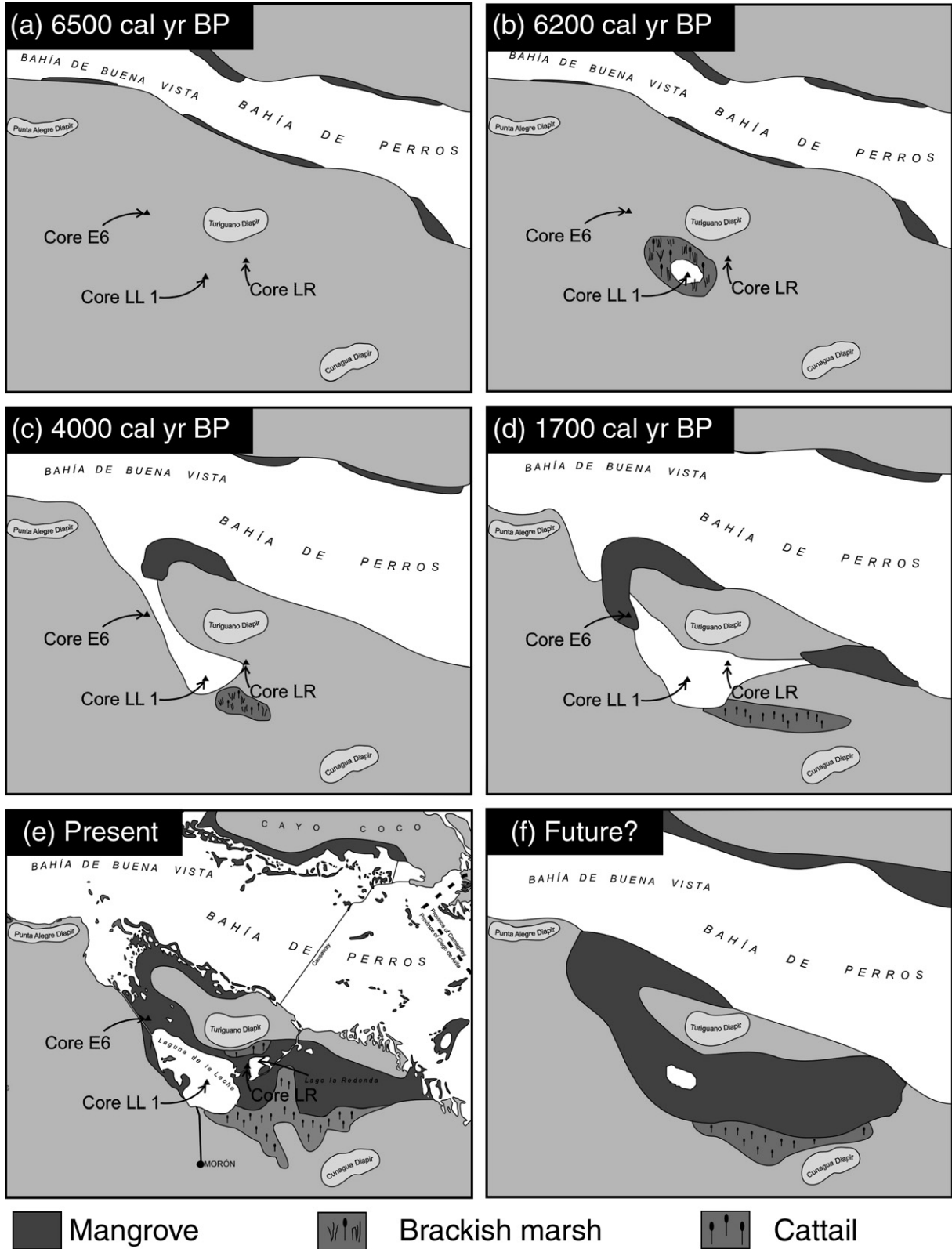
Figure 8. Model of the evolution of the Laguna de la Leche region.

sediment cores show that ~50–200 cm of carbonate-rich sediment also overlies a silicate-dominated unit (Peros et al., 2006). This stratigraphy suggests that a single silicate-rich horizon extends from Laguna de la Leche to the Los

Buchillones site and likely represents a late Pleistocene/early Holocene soil.

By 6200 cal yr BP, water began to fill the Laguna de la Leche basin and a shallow lake formed (Fig. 8b). Initiation of the lake

was likely caused by a rise in RSL that increased the elevation of the phreatic aquifer (cf. Hodell et al., 1991). The oligohaline nature of the lake indicates that Laguna de la Leche was more or less permanently isolated from the sea. This claim is consistent with oxygen and strontium isotopic data measured from *A. beccarii* in core LL1 that suggest a system with high evaporation but low salinity (Peros et al., in press).

Water level rose slightly between ∼4800 to ∼4200 cal yr BP, as evidenced by a shift from a non-arboreal (local) to arboreal (mostly regional) pollen rain and a decrease in pollen influx. Indicators of freshening imply that lake level changes may have been climatically driven and were not directly determined by sea level changes, although local-scale processes, such as a change in drainage, cannot be ruled out.

Water level continued to increase after ∼4200 cal yr BP as rising seawater exceeded the elevation of the sill (Fig. 3) separating the Ensenada de Buena Vista from Laguna de la Leche (Fig. 8c). This claim is consistent with the foraminiferal data as well as strontium isotopic measurements from core LL1 that show a shift toward more marine values (Peros et al., in press). From ∼4200 to ∼2000 cal yr BP, Laguna de la Leche was a shallow lagoon that had frequent, and perhaps a permanent, connection with the sea.

The period from ∼1,700 cal yr BP to the present has been characterized by a large-scale expansion of mangroves (Fig. 8d). The rise in *Rhizophora mangle* pollen in zone 2 of core LL1 (Fig. 7) reflects the increasing proximity of this plant to the

LL1 coring site and is roughly synchronous with the initiation of peat development at site E6 (Fig. 2). Mangrove progradation may have been facilitated by a decrease in the rate of RSL rise and the protection afforded by the Turiguano diapir, which dampened wave energy and encouraged mangrove establishment (Hogarth, 1999). Marsh plants such as *Typha domingensis* were confined to the lagoon's periphery because of rising water levels and increasing salinity. With the expansion of mangroves, Laguna de la Leche changed from an open lagoon to a closed, brackish lake (Fig. 8e) — although the name 'Isla de Turiguano' suggests that there may have been some communication with the sea when the Spanish arrived in the 18th century (Fig. 1). Given the pattern of mangrove growth during the late Holocene, it is likely (barring significant human intervention) that Laguna de la Leche will continue to infill with mangroves (Fig. 8f).

Regional implications

The record from Laguna de la Leche can be correlated with similar records from the southeastern United States. Pollen records from Florida (e.g., Lake Tulane, Grimm et al., 1993; Sheelar Lake, Watts and Stuiver, 1980; and Mud Lake, Watts, 1969), southern Alabama (e.g., Goshen Springs, Delcourt, 1980), and southern Georgia (Lake Louise, Watts, 1971) record a shift from a drier *Quercus*/Poaceae (oak grassland) dominated system to a moister *Pinus*-dominated system during the middle Holocene. The initiation of Laguna de la Leche is synchronous with the beginning of the transition to a *Pinus* system at Lake
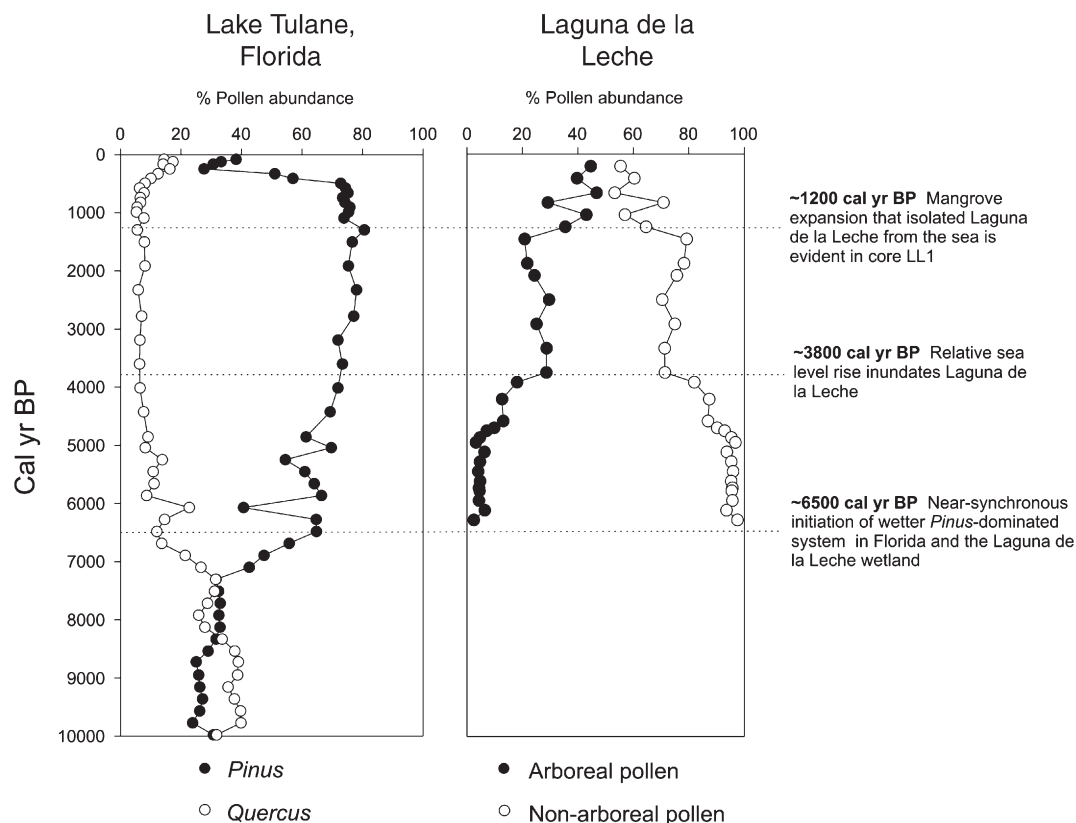

Figure 9. Comparison of pollen records from Lake Tulane, Florida (Grimm et al., 1993) and Laguna de la Leche (this paper).

Tulane, indicating that enhanced moisture drove middle Holocene vegetation change in north-coastal Cuba, Lake Tulane, and other sites in the southeastern United States (Fig. 9). Watts and Hansen (1994) concluded that increasing wetness was caused by a decrease in insolation, an increase in precipitation, and an elevated sea level from the earlier to the later Holocene.

Based on the synchronicity of these events (Fig. 9) and the oligohaline nature of Laguna de la Leche, we argue that RSL rise was the dominant cause of middle Holocene vegetation change on both the north coast of central Cuba and many sites throughout the southeastern United States. Climate change may have been unimportant as a driver of vegetation change over this period. Paleoclimatic records from elsewhere in the Caribbean and Central America record a shift from wetter to drier conditions during the Holocene; in central Mexico and the Yucatan peninsula, for example, stable isotope and pollen records typically indicate higher lake levels and more mesic forest conditions during the early Holocene, and a shift toward lower lakes levels and a reduction in climax forest by the late Holocene (although this shift may be due in part to anthropogenic activity) (Islebe et al., 1996; Curtis et al., 1996), whereas at Lake Miragoane, Haiti, lake levels were highest around 6000 ^{14}C yr BP and then decreased (Hodell et al., 1991).

These results have implications for the testing of regional-scale models of Holocene climate changes. Some recent models assume that increased moisture and subsequent vegetation changes at sites in the southeastern United States are indicative of past climate changes (e.g., Ruter et al., 2004: 899). It is important to emphasize that at some coastal and low-elevation sites (whether in Florida or elsewhere), sea level changes must be considered alongside climatic variability as causes of ecosystem change, and that paleoclimatological signals may in fact be masked by changes in water level, salinity, etc., brought on by sea level fluctuations. Thus, understanding local sea level history is critical for interpreting paleoenvironmental records from coastal areas, and it may be beneficial to reevaluate existing paleoenvironmental results in areas where recent sea level studies have been undertaken.

Conclusions

Laguna de la Leche provides valuable paleoenvironmental information with which to understand the Holocene environmental history of the northern Caribbean, as well as the processes driving millennial-scale ecological, hydrological, and climatic variability on tropical coastlines. The Laguna de la Leche region underwent three major transformations during the middle to late Holocene: a lake that formed slightly before 6200 cal yr BP was replaced by a shallow lagoon by ~4200 cal yr BP. A significant expansion of mangroves occurred over the last two thousand years. The initiation of Laguna de la Leche is correlated with paleolimnological records from the southeastern United States that indicate a rising water table during the middle Holocene. The environmental changes at Laguna de la Leche were driven mostly by relative sea level rise, although a brief (<1000 yr) freshening suggests that climate change may have played a minor role. Our paleoenvironmental results underscore the complexity of tropical coastal environments and have important implications for understanding the biogeography and prehistory of the Caribbean. Multiple proxy studies are essential to unravel the often convoluted environmental signals that are typical of many coastal paleoenvironmental records.

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