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# An 85-ka record of climate change in lowland Central America

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ABSTRACT

Drill cores obtained from Lake Petén Itzá, Petén, Guatemala, contain a ~85-kyr record of terrestrial climate from lowland Central America that was used to reconstruct hydrologic changes in the northern Neotropics during the last glaciation. Sediments are composed of alternating clay and gypsum reflecting relatively wet and dry climate conditions, respectively. From ~85 to 48 ka, sediments were dominated by carbonate clay indicating moist conditions during Marine Isotope Stages (MIS) 5a, 4, and early 3. The first gypsum layer was deposited at ~48 ka, signifying a shift toward drier hydrologic conditions and the onset of wet–dry oscillations. During the latter part of MIS 3, Petén climate varied between wetter conditions during interstadials and drier states during stadials. The pattern of clay–gypsum (wet–dry) oscillations during the latter part of MIS 3 (~48–23 ka) closely resembles the temperature records from Greenland ice cores and North Atlantic marine sediment cores and precipitation proxies from the Cariaco Basin. The most arid periods coincided with Heinrich Events when cold sea surface temperatures prevailed in the North Atlantic, meridional overturning circulation was reduced, and the Intertropical Convergence Zone (ITCZ) was displaced southward. A thick clay unit was deposited from 23 to 18 ka suggesting deposition in a deep lake, and pollen accumulated during the same period indicates vegetation consisted of a temperate pine-oak forest. This finding contradicts previous inferences that climate was arid during the Last Glacial Maximum (LGM) chronozone (21±2 ka). At ~18 ka, Petén climate switched from moist to arid conditions and remained dry from 18 to 14.7 ka during the early deglaciation. Moister conditions prevailed during the warmer Bolling–Allerod (14.7–12.8 ka) with the exception of a brief return to dry conditions at ~13.8 ka that coincides with the Older Dryas and meltwater pulse 1A. The onset of the Younger Dryas at 12.8 ka marked the return of gypsum and hence dry conditions. The lake continued to precipitate gypsum until ~10.3 ka when rainfall increased markedly in the early Holocene.



## 1. Introduction

Understanding climatic linkages between low and high latitudes of the northern hemisphere during the last glaciation may be important for explaining the cause(s) of abrupt, millennial-scale climate change. The prevailing paradigm is that stadial–interstadial (Dansgaard–Oeschger) oscillations were related to changes in Atlantic meridional overturning circulation (AMOC). The northern Neotropics may have also acted as an important driver and/or feedback mechanism for this process (Broecker et al., 1990; McIntyre and Molfino, 1996; Peterson et al., 2000; Schmidt et al., 2004, 2006; Leduc et al., 2007). Paleoclimate proxies (e.g., Fe, Ti, color) from the Cariaco Basin off northern Venezuela demonstrate a remarkable resemblance to $\delta^{18}O$ variations in Greenland ice cores during the last glaciation and deglaciation, suggesting a strong coupling between the tropical Atlantic hydrologic cycle and temperature in the high-latitude North Atlantic (Hughen et al., 1996, 1998, 2000; Peterson et al., 2000; Lea et al., 2003). Peterson et al. (2000) proposed that changes in precipitation in the northern Neotropics were related to meridional displacements in the mean position of the Atlantic

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Intertropical Convergence Zone (ITCZ). Reduced precipitation coincided with cooler North Atlantic SSTs (e.g., Younger Dryas and cold stadial periods), and is attributed to increased Trade Wind strength and a more southerly mean position of the ITCZ (Peterson et al., 2000; Peterson and Haug, 2006). In contrast, warm periods (e.g., early Holocene climatic optimum and interstadials of the last glaciation) were wetter and associated with weakened wind strength and a more northerly ITCZ position. The reverse pattern is observed in the southern hemisphere Neotropics where increased precipitation occurred during cold periods such as Heinrich Events and the Younger Dryas (Arz et al., 1998; Jennerjahn et al., 2004; Wang et al., 2004; Jaeschke et al., 2007).

We sought to test the hydrologic inferences derived from marine records, such as those from the Cariaco Basin, by examining lacustrine sediment records from the lowlands of Central America. Tropical closed-basin lakes are highly sensitive recorders of changes in the balance between precipitation and evaporation. Identifying lakes with Pleistocene-age deposits has proved difficult, however, because most shallow lakes in Central America were dry during the last glacial period, owing to pronounced aridity and lowered sea level. After a 40-year search, Deevey et al. (1983) reported the first Pleistocene-age lacustrine deposits from low-elevation Lakes Quexil and Salpetén, in the Department of Petén, northern Guatemala (Fig. 1). Pleistocene sediments had abundant gypsum in a clay matrix containing shells, sponge spicules, pine pollen, and humified organic layers (Deevey et al., 1983). These sediments were interpreted as having been deposited in water ~30–40 m shallower than today, indicating climate conditions significantly more arid than present.

Pollen analysis of Lake Quexil Core 80-1 indicated that glacial-age vegetation was dominated by temperate xeric thorn scrub, suggesting that Petén climate was colder and drier during glacial periods of the late Pleistocene (Leyden, 1984; Leyden et al., 1993, 1994). The finding had important ecological implications because it indicated that Petén's seasonal tropical forest is no older than ~11 ka (Deevey et al., 1983; Leyden, 1984). Contemporaneous lowering of African lake levels led some researchers to propose that aridity may have been pantropical during the last glaciation, but this hypothesis has been called into question (Liu and Colinvaux, 1985; Colinvaux and De Oliveira, 2000; Mayle et al., 2000). With observations in the early 1990s of millennial-scale climate variability in Greenland ice cores, it soon became evident that considerable tropical climate variability also existed during the last glacial period with both relatively wetter and drier conditions (Peterson et al., 2000; González et al., 2008).

Following the lead of Deevey and co-workers, we targeted Lake Petén Itzá, northern Guatemala for drilling (Fig. 1). It is the largest (100 km$^2$) and deepest ($z_{max} = 160$ m) lake in the Petén Lake District, considerably deeper than Lakes Quexil ($z_{max} = 32$ m) and Salpetén ($z_{max} = 32$ m) (Deevey et al., 1983). Its great depth suggested that the basin held water during the driest periods of the late Pleistocene and that the deep basin would contain a long, continuous sequence of lacustrine sediment. Seismic surveys were conducted in 1999 and 2002, and showed thick deposits of sediment overlying basement (Anselmetti et al., 2006). Kullenberg piston coring in 2002 retrieved complete Holocene sections, but recovery was limited to the upper 6 m of sediment because a thick Holocene clay unit impeded penetration of the corer. These piston cores extended to ~11.3 ka in the Preboreal period (Hillesheim et al., 2005), but did not recover the Younger Dryas chronozone (12.9–11.57 ka) when proxies from the Cariaco Basin indicate a dramatic change in climate during the last deglaciation (Hughen et al., 1996, 1998, 2004).

Between 3 February and 11 March 2006, we drilled a total of 1327 m of sediment at seven sites as part of the Petén Itzá Scientific Drilling Project (Hodell et al., 2006) with sponsorship from the International Continental Scientific Drilling Program (ICDP). Most coring was done using a hydraulic piston corer aboard the GLAD800 (R/V *Kerry Kelts*) operated by Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC), Inc. Here we report initial results from two sites (PI-3

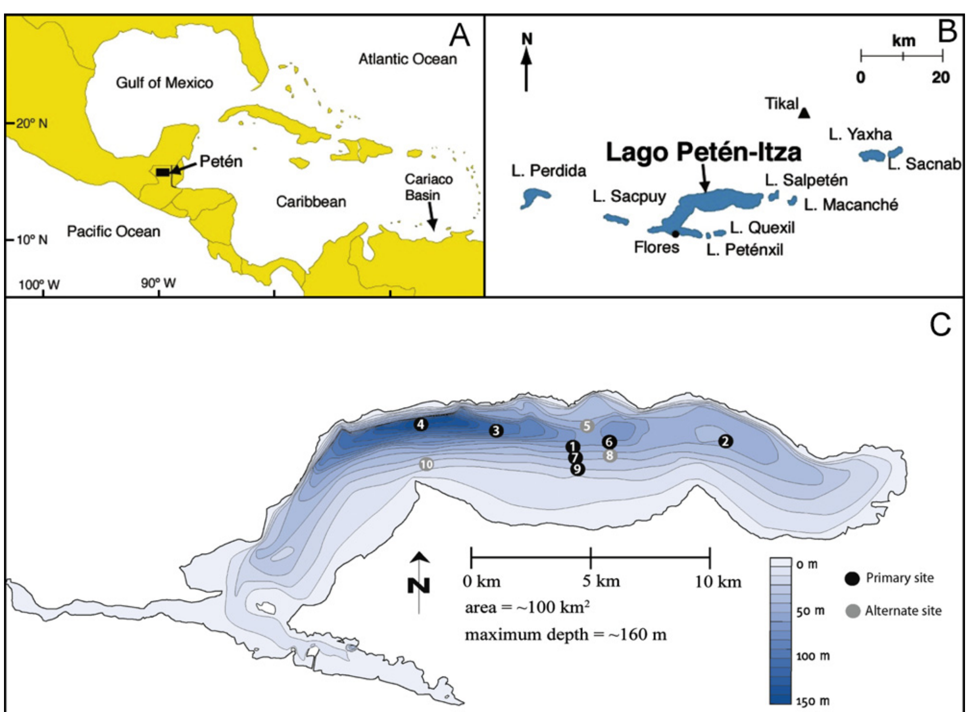


**Fig. 1.** (A) Map of the Intra America Seas showing the location of the Department of Petén, northern Guatemala and Cariaco Basin off northern Venezuela. (B) Map of the Petén Lake District. (C) Bathymetric map of Lake Petén Itzá showing the location of primary and alternate coring sites.

and PI-6) located in the central basin of Lake Petén Itzá at water depths of 100 and 71 m, respectively (Fig. 1). Age/depth relations for the last ~40 ka are derived from 28 radiocarbon dates on terrestrial organic matter, which constitutes a vast improvement over previous lake sediment core chronologies from the region. We used core logging and sedimentological data to interpret the paleoclimate history of the region for the last ~85 ka, and compared the results with marine sediment cores from the Cariaco Basin (off northern Venezuela) and North Atlantic, and with polar ice cores from Greenland and Antarctica.

## 2. Modern limnology and climate

Lake Petén Itzá is located at ~16°55′N, 89°50′W in the Department of Petén, northern Guatemala (Fig. 1). The modern lake surface is ~110 m above sea level. Lake water is dominated by bicarbonate and sulfate anions and calcium and magnesium cations (Table 1). High dissolved sulfate is from dissolution of gypsum outcrops in the watershed. Lake water pH is high (~8.0) and saturated with calcium carbonate. The lake water is undersaturated with calcium sulfate today, but gypsum deposits at depth in sediment cores suggest that the water was saturated with $CaSO_4$ in the past (Hillesheim et al., 2005). The lake is fed by direct rainfall, runoff, and subsurface groundwater inputs. The basin lacks surface outlets and is thus effectively closed, though subsurface seepage may occur. Thermal stratification is persistent through much of the year, with the top of the thermocline at ~25 m. The hypolimnetic temperature averages ~25.4 °C.

Petén is marked by a mean annual air temperature of ~25 °C. It is located on the western side of the Atlantic warm pool (AWP) that is part of the Western Hemisphere warm pool (WHWP), which is the second largest body of warm water on Earth (Wang and Enfield, 2001, 2003; Wang et al., 2006, 2007). Annual precipitation varies from 900 to 2500 mm/yr with a regional mean of ~1601 mm/yr (Deevey et al., 1980). Petén is near the southern end of a steep north–south rainfall gradient on the Yucatan Peninsula, which varies from <500 mm along the northwest coast near Progreso (~21°N) to >2000 mm in southern Petén, Guatemala (~16°N) (Wilson, 1984).

The rainy season occurs between May and October as easterly trade winds produced by the North Atlantic Subtropical High (NASH) transport moisture from the Atlantic into the Caribbean Sea where the flow intensifies forming the Caribbean Low Level Jet (CLLJ) (Fig. 2; Amador, 1998; Amador and Magaña, 1999; Mestas-Nunez et al., 2005, 2007). During boreal summer in the western Caribbean, the CLLJ splits into two branches: one branch turns northward over the western Gulf of Mexico bringing moisture to the Yucatan Peninsula, northern Mexico, and the central US (Fig. 2). The geometry of the coastline in the Gulf of Honduras and presence of the Maya Mountains direct moisture-laden winds into Belize and northern Guatemala (Wilson, 1984). The southerly branch of the CLLJ continues westward and carries moisture across the Central American Isthmus to the Pacific. The rainy season in Petén usually ends by late October and the dry season persists from January through May.

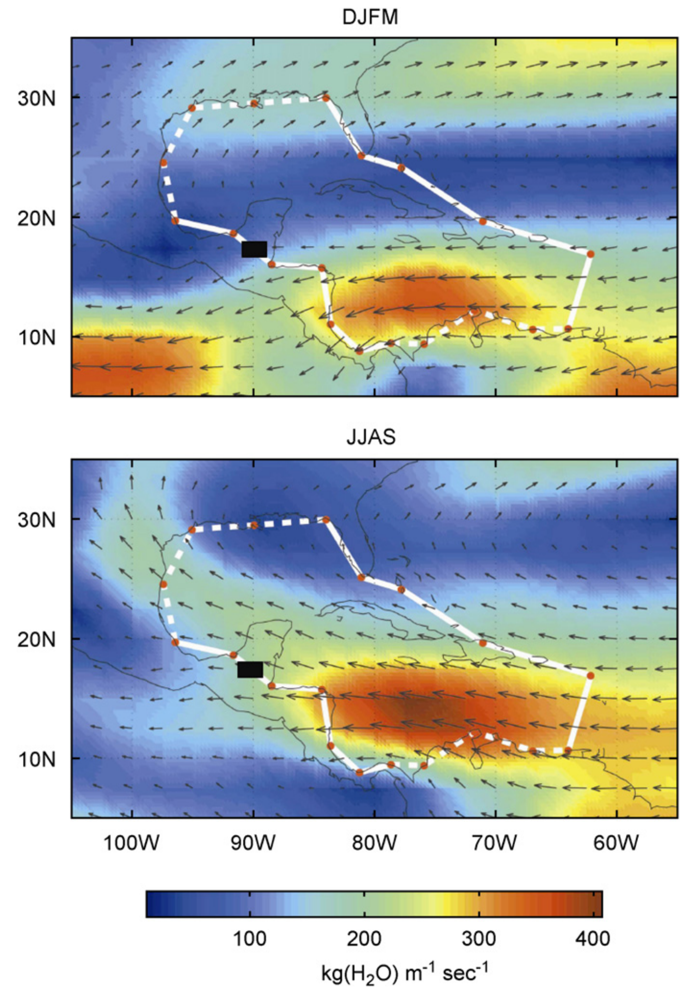


**Fig. 2.** Vertically integrated water vapor flux for boreal winter (top) and summer (bottom) for the period 1960–2003. The magnitudes of the water vapor flux vectors are color contoured. During summer (JJAS), the Caribbean LLJ is split into two branches: a northward branch that transports moisture over the Yucatan Peninsula and into the southwestern US and a southern branch that carries moisture westward to the Pacific across the Central American Isthmus. Black rectangle indicates the position of the Petén Lake District. The boundaries of the Inter-America Seas are shown in white (after Mestas-Nunez et al., 2007).

During winter, the NASH dominates in the Intra-Americas Sea and moisture transport is shifted south of the Yucatan Peninsula (Fig. 2). The atmosphere over the Yucatan Peninsula is marked by subsidence related to the descending limb of the Hadley cell, which is centered at ~20°N (Waliser et al., 1999). Precipitation is low, but polar air masses carried by northerly winds (known locally as *nortes*) occasionally bring light winter rains to the Yucatan Peninsula with cold fronts.

The ITCZ does not technically reach latitudes higher than ~15°N today in the Caribbean and summer rains on the Yucatan Peninsula are related to intense convection. We use the term ITCZ loosely to include both the zonally elongated, narrow band of convection as well as other tropical convective activity that is less spatially oriented. The migration of the ITCZ follows the seasonal insolation cycle, but lags the zenithal position by approximately 1 month (Poveda et al., 2006). Rainfall anomalies in the Caribbean are closely related to the intensity of the annual cycle (Hastenrath, 1984), which is also expressed by interannual variability in the position of the ITCZ. Enhancement of the annual cycle occurs

**Table 1**
Mean ion concentrations of Petén Itzá lakewater ($n = 24$)

| | | |
|---|---|---|
| $Ca^{2+}$ | 3.15 meq l$^{-1}$ | 63.13 mg l$^{-1}$ |
| $Mg^{2+}$ | 1.86 meq l$^{-1}$ | 22.62 mg l$^{-1}$ |
| $Na^{+}$ | 0.60 meq l$^{-1}$ | 13.80 mg l$^{-1}$ |
| $Cl^{-}$ | 0.26 meq l$^{-1}$ | 9.22 mg l$^{-1}$ |
| $SO_4^{2-}$ | 2.11 meq l$^{-1}$ | 101.34 mg l$^{-1}$ |
| $HCO_3^{-}$ | 3.24 meq l$^{-1}$ | 197.67 mg l$^{-1}$ |
| Total | 11.22 meq l$^{-1}$ | 407.78 mg l$^{-1}$ |

After Hillesheim et al. (2005).

during years of anomalously high precipitation in the Caribbean and is associated with a more northerly position of the ITCZ, whereas reduction occurs when there are deficient summer rains and a more southerly ITCZ position.

Lake Petén Itzá's water level is sensitive to the balance between precipitation and evaporation and its stage has fluctuated substantially in the recent past. For example, the period from 1934 to 1942 was relatively wet (mean = 2055 mm/yr), which caused high lake levels and flooding, as commemorated by a plaque marking the 1938 high water mark in Flores (Fig. 1B). In contrast, the early to mid-1970s were dry (1415 mm/yr) with correspondingly low lake levels. Lake stage also varies seasonally by as much as 80 cm and lags precipitation by 1–2 months (Deevey et al., 1980). Seismic evidence showed that the amplitude of lake level variations was much greater in the past (Anselmetti et al., 2006). For example, evidence for a buried paleoshoreline indicates that the lake was ~56 m lower than today during the Late glacial period, which is equivalent to an 87% reduction in lake volume. At that time, Lake Petén Itzá would have been a moderately saline lake that was supersaturated with gypsum (Hillesheim et al., 2005).

## 3. Methods

### 3.1. Composite sections

Three holes were drilled at both Sites PI-3 and PI-6 to ensure complete recovery of the stratigraphic section (Table 2). Most cores were retrieved using the hydraulic piston corer. A maximum depth of 96.9 m below lake floor (mblf) was achieved at Site PI-3 and 75.9 mblf was reached at Site PI-6. Composite stratigraphic sections were constructed at Sites PI-3 and PI-6 using Splicer (Supplementary Data Tables 1 and 2), a software program developed by the Ocean Drilling Program that permits alignment of features among holes using core logging data. Stratigraphic tie points were verified visually by aligning features in the split cores from the three holes. The cores from Site PI-6 provide a continuous stratigraphic sequence to ~75.9 m composite depth (mcd). At Site PI-3, a continuous composite section could only be constructed to 34.92 mcd because of slumping in underlying deposits.

### 3.2. Core logging

Whole cores were logged at the US National Lacustrine Core Repository (LacCore), University of Minnesota, using a GEOTEK multi-sensor core logger. Logging was done at 0.5-cm resolution. Sediment bulk density was estimated by gamma-ray attenuation (GRA) and the instrument was calibrated at the start of each day using a plastic core liner filled with distilled water and aluminum standards of varying thickness. Magnetic susceptibility was measured using the 8.8-cm Bartington loop sensor. These data were highly variable and subject to drift because of the low susceptibility of Petén Itzá's sediments. Consequently, we took u-channel samples (1.8 cm × 1.9 cm plastic channels cut to length; Tauxe et al., 1983) from the center of cores along the spliced composite section and re-measured magnetic susceptibility using a custom-built instrument in the Paleomagnetic Laboratory at the University of Florida (Thomas et al., 2003). The 3.3-cm$^2$ coil of this instrument has a much smaller response function (~3-cm half peak width) than the 8.8-cm Bartington loop sensor. The susceptibility meter was zeroed before each section was analyzed and a drift correction was applied between the beginning and end of each section analyzed.

## 4. Results

### 4.1. Chronology

We obtained AMS-$^{14}$C dates at 21 stratigraphic depths in core PI-6 and seven depths in core PI-3 (Fig. 3A) (Tables 3 and 4). With few exceptions, radiocarbon dates are in stratigraphic order and yield a mean sedimentation rate of ~1 m/ka (1 mm/yr). The magnetic susceptibility records from Sites PI-3 (100 m water depth) and PI-6 (71 m water depth) are nearly identical and can be readily correlated stratigraphically (Fig. 4). This correlation enables use of radiocarbon dates from both sites to produce a detailed age–depth model (Fig. 3B) (Table 5).

Beyond the range of radiocarbon dating, Site PI-6 is dated by identification of tephra layers using electron microprobe glass analyses. The recognition and correlation of ash layers is assisted by the widespread distribution of the tephra in the entire Central American region up to the Gulf of Mexico in the north and offshore Equador in the south (Kutterolf et al., 2007, 2008). Four ash layers have been identified: Congo Tephra (CGT; 53 ± 3 ka; dated by $^{14}$C; Kutterolf et al., 2008), Guasal1 (~55 ka; dated by stratigraphic interpolation; Kutterolf, pers. comm.), Arce Tephra (ACT; 72 ± 3 ka; dated by Ar/Ar; Rose et al., 1999), and Los Chocoyos Tephra (LCY; 84 ± 0.5 ka; dated by oxygen isotope stratigraphy). The position of the ACT ash introduces a large change in sedimentation rate and has been discarded until the Ar/Ar age can be verified (Rose et al., 1999). The age of the base of the PI-6 section is constrained by a tephra from the Los Chocoyos eruption of the Atitlán Caldera in the Guatemalan highlands, which is dated to 84 ka by its occurrence in Marine Isotope Stage 5a in offshore marine sediment cores (Ledbetter, 1984).

### 4.2. Lithostratigraphy

The lithostratigraphy of Sites PI-3 and PI-6 is very similar to a depth of ~38 mcd (Fig. 5). Below this depth, the Site PI-3 section from deeper water shows evidence of slumping and disturbance. We describe the downhole lithostratigraphy starting from the lake floor (i.e. sediment surface) using the mcd scale of Site PI-6. The top 10.8 mcd were deposited during the Holocene and consist primarily of gray clay and organic-rich clay (Unit I). The Holocene section was described previously using numerous Kullenberg piston cores (Hillesheim et al., 2005). The Pleistocene/Holocene boundary occurs at 10.8 mcd and is marked by a transition from organic-rich clay to interbedded gypsum sand and clay that were

**Table 2**
Location, water depth, and coring summary of the three holes drilled at Sites PI-3 and PI-6

| Site | Latitude | | Longitude | | Water depth (m) | Penetration | | Depth (mblf) | Average % recovery |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Hole A | Hole B | Hole C | |
| PI-3 | 17° | 0.20′N | 89° | 49.24′W | 100 | 96.9 | 95.3 | 90.0 | 92.9 |
| PI-6 | 17° | 0.02′N | 89° | 47.09′W | 71 | 75.9 | 66.4 | 66.8 | 94.9 |

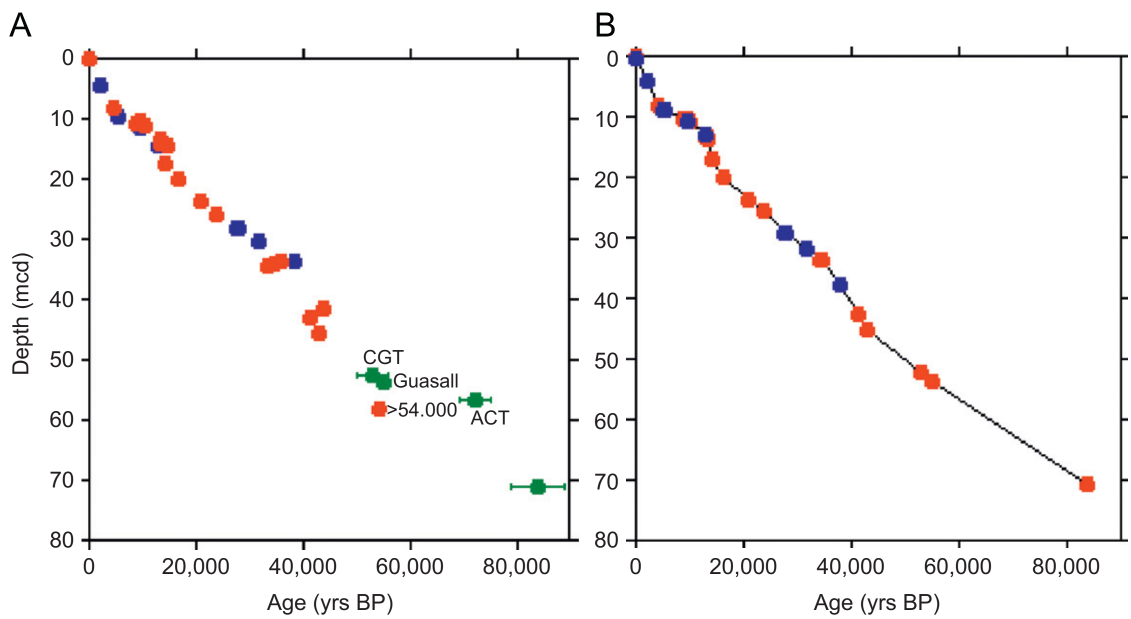


**Fig. 3.** (A) Radiocarbon dates calibrated using Fairbanks et al. (2005) versus mcd for Sites PI-3 (blue) and PI-6 (red). A sample at 59.44 mcd yielded an infinite radiocarbon age (>54 kyr). Green dots represent the position of tephra layers. CGT = Congo Tephra; Guasal1 = Guatemala–El Salvador Tephra 1; ACT = Arce Tephra; LCY = Los Chocoyos Tephra B. Combined radiocarbon dates from Sites PI-3 (blue open circles) and PI-6 (red open circles) based upon correlation of the magnetic susceptibility records in Fig. 4. Age model (line) was derived using a weighted fit through selected age–depth points from Sites PI-3 and PI-6 and three ash layers (CGT, Guasal1 and LCY).

**Table 3**
Radiocarbon dates on terrestrial organic material from Site PI-6

| Accession # | Sample<br>Site-hole-core-type-section interval | Depth (mcd) | Age $^{14}$C yr BP | ±(1σ) | Age cal yr BP | (1σ) |
|---|---|---|---|---|---|---|
| CAMS 125895 | 6C 3H-1 141.5 cm | 8.076 | 3920 | 35 | 4376 | 53 |
| CAMS 125903 | 6C 3H-1 141.5 cm | 8.076 | 3905 | 35 | 4355 | 61 |
| CAMS 125896 | 6B 4H-2 77.5 cm | 10.406 | 8655 | 30 | 9579 | 31 |
| CAMS 125904 | 6B 4H-2 77.5 cm | 10.406 | 8630 | 60 | 9572 | 52 |
| CAMS 131225 | 6C 4H-1 59 cm | 10.436 | 7985 | 40 | 8882 | 102 |
| CAMS 131226 | 6C 4H-1 101 cm | 10.856 | 9040 | 35 | 10,213 | 16 |
| CAMS 128611 | 6B 5H-2 33 cm | 13.354 | 11,290 | 60 | 13,125 | 72 |
| CAMS 128613 | 6B 5H-2 39 cm | 13.414 | 11,380 | 140 | 13,229 | 154 |
| CAMS 131224 | 6B 5H-2 85 cm | 13.874 | 11,390 | 50 | 13,236 | 74 |
| CAMS 128612 | 6C 5H-2 7 cm | 14.448 | 12,460 | 60 | 14,396 | 150 |
| CAMS 131223 | 6C 6H-1 120 cm | 17.12 | 12,280 | 60 | 14,079 | 95 |
| CAMS 125897 | 6A 7H-1 128 cm | 20.026 | 14,130 | 120 | 16,537 | 212 |
| CAMS 125898 | 6C 8H-2 6 cm | 23.636 | 17,650 | 240 | 20,896 | 321 |
| CAMS 125899 | 6C 9H-1 62 cm | 25.729 | 19,990 | 180 | 23,880 | 217 |
| CAMS 125900 | 6A 11H-2 145 cm | 33.733 | 30,700 | 3600 | 36,000 | 3663 |
| CAMS 125901 | 6B 12H-1 82.5 cm | 33.828 | 29,120 | 170 | 34,536 | 224 |
| CAMS 125905 | 6B 12H-1 82.5 cm | 33.828 | 29,010 | 170 | 34,421 | 222 |
| CAMS 126525 | 6B 12H-1 138.5 cm | 34.388 | 28,040 | 470 | 33,406 | 517 |
| CAMS 126526 | 6C 14H-1 80.5 cm | 41.303 | 39,000 | 700 | 43,855 | 634 |
| CAMS 126528 | 6B 15H-1 60 cm | 42.762 | 35,900 | 1200 | 41,145 | 1103 |
| CAMS 126527 | 6A 15H-2 90.5 cm | 45.307 | 38,100 | 1100 | 43,080 | 967 |
| CAMS 126529 | 6A 16H-2 85 cm | 46.879 | 40,500 | 2600 | | |
| CAMS 126530 | 6A 20E-1 45 cm | 57.912 | >54,000 | | | |

Dates were calibrated using Fairbanks et al. (2005) using the on-line radiocarbon calibration program: http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm. Reporting of ages follows the convention of Stuiver and Polach (1977). No reservoir correction was applied to radiocarbon dates because the material dated was terrestrial organic matter and assumed to reflect atmospheric $CO_2$.

deposited during the last deglaciation. Between ~21.2 and 10.8 mcd (~17–10 ka) the overall lithostratigraphy consists of three gypsiferous and two intercalated clay-rich units (Unit II). Between 25.4 and 21.2 mcd (~23–17 ka) sediments consist of gray carbonate clay (Unit III). This clay unit was preceded by interbedded gypsum sand and clay between 50.3 and 25.4 mcd (Units IV and V), corresponding to the latter part of MIS 3. Gypsum is absent in the section below 50.3 mcd, and the interval from 55 to 50.3 mcd (Unit VI) consists of a dark gray clay similar to Units I and III. From 67.25 to 55 mcd Unit VII), sediments consist of carbonate mud that is rich in diatoms and carbonate microfossils. The lowermost unit from 71.8 to 67.25 mcd (Unit VIII) consists of coarse carbonate sand. Limestone gravel was recovered at the base of the section and may represent fragmented bedrock.

### 4.3. Density and magnetic susceptibility

Variations in magnetic susceptibility and density reflect changes in sediment lithology (Fig. 5). Magnetic susceptibility of

**Table 4**
Radiocarbon dates on terrestrial organic material from Site PI-3

| Accession # | Sample Site-hole-core-type-section interval | Depth (mcd) | Age $^{14}$C yr BP | $\pm(1\sigma)$ | Age cal yr BP | $(1\sigma)$ |
|---|---|---|---|---|---|---|
| CAMS 128603 | 3B 2H-1 93 | 4.225 | 2140 | 40 | 2130 | 70 |
| CAMS 128604 | 3A 3H-2 17 | 9.37 | 4590 | 40 | 5311 | 66 |
| CAMS 128614 | 3A 3H-2 17 rep | 9.37 | 4550 | 35 | 5254 | 81 |
| CAMS 128605 | 3C 4H-2 140 | 11.32 | 8625 | 35 | 9559 | 24 |
| CAMS 128615 | 3C 4H-2 140 rep | 11.32 | 8675 | 35 | 9602 | 46 |
| CAMS 128606 | 3B 5H-2 25 | 14.17 | 11210 | 35 | 13048 | 43 |
| CAMS 128607 | 3A 9H-1 71 | 28.09 | 23210 | 90 | 27845 | 173 |
| CAMS 128616 | 3A 9H-1 71 rep | 28.09 | 23040 | 90 | 27653 | 172 |
| CAMS 128608 | 3B 10H-1 144.5 | 30.09 | 26560 | 130 | 31836 | 206 |
| CAMS 128609 | 3B 11H-2 9.5 | 33.42 | 32820 | 260 | 38218 | 300 |
| CAMS 128610 | 3A 12H-2 6 | | 43560 | 960 | 47786 | 977 |

Dates were calibrated using Fairbanks et al. (2005) using the on-line radiocarbon calibration program: http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm. Reporting of ages follows the convention of Stuiver and Polach (1977). No reservoir correction was applied to radiocarbon dates because the material dated was terrestrial organic matter and assumed to reflect atmospheric $CO_2$.

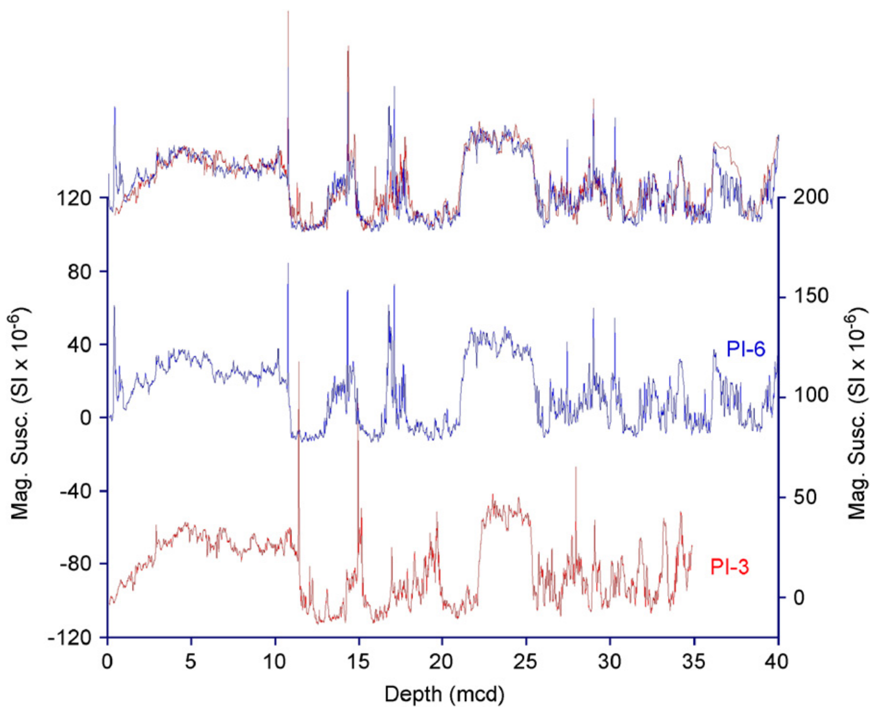


**Fig. 4.** (Lower panels) Spliced magnetic susceptibility records from Sites PI-3 (red) and PI-6 (blue). (Upper panel) Comparison of magnetic susceptibility records after the PI-3 record was correlated to the mcd scale of PI-6.

Petén Itzá's sediment is generally low ($<60\times10^{-6}$ SI) except for a few peaks associated with ash layers. Some volcanic eruptions in the Guatemalan highlands to the south and in Mexico to the west of Petén produce magnetite as a phenocryst mineral, which has very high magnetic susceptibility. Magnetic susceptibility is relatively greater in clay deposits and lower ($<0\times10^{-6}$ SI) in sediments that are rich in gypsum or calcite, reflecting the different susceptibilities of these minerals (Table 6). Sediment bulk density varies between ~1 and 2 g cm$^{-3}$. Higher values are associated with gypsum sands whereas clay-rich units have lower values.

## 5. Discussion

### 5.1. Working hypothesis

Our working hypothesis is that past changes in summer precipitation in Petén were related to the meridional displacement in the mean position of the Atlantic ITCZ. The concept is supported by tight coupling between paleoclimate proxies (e.g., Fe, Ti, color) from the Cariaco Basin off northern Venezuela and the $\delta^{18}$O record of Greenland ice cores during the last glacial period (Peterson et al., 2000; Peterson and Haug, 2006). Because the Petén Lake District (17°N) is influenced by the same seasonal variations in the ITCZ and NASH as the Cariaco Basin (11°N), proxies that are sensitive to precipitation should correlate between sediment cores from Lake Petén Itzá and the Cariaco Basin. Comparison of these records can establish the regional importance of abrupt humidity changes in the northern Neotropics, and their linkages to extra-tropical climate variability.

The position of the Atlantic ITCZ is determined by latitudinal gradients in sea surface temperature that result in atmospheric surface pressure gradients (Chiang and Bitz, 2005). The Atlantic ITCZ favors the warmer of the two hemispheres and transports moisture away from the colder into the warmer hemisphere. Mechanisms controlling interannual migration of the ITCZ may provide insight into longer-term shifts in the Atlantic ITCZ on millennial time scales (Chiang et al., 2003). Modeling experiments

**Table 5**
Age-depth points for Site PI-6 used to derive chronology shown in Fig. 3B

| Depth (mcd) | Age (ka) |
|---|---|
| 0.00 | 0 |
| 4.18 | 2130 |
| 8.08 | 4366 |
| 8.90 | 5283 |
| 10.41 | 9576 |
| 10.86 | 10,213 |
| 13.06 | 13,048 |
| 13.41 | 13,229 |
| 13.87 | 13,236 |
| 17.12 | 14,079 |
| 20.03 | 16,537 |
| 23.64 | 20,896 |
| 25.73 | 23,880 |
| 29.16 | 27,749 |
| 31.77 | 31,836 |
| 33.83 | 34,421 |
| 37.82 | 38,218 |
| 42.76 | 41,145 |
| 45.31 | 43,080 |
| 52.48 | 53,000 |
| 53.75 | 55,000 |
| 70.99 | 84,000 |

have shown that the Atlantic ITCZ is especially sensitive to land–sea ice cover in the Northern Hemisphere (Chang et al., 1997; Chiang et al., 2002, 2003; Chiang and Bitz, 2005) and AMOC (Cheng et al., 2007). The latitudinal asymmetry of the ITCZ is partly controlled by AMOC in that strong bottom water formation increases the cross equatorial heat flux from the South to North Atlantic and the meridional position of the ITCZ moves farther north. In contrast, a slowdown of the AMOC, as might be caused by a freshening of the North Atlantic during Heinrich events, strengthens the northeast Trade Winds and results in a southern migration of the ITCZ (Timmermann et al., 2005; Zhang and Delworth, 2005; Cheng et al., 2007).

Changes in solar insolation forced by orbital precession also influence the position of the ITCZ on long time scales with more precipitation in the Caribbean when perihelion occurs during boreal summer (Hodell et al., 1991; Haug et al., 2001; Clement et al., 2004). Additional factors that can influence the Atlantic ITCZ meridional position on shorter time scales include the El Niño Southern Oscillation and North Atlantic Oscillation (Giannini et al., 2000, 2001a, b).

### 5.2. *Sediment composition and proxy interpretation*

Pleistocene-age sediments consist of a mixture of authigenic (gypsum, calcite, and dolomite) and detrital (clay) components, and are similar to those described from Lakes Quexil and Salpetén (Deevey et al., 1983; Leyden et al., 1993). Sand-sized gypsum grains are euhedral with lenticular twinning and were precipitated from lake water, perhaps in the littoral zone where evaporation rates are greater than in deep, open water (Hillesheim et al., 2005). The gypsum formed authigenically during dry periods of the late Pleistocene when Lake Petén Itzá was significantly reduced in volume and more saline than today.

In contrast, wetter climate is represented by clay deposition when runoff and detrital input to the lake were relatively high. In nearby Lakes Quexil and Salpetén, the most abundant clay mineral in sediment cores is montmorillonite, which is the residue derived from dissolution of limestone bedrock (Brenner, 1983; Deevey et al., 1983). Alternations between gypsum and clay deposition therefore reflect wet–dry cycles that are recorded by variations in sediment density and magnetic susceptibility. These alternations provide a robust signal in core logging variables that can be correlated precisely among deep sites in Lake Petén Itzá (Hodell et al., 2006), indicating a consistent whole-basin response to climate change. Gypsum was deposited during lake lowstands (i.e., dry climate) and is marked by low magnetic susceptibility and high density, whereas clay-rich sediments were deposited during lake highstands (i.e., wet climate) and are marked by relatively high magnetic susceptibility and low density.

### 5.3. *Paleoclimate history*

Although we present the full 85-kyr record, we focus our paleoclimatic interpretations and correlations on the last ~40 ka because this is the period for which we have reliable age control (Fig. 3). To test our working hypothesis, the inferred paleoclimate history from Lake Petén Itzá is compared with marine sediment records from the Cariaco Basin and North Atlantic, and with polar ice cores from Greenland and Antarctica.

#### 5.3.1. *85 to 48 ka (MIS 5a, 4, and early 3)*

The interval from ~85 to 48 ka consists mainly of carbonate mud and clay with the first gypsum layer appearing at ~48 ka (Fig. 6). This suggests that conditions were relatively moist between 85 and 48 ka during MIS 5a, 4, and the early part of MIS 3. Moist conditions during glacial stage 4 are consistent with the cool, moist conditions found during the Last Glacial Maximum (LGM) Chronozone between 23 and 18 ka (see discussion in Section 5.4.1).

The first gypsum layer occurs at ~48 ka (50 mcd) and may have been deposited at the same time as Heinrich event 5, although the dating uncertainty in this interval is high. The onset of gypsum precipitation at ~48 ka signifies a hydrologic regime shift in lowland Central America toward wet–dry cycles beginning in the latter part of MIS 3 (Fig. 6). We suggest this change may have been related to a more dynamic Laurentide ice sheet with increased meltwater input to both the North Atlantic and Gulf of Mexico. The frequency of D–O events appears to increase following HE 5 as the length of the Bond cycles become shorter (Bond et al., 1993; Martrat et al., 2004). Marshall and Clark (2002) found that a substantial fraction (60–80%) of the Laurentide ice sheet was frozen to the bed for the first 75 kyrs of a 120-kyr simulation of the last glacial cycle that used an ice sheet model driven by Greenland temperature. The fraction of warm-based ice increased substantially in the latter part of the glacial cycle as the ice sheet thickened and expanded, thereby increasing basal flow resulting in thinning of the ice sheet interior and intense calving at marine margins. We note, however, that the inferred hydrologic shift observed at ~48 ka in the Lake Petén Itzá record has no obvious expression in the Cariaco Basin record further south (Peterson et al., 2000; Hughen et al., 2006), although a similar time for a major climate transition was noted for El Valle, Panama (Bush, 2002).

### 5.4. *48–23 ka (late MIS 3)*

The Petén region underwent rapid climate changes during late MIS 3 as marked by millennial-scale oscillations in gypsum and clay deposition. Greenland interstadials 3 through 8 correlate with increased clay content in PI-6, indicating increased precipitation and runoff. In contrast, the thickest gypsum beds, indicating arid climate, occurred at the same time as Heinrich Events in the North Atlantic when temperatures in Greenland and the North Atlantic were coldest (Fig. 7). These events are associated with the delivery of abundant icebergs to the North Atlantic that may have lowered the salinity of surface waters, increased sea ice extent, and led to a slowdown of ocean

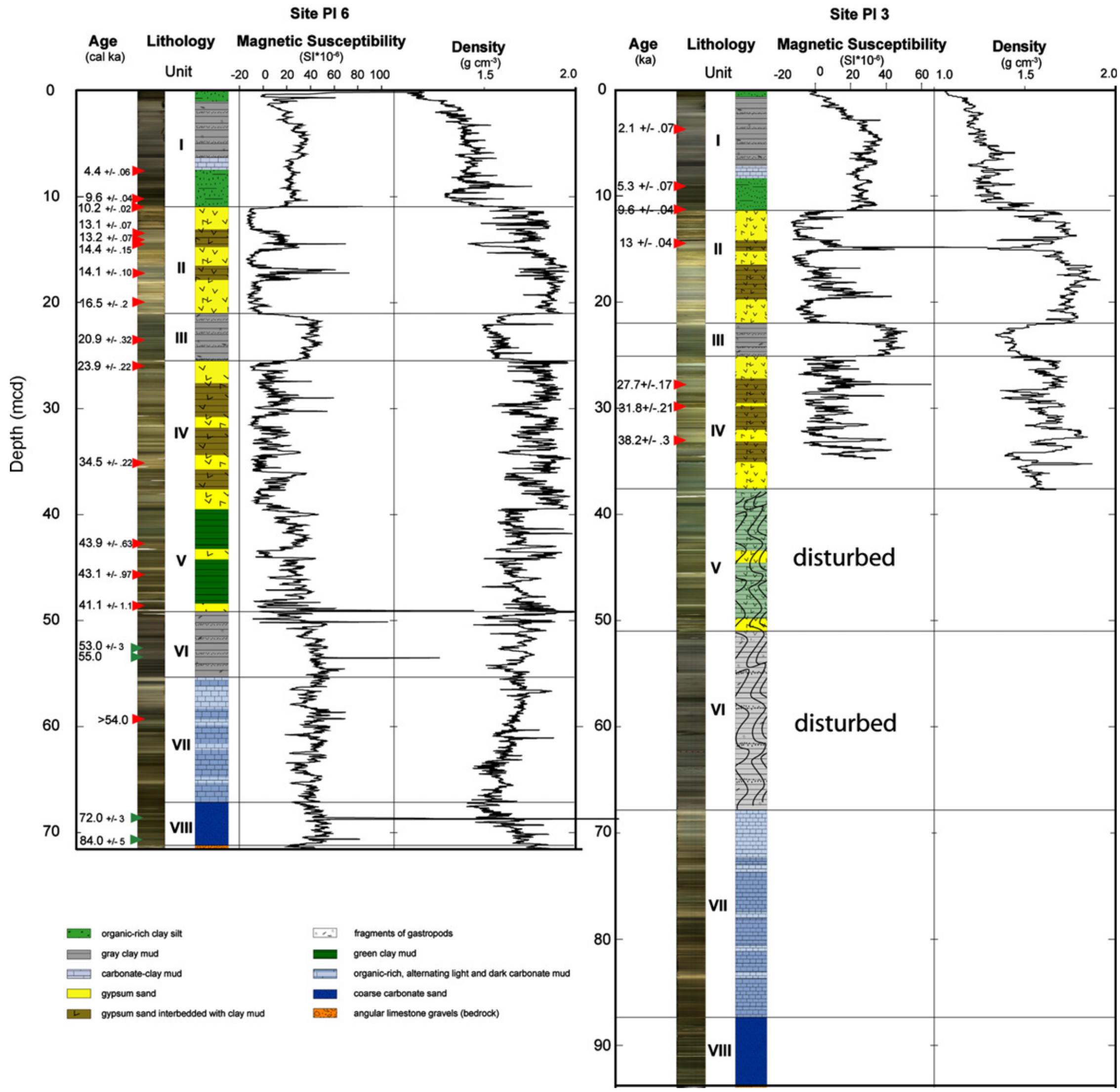


**Fig. 5.** Normalized composite images, lithostratigraphy, magnetic susceptibility, and density for Sites PI-6 and PI-3. Gypsum beds (yellow) are marked by relatively low susceptibility and high density, whereas more clay-rich units (gray and brown) are characterized by higher susceptibility and low density. Red arrows indicate position of radiocarbon dates corrected using calibration of Fairbanks et al. (2005).

**Table 6**
Density and magnetic susceptibility of common minerals found in Petén Itzá's sediment

| Mineral | Density ($g\,cm^{-3}$) | Volume susceptibility $\times 10^{-6}$ SI |
|---|---|---|
| Gypsum | 2.34 | −13 to −29 |
| Calcite | 2.71 | −7.5 to −39 |
| Clay | 1.70 | 170 to 250 |

*Source*: Hunt et al. (1995).

thermohaline circulation. Modeling results suggest that increased sea ice and reductions in AMOC during Heinrich Events are associated with a southward shift of the Atlantic ITCZ (Vellinga and Wood, 2002; Chiang et al., 2003; Dahl et al., 2005; Cheng et al., 2007), which would reduce precipitation over large parts of Central America and northern South America.

The magnetic susceptibility record of PI-6 correlates well with sea surface temperature in the subtropical northeastern Atlantic (Fig. 7; Bard et al., 2000), indicating that Petén climate was dry during periods of cooler SST. The magnetic susceptibility signal from PI-6 is also consistent with findings from the Cariaco Basin during the last glacial period (Fig. 7: Peterson et al., 2000). The Cariaco color and titanium signals indicate enhanced upwelling and reduced precipitation associated with cold stadials in Greenland during the last glaciation. Our results for MIS 3 from Petén Itzá support the hypothesis of northerly shifts of the ITCZ associated with interstadials, and southerly shifts of the ITCZ during stadials, especially during Heinrich Events when AMOC was reduced (Peterson et al., 2000; Leduc et al., 2007).

Because of the anti-phase relationship of millennial-scale climate variability between Greenland and Antarctica during the last glaciation (EPICA Community Members, 2006), dry periods in Petén are generally associated with warmings in Antarctica during MIS 3 (Fig. 8). The Petén record is also anti-phase relative to precipitation in the southern hemisphere Neotropics. Dry periods in Petén associated with Heinrich events are correlated with increased precipitation in the southern hemisphere (Fig. 8), as inferred from lake records in the Andes (Baker et al., 2001), northern Brazil (Colinvaux et al., 1996; Bush et al., 2004), and marine sediment cores off northeastern Brazil and are attributed to the southward displacement of the ITCZ and enhanced northeast Trade Winds (Arz et al., 1998; Jennerjahn et al., 2004; Jaeschke et al., 2007). Speleothems from northeastern Brazil are

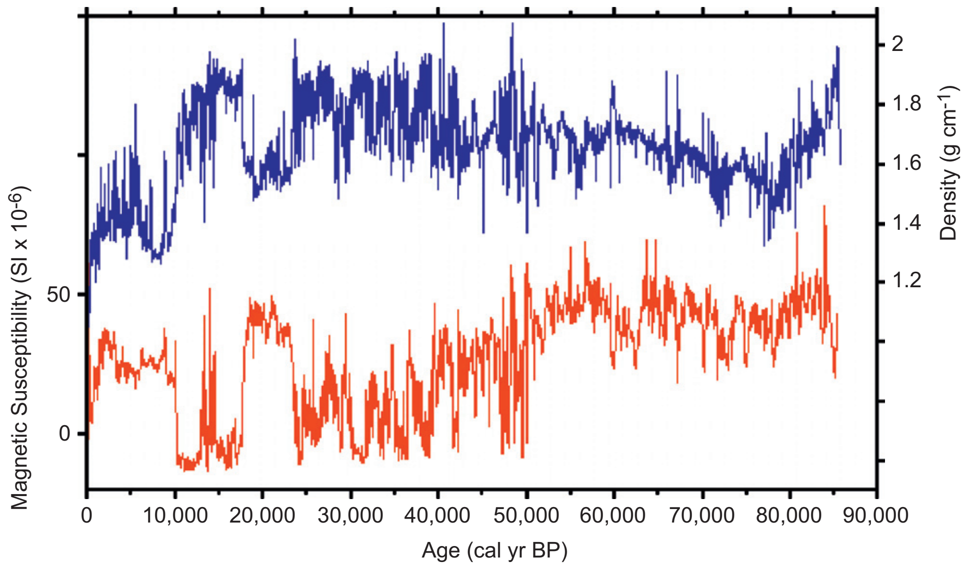


**Fig. 6.** Magnetic susceptibility (red) and density (blue) of Site PI-6 for the last 85 ka.

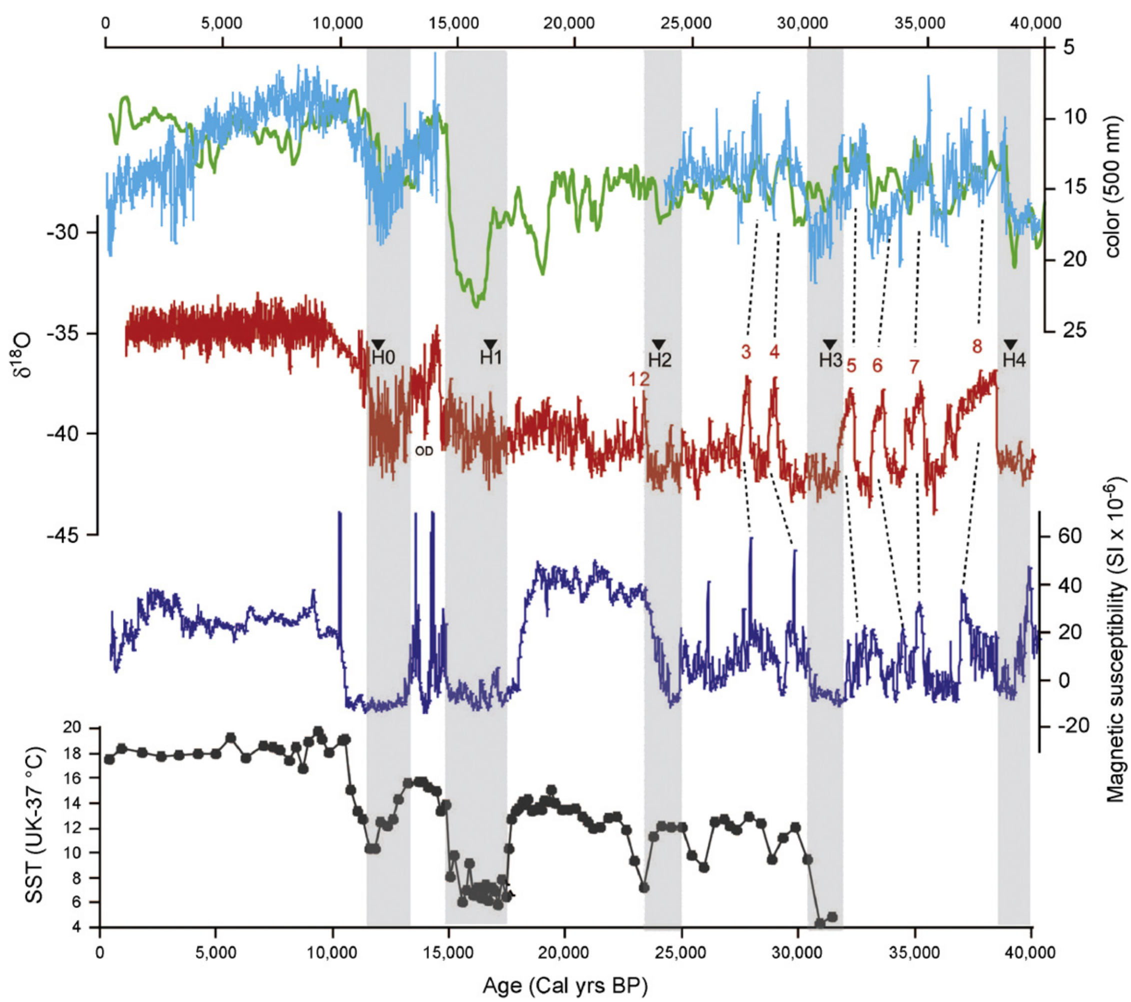


**Fig. 7.** Magnetic susceptibility record of Site PI-6 (blue) compared to the $\delta^{18}O$ of the Greenland Ice Core (red; Grootes et al., 1993), color reflectance (green) and titanium (light blue; scale is relative counts measured by scanning XRF) in the Cariaco Basin (Peterson et al., 2000; Haug et al., 2001), and sea surface temperature derived from alkenones in core SU8118 from the subtropical NE Atlantic (gray; Bard et al., 2000). Each record is plotted on its independent time scale. The mid-point of Heinrich Events (H) is indicated by black triangles. The thickest gypsum deposits (marked by low magnetic susceptibility) are highlighted by gray shading and correlate with Heinrich Events that occur in the coldest stadials in Greenland, increased Trade Wind intensity and reduced precipitation in Cariaco Basin sediment cores, and cool sea surface temperatures (SST) in the subtropical northeast Atlantic. Red numbers denote Greenland interstadials and OD = Older Dryas.

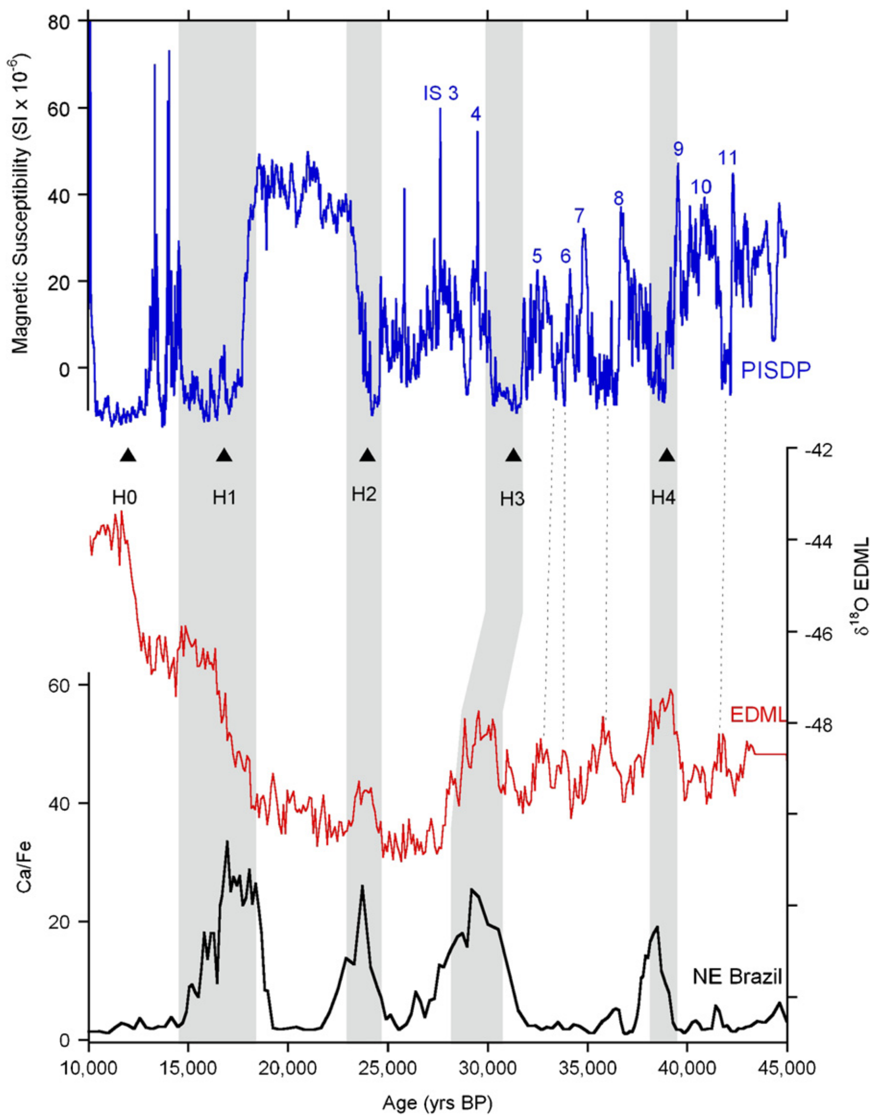


**Fig. 8.** Comparison of the magnetic susceptibility record from Site PI-6 (blue) with the $\delta^{18}$O of the EPICA Dronning Maud Land (EDML) Ice Core, Antarctica (red; EPICA Community Members, 2006) and Fe/Ca from Core GeoB 3104-1 off northeastern Brazil (Arz et al., 1998). Each record is plotted on its independent time scale. Arid conditions in the Lake Petén Itzá core are marked by gypsum precipitation (low magnetic susceptibility) and correlate with warm periods in Antarctica and increased rainfall and terrigenous input off northeast Brazil.

also marked by growth phases during Heinrich events, indicating wet climate (Wang et al., 2004).

*5.4.1. 23–18 ka (LGM Chronozone)*

Clay-rich sediments accumulated between ~23 and 18 ka (Figs. 6 and 7), corresponding approximately to the working definition of the LGM chronozone adopted by Mix et al. (2001). We note, however, that the LGM chronozone may be a misnomer if minimum sea level and maximum ice volume occurred 5000 yr earlier at 26 ka (Peltier and Fairbanks, 2006). Nonetheless, clay-rich sediments were deposited between ~23 and 18 ka suggesting deposition in deep water under relatively wet climate conditions.

Pollen analysis at Site PI-6 indicates that vegetation at that time consisted of a montane pine-oak forest that existed under relatively cool and moist conditions (Fig. 9; Bush et al., submitted for publication). This finding contradicts previous results from Lake Quexil suggesting that conditions in Petén during the LGM Chronozone were arid and vegetation dominated by xeric thornscrub taxa (Leyden et al., 1993, 1994). The apparent discrepancy is probably the result of poor time control in the Lake Quexil 80-1 core. Radiocarbon dates on shell carbonate were probably affected by hard-water lake error, making age estimates too old. For example, Leyden et al. (1993, 1994) reported a pine-oak pollen assemblage for MIS 3, but this interval probably represents the LGM instead. The pine-oak assemblage recorded in PI6 also contains mesic tropical elements (Fig. 9; Bush et al., submitted for publication), suggesting the presence of a 'no-analog' vegetation type. Such assemblages have been interpreted to represent climates without precise modern analog (Jackson and Williams, 2004; Williams et al., 2007). The only other lowland vegetation record spanning MIS2 from lower Central America is that of El Valle, Panama, which also shows a mixture of montane oak and mesic forest elements at the LGM (Bush and Colinvaux, 1990).

The cool, moist conditions in Petén from 23 to 18 ka may have been related to a relative increase in summer precipitation and reduced evaporation rates. The clay unit stands out because it occurs between Heinrich Events 1 and 2 when climate was dry and marked by gypsum precipitation. The mean position of the ITCZ was likely farther north between 23 and 18 ka than it was

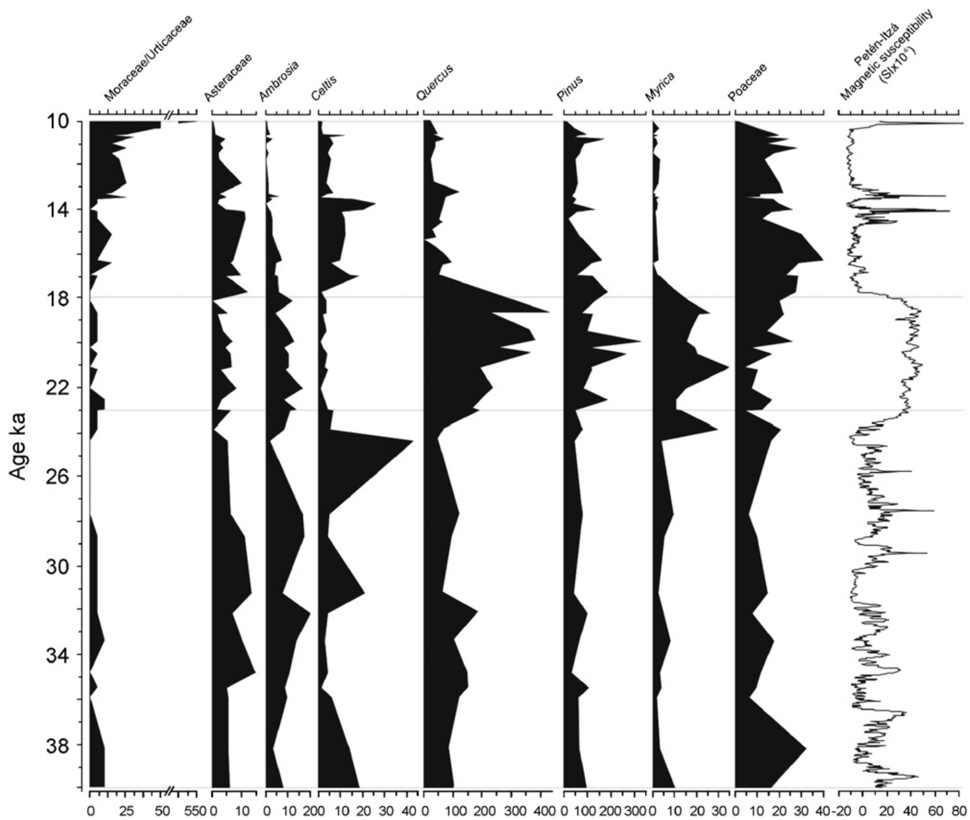


**Fig. 9.** Pollen accumulation rates, charcoal concentration, and magnetic susceptibility from Site PI-6 (Bush et al., submitted for publication).

during the Heinrich events when the ITCZ was located farther south (Arz et al., 1998; Jennerjahn et al., 2004; Jaeschke et al., 2007). Bard et al. (2000) noted that the LGM chronozone (21,000 ± 2000 cal yr BP) was a rather mild period in the subtropical North Atlantic, with SST on the order of ~13 °C (Fig. 7), only ~5 °C lower than present.

Other studies have suggested a mean southerly position for the ITCZ during the LGM (Koutavas and Lynch-Stieglitz, 2004). Interpretation of the Cariaco Basin record is complicated for the LGM because the basin would have been increasingly isolated from the open Caribbean by lowered sea level. If summer precipitation cannot account for the high lake levels of Petén Itzá between 23 and 18 ka, then perhaps winter rainfall increased. Cold air masses from the interior of North America often penetrate southward today into Mexico and Central America during the winter, bringing rain to Petén. The amount is insignificant relative to summer precipitation today but cold surges were likely more frequent and intense during the LGM (Bush and Silman, 2004; Bush et al., submitted for publication). Increases in winter precipitation during the LGM have been inferred from high lake stands in the American Southwest and in northwestern Mexico, as far south as 20°N (Bradbury, 1997; Metcalfe et al., 2000).

The pine-oak forest of the LGM Chronozone is consistent with a cooling of ~4–6 °C for the Central America lowlands (Bush et al., submitted for publication). The western Caribbean was 2.5 °C cooler during the LGM and salinities were 2.3–2.7 p.s.u. (practical salinity units) higher than modern (Schmidt et al., 2004). Lower temperature between 23 and 18 ka would have reduced evaporative losses from the lake and contributed to maintaining relatively high lake levels.

#### 5.4.2. 18–10 ka (Deglaciation)

At the end of the LGM, a shift from relatively moist to arid conditions occurred at ~18 ka coinciding with Heinrich Event 1 and the beginning of the so-called "mystery interval" (Fig. 10; Broecker and Barker, 2007). This period represents the start of the last deglaciation when a severe slowdown occurred in AMOC as expressed by a sharp drop in $^{231}Pa/^{230}Th$ (McManus et al., 2004). This event was also associated with an abrupt cooling in both Greenland (Fig. 7) and sea surface temperature records from the subtropical North Atlantic (Fig. 10). The ITCZ was located at a far southerly position (Leduc et al., 2007) and dry conditions prevailed in Petén.

At the start of the Bolling–Allerod warm period at 14.7 ka, gypsum precipitation declined and sediment clay content increased. This signal of wetter conditions is consistent with rising lake levels at El Valle and La Yeguada, Panama (Bush et al., 1992). The switch from dry to more humid conditions coincided with resumption of AMOC and warming of the North Atlantic (Fig. 10). Caribbean temperatures warmed and surface salinity decreased rapidly at the onset of the Bolling–Allerod interval (Lea et al., 2003; Schmidt et al., 2004). Elemental and sedimentologic data from the Cariaco Basin suggest that rainfall in the Caribbean region increased during the Bolling–Allerod associated with a northward migration of the ITCZ (Hughen et al., 1996; Peterson et al., 2000).

In Petén Itzá, the clays deposited during the Bolling and Allerod periods surround a gypsum layer that indicates a return to dry conditions that may coincide with the Older Dryas event (~13.8 ka) recorded in Greenland (Fig. 7) and Europe. The Older Dryas has been associated with Meltwater pulse 1A (Stanford et al., 2006) and also coincided with the peak of meltwater input

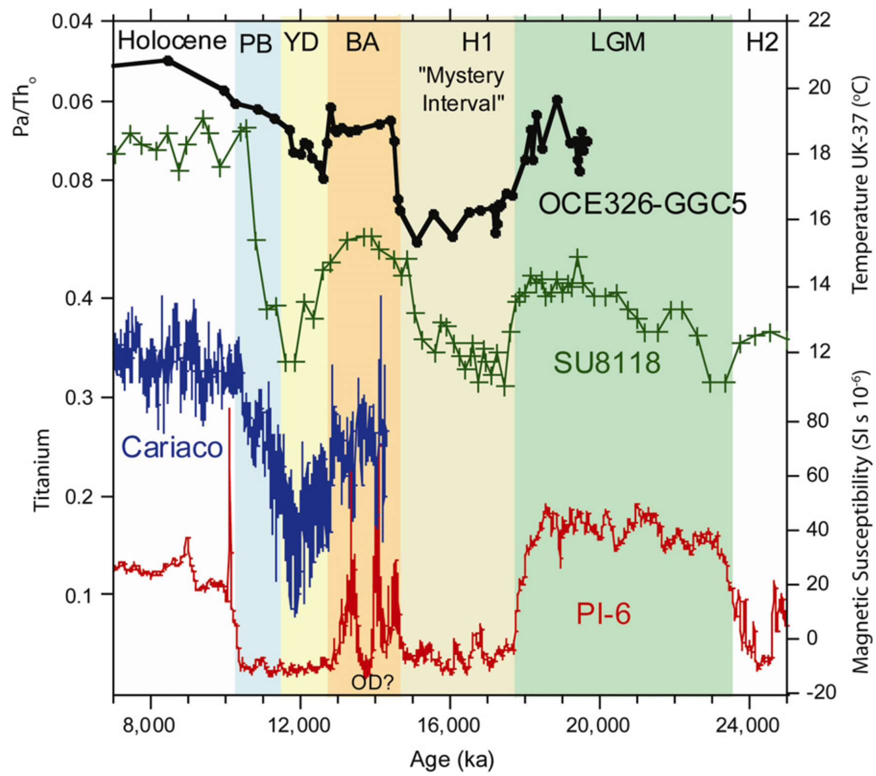


**Fig. 10.** Comparison of magnetic susceptibility from Site PI-6 (red), titanium from the Cariaco Basin (blue; Haug et al., 2001) reflecting precipitation in northern South America, sea surface temperature derived from alkenones in core SU8118 from the Gulf of Cadiz (green; Bard et al., 2000), and $^{231}Pa/^{230}Th$ from OCE326-GGC5 reflecting intensity of AMOC (black; McManus et al., 2004).

to the Gulf of Mexico (Flower et al., 2004). Our results indicate a strong drying in lowland Central America associated with these events.

At the start of the Younger Dryas at 12.8 ka, clay deposition ceased and gypsum deposition resumed, indicating a return to dry conditions (Fig. 10). This finding is consistent with data from the Cariaco Basin that show evidence for enhanced upwelling and reduced precipitation in response to increased Trade Wind strength and a more southerly mean position of the ITCZ (Peterson et al., 2000). Sea surface temperatures in the Cariaco Basin dropped by 3–4 °C during the Younger Dryas (Lea et al., 2003) and changes also occurred in tropical vegetation, but lagged climate shifts by several decades (Hughen et al., 2004). Cool temperatures prevailed in the North Atlantic and Pa/Th measurements suggest reduced strength of AMOC during the Younger Dryas (Fig. 10).

The end of the Younger Dryas at ~11.5 ka is not marked by a lithologic change in Petén Itzá. Sediment properties suggest that the lake continued to precipitate gypsum until the end of the Preboreal Period at ~10.3 ka. In the Cariaco Basin, the end of the Younger Dryas (11,490 ± 70 yr BP) coincided with an abrupt change to warmer, wetter conditions that were accompanied by a shift from arid grassland to wet forest (Hughen et al., 1996, 2004; Peterson et al., 2000; Haug et al., 2001; Lea et al., 2003).

Pollen studies in Petén indicate that tropical forest arose after 12.5 ka and was dominant by ~11 ka (Leyden, 1984; Leyden et al., 1993, 1994; Hillesheim et al., 2005). In the Petén Itzá record, pollen assemblages suggest there was a gradual change toward more mesic conditions between 13 and 11 ka (Bush et al., submitted for publication). An abrupt increase in rainfall is indicated by elevated Moraceae concentrations between ~11 and 10.3 ka at the time when gypsum precipitation ceased (Fig. 9).

## 6. Conclusion

Cores from Site PI-6 in Lake Petén Itzá, Guatemala, comprise a complete, spliced stratigraphic section to 75.9 m composite depth (mcd). Radiocarbon dates on terrestrial organic matter provide a reliable chronology for the last 40 ka, and the chronology is extended to 85 ka using tephrostratigraphy. From ~85 to 48 ka, sediments were dominated by carbonate clay indicating moist conditions during Marine Isotope Stages (MIS) 5a, 4, and early 3. The first gypsum layer was deposited at ~48 ka, signifying a shift in hydrologic regime toward drier conditions and the onset of dry–wet oscillations. During the latter part of MIS 3 (48–23 ka), Lake Petén Itzá sediments record millennial-scale, dry–wet cycles that correlate with stadial–interstadial stages (Dansgaard–Oeschger events) in Greenland. Gypsum was deposited under arid conditions during the stadials in the North Atlantic, especially those associated with Heinrich Events when cold sea surface temperatures prevailed in the North Atlantic and the ITCZ was displaced to the south. Interstadials were marked by higher clay content, indicating increased precipitation, runoff, and fine sediment transport. The pattern of clay–gypsum (wet–dry) oscillations during MIS 3 closely resembles the temperature record from Greenland ice cores and North Atlantic marine sediment cores and precipitation proxies from the Cariaco Basin. Our results support a southward displacement of the Atlantic ITCZ during stadials and northward during interstadials, as suggested by other paleoproxy records and modeling results (Peterson et al., 2000; Chiang et al., 2003; Schmidt et al., 2004; Wang et al., 2004; Leduc et al., 2007).

Contrary to previous findings (Leyden et al., 1993, 1994), a prolonged period of cold, wet conditions prevailed from 23 to 18 ka. The catchment was dominated by temperate elements such as *Quercus, Pinus* and *Myrica*. The source of moisture supporting the vegetation was derived from increased summer precipitation related to a more northerly ITCZ and/or winter precipitation related to more frequent and intense polar outbreaks ("*norte*" winds). Petén climate switched from moist to arid conditions during the so-called "Mystery Period" from 18 to 14.7 ka, which includes Heinrich Event 1. Moist conditions prevailed during the warmer Bolling–Allerod (14.7–12.8 ka), with the exception of a brief return to dry conditions at ~13.8 ka that coincided with the Older Dryas and Meltwater Pulse 1A. The onset of the Younger Dryas at 12.8 ka marked the return of dry conditions and gypsum precipitation continued until ~10.4 ka.

Our results generally support the hypothesis that summer precipitation in the northern Neotropics was controlled by migrations in the meridional position of the Atlantic ITCZ during the stadial–interstadial events of late MIS 3 and the last deglaciation. The ITCZ was located farther south during cold periods when arid conditions prevailed in the northern Neotropics, especially during Heinrich Events.

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## Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.quascirev.2008.02.008.

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