Late Quaternary Environmental Change in the Lowland Neotropics:
The Petén Itzá Scientific Drilling Project, Guatemala

A dissertation submitted to the
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# Contents

<table>
<thead>
<tr>
<th>Summary</th>
<th>v</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zusammenfassung</td>
<td>vii</td>
</tr>
</tbody>
</table>

## 1 Introduction 1

1.1 Research motivation and general objectives ............................................. 1

1.2 Site Description .................................................................................. 6

1.3 Climate in Petén ............................................................................... 8

1.4 Cultural history of the Petén ............................................................... 9

1.5 Thesis outline .................................................................................. 11

## 2 Late Quaternary palaeoenvironment of northern Guatemala 15

2.1 Introduction .................................................................................. 16

2.2 Study site ...................................................................................... 19

2.3 Methods ......................................................................................... 19

2.4 Results .......................................................................................... 20

2.4.1 Core recovery and sediment chronology ......................................... 20

2.4.2 Sediment types ........................................................................... 23

2.4.3 Lithostratigraphic units ................................................................ 23

2.4.4 Seismic stratigraphy .................................................................... 34

2.4.5 Core-to-seismic correlation .......................................................... 35

2.5 Discussion ...................................................................................... 36

2.5.1 Comparisons with the seismic model of Anselmetti et al. (2006) ......... 36

2.5.2 Lake level and sedimentation history of Lake Petén Itzá ................. 37

2.6 Conclusions .................................................................................... 42

## 3 An 85-ka record of climate change in lowland Central America 45

3.1 Introduction ................................................................................... 46

3.2 Modern limnology and climate ............................................................ 48

3.3 Methods .......................................................................................... 51

3.3.1 Composite sections ................................................................. 51

<table>
<thead>
<tr>
<th>Summary</th>
<th>v</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zusammenfassung</td>
<td>vii</td>
</tr>
</tbody>
</table>

## 1 Introduction 1

1.1 Research motivation and general objectives ............................................. 1

1.2 Site Description .................................................................................. 6

1.3 Climate in Petén ............................................................................... 8

1.4 Cultural history of the Petén ............................................................... 9

1.5 Thesis outline .................................................................................. 11

## 2 Late Quaternary palaeoenvironment of northern Guatemala 15

2.1 Introduction .................................................................................. 16

2.2 Study site ...................................................................................... 19

2.3 Methods ......................................................................................... 19

2.4 Results .......................................................................................... 20

2.4.1 Core recovery and sediment chronology ......................................... 20

2.4.2 Sediment types ........................................................................... 23

2.4.3 Lithostratigraphic units ................................................................ 23

2.4.4 Seismic stratigraphy .................................................................... 34

2.4.5 Core-to-seismic correlation .......................................................... 35

2.5 Discussion ...................................................................................... 36

2.5.1 Comparisons with the seismic model of Anselmetti et al. (2006) ......... 36

2.5.2 Lake level and sedimentation history of Lake Petén Itzá ................. 37

2.6 Conclusions .................................................................................... 42

## 3 An 85-ka record of climate change in lowland Central America 45

3.1 Introduction ................................................................................... 46

3.2 Modern limnology and climate ............................................................ 48

3.3 Methods .......................................................................................... 51

3.3.1 Composite sections ................................................................. 51
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.2</td>
<td>Core logging</td>
</tr>
<tr>
<td>3.4</td>
<td>Results</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Chronology</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Lithostratigraphy</td>
</tr>
<tr>
<td>3.4.3</td>
<td>Density and magnetic susceptibility</td>
</tr>
<tr>
<td>3.5</td>
<td>Discussion</td>
</tr>
<tr>
<td>3.5.1</td>
<td>Working hypothesis</td>
</tr>
<tr>
<td>3.5.2</td>
<td>Sediment composition and proxy interpretation</td>
</tr>
<tr>
<td>3.5.3</td>
<td>Paleoclimate history</td>
</tr>
<tr>
<td>3.6</td>
<td>Conclusion</td>
</tr>
</tbody>
</table>

4 Climate drying and associated forest decline in the lowlands of northern Guatemala 69

4.1 Introduction .............................................................................................................. 70
4.2 Study site .................................................................................................................. 70
4.3 Materials and methods ............................................................................................. 71
4.4 Proxy indicators of environmental changes ............................................................ 75
4.5 Results ...................................................................................................................... 76
4.5.1 Lithostratigraphy and chronology ......................................................................... 76
4.5.2 Pollen and $\delta^{13}$C Isotopes ........................................................................ 78
4.5.3 Modern sedimentology of Lake Petén Itzá ........................................................... 79
4.6 Discussion .................................................................................................................. 79
4.6.1 Palaeoenvironmental interpretation ...................................................................... 79
4.7 Conclusions ................................................................................................................ 84

5 Recovery of the tropical ecosystem after disintegration of Classic Maya polities 87

5.1 Introduction ................................................................................................................ 88
5.2 Study site .................................................................................................................... 89
5.3 Methods ....................................................................................................................... 89
5.4 Results ........................................................................................................................ 91
5.5 Discussion .................................................................................................................. 94
5.5.1 Human ecology in Petén at the Terminal Classic to Early Post-classic Transition .............................................................................................................. 94
5.6 Conclusions ................................................................................................................. 95

6 A comparison between the Maya-Clay and the LGM-Clay 97

6.1 Introduction ................................................................................................................ 98
6.2 Study site .................................................................................................................... 99
6.3 Methods ................................... 99
6.4 Results ....................................100
   6.4.1 Maya-Clay (∼3.0 to 1.0 ka BP) ..................100
   6.4.2 LGM Clay (∼23.0 to 18.0 ka BP) ................102
6.5 Discussion ..................................105
6.6 Conclusion .................................105

7 Conclusions and Future Prospects 107
   7.1 Conclusions .................................107
   7.2 Future Prospects ...............................109

Bibliography 111
Acknowledgements 127
Curriculum Vitae 129
Summary

The aim of this thesis was to recover and to interpret high-quality sediment cores spanning multiple glacial to interglacial cycles from Lake Petén Itzá (16°55′N, 89°50′W) in Petén, Guatemala, the deepest (max. water depth > 160 m) and largest (area ∼100 km²) lake in the Neotropical lowlands of Central America. Its sediment record was drilled in spring 2006 within a project of the International Continental Scientific Drilling Program (ICDP). In this thesis, the entire sediment record from Lake Petén Itzá is described and interpreted in detail to explore the sedimentological history of Lake Petén Itzá and the related Late Quaternary palaeoclimate and palaeoenvironment of the lowland of Mesoamerica.

The sediment record of Lake Petén Itzá extends back to >200’000 cal yrs BP and consists mainly of alternating clay, gypsum and carbonate units. Clay units are associated with times of high detrital input and high lake-level stands (i.e. wet climate), gypsum units are related to chemical precipitation during low lake-level stands (i.e. dry climate), whereas carbonate units are related either to detrital input (reflecting high runoff, i.e. wet climate) or authigenic carbonate precipitation (reflecting rather low lake levels, i.e. dry climate), respectively. Most of these lithogenic units are laterally trackable throughout the basin along stratigraphic boundaries that can be mapped on seismic profiles as reflections, suggesting the use of the lithology as a valuable proxy to infer palaeoenvironmental changes on a regional scale.

In summary, data and results presented in this thesis reveal that from ∼200’000 to 90’000 cal yrs BP, sediments are dominated by a detrital origin suggesting relatively wet climate conditions during this period. Between ∼90’000 and 85’000 cal yrs BP, a horizon characterized by very reduced sedimentation or non-deposition, sometimes containing bedrock clasts, was formed. This suggests shallow water conditions and a partial basin desiccation pointing to a very dry climate at that time. This horizon is overlain by coarse transgressive lake sediments suggesting a lake level rise beginning at ∼85’000 cal yrs BP. Following this rise, the lake level stabilised at a relatively high stage until ∼48’000 cal yrs BP indicated by clayey sediments. From ∼48’000 to 23’000 cal yrs BP, clay and gypsum alternations (i.e. alternating deep and shallow water conditions) correlate well with stadial-interstadial stages (Dansgaard-Oeschger events) from Greenland ice cores and North Atlantic marine sediment cores, as well as with precipitation proxies from the Cariaco Basin off northern Venezuela. Gypsum units are associated with cold stadials, especially those containing Heinrich Events, whereas clay units are related to warm interstadials. An unexpected finding was that sediments deposited during the Last Glacial Maximum (LGM, from ∼23’000 to 18’000 cal yrs BP) consist of a thick clay unit. This suggests substantial detrital input and a high lake level, hence, humid climate conditions during the LGM in Petén. This contradicts previous palaeoclimatic interpretations that proposed a dry LGM in the lowland Neotropics of

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Central America. The driest period of the last gliation was the deglacial period (~18,000 to 11,000 cal yrs BP), when the lake level of Lake Petén Itzá fluctuated between low and intermediate stands, as indicated by alternating gypsum- and clay sediments. In addition, low lake levels are documented in seismic data by corresponding palaeoshorelines in the lake-margin area.

Comparisons with other palaeoclimate records suggest that climate conditions in Petén during the last 48,000 years were controlled by migrations in the meridional position of the Atlantic Intertropical Convergence Zone (ITCZ). The ITCZ was located farther south during cold periods, especially during Heinrich Events, when arid conditions prevailed in the northern hemisphere Neotropics, and vice versa. However, a different mechanism is proposed for the “out-of-phase” LGM, when moisture was rather controlled by winter precipitation related to more frequent and intense polar outbreaks (“nortewinds”).

In addition to the drilled ICDP-sediment cores, seismic data from Lake Petén Itzá collected in 1999 and 2002 are integrated and partly reinterpreted. Furthermore, Kullenberg cores and short gravity cores were used to investigate climate-environment-human interactions during the late Holocene. Analysis of these cores indicate that late Holocene tropical forest decline in Petén was not exclusively a consequence of anthropogenic deforestation by ancient Maya, as previously suggested, but was partly attributable to a climate drying trend throughout the circum-Caribbean between 4,600 and 3,000 cal yrs BP. These dry conditions were driven, analogue to the late Pleistocene, by a southwards displacement of the mean position of the Atlantic ITCZ. The short cores were also used to demonstrate that the tropical forest ecosystem in the watershed of Lake Petén Itzá had been re-established by the early Postclassic period (AD 1000-1200) after widespread abandonment of agricultural systems associated with the disintegration of Classic Maya states between ~AD 800 and 1000.
Zusammenfassung


Zusammengefasst lässt sich sagen, dass Sedimente, welche in einem Zeitraum von 200'000 bis 90'000 Jahren vor heute (BP, before present) abgelagert wurden, hauptsächlich detritischer Natur sind. Dies deutet auf relativ feuchtes Klima während dieser Zeitspanne hin. Zwischen 90'000 und 85'000 Jahren BP wurden nur wenig bis gar keine Seesedimente abgelagert (an einigen Stellen sind feste carbonatische Geröllkomponenten vorhanden). Diese Beobachtungen weisen auf einen tiefen Wasserstand verbunden mit einer partiellen Austrocknung des Sees und somit auf ein trockenes Klima um diese Zeit hin. Vor 85'000 Jahren lagerten sich als Folge eines ansteigenden Seespiegels, grobkörnige, transgressive Seesedimente ab. Der Wasserspiegel blieb danach bis 48'000 Jahren BP relativ hoch, was auf Grund von feinen, tonigen Sedimenten postuliert werden kann. Zwischen 48'000 und 23'000 Jahren BP wurden hauptsächlich alternierende Gips- und Tonschichten abgelagert. Dies bedeutet, dass während dieser Zeit der Lake Petén Itzá durch wechselnde Flach- und Tiefwasserbedingungen beschrieben werden kann. Eine wichtige Beobachtung dieser Gips-Ton-Wechsellagerung ist deren zeitliche Korrelation zu Stadial-Interstadial-Phasen (Dansgaard-Oeschger Ereignisse), welche in Eisbohrker-


Chapter 1

Introduction

1.1 Research motivation and general objectives

Climate - Environment - Human interactions have been the focus of scientific investigations and political discussions in the last few decades. An example of human impact on climate and environment is current global warming, which focuses on human-generated greenhouse gases and their effect on global climate (IPCC report, 2008). In addition to the interest in anthropogenic influence on climate, researchers have also become intrigued by the influence that natural climate changes have on environmental and/or human cultural development (e.g. Diamond, 2005; Hodell et al., 1995). Understanding such relationships is a fundamental and societally-relevant goal of modern Earth Science. It is therefore essential to establish a broad picture of past climate and environmental changes, which may potentially be linked to cultural shifts. A substantial late Quaternary palaeoclimate database exists for the high latitudes, for instance from ice cores in Antarctica (EPICA Community Members, 2004) and Greenland (NGRIP Members, 2004). Relatively little, however, is known about terrestrial late Quaternary palaeoclimate in the low latitudes. Attention has increasingly focused on tropical paleoclimate archives because the tropics drive global climate changes (Bush and Philander, 1998; Chang et al., 1997; Kerr, 2001). Just as ice cores provide high-resolution records of past climate at high latitudes, lake sediment cores from closed-basin, tropical lakes provide valuable archives to infer past climate and environmental changes in the continental low latitudes. Long lacustrine sediment cores from the low latitudes, especially those extending into the Pleistocene, are scarce. They are particularly rare in the circum-Caribbean area, as it appears that most shallow basins in the region were dry at the end of the last Ice Age. The longest lacustrine record from the region, at least until now, was a core from Lake Quexil, northern Guatemala (Fig. 1.1), which was thought to span the last 36 kyr (Leyden et al., 1993). Given the scarcity of long lacustrine sediment cores from the circum-Caribbean area, retrieval of such sections became an important goal for palaeoenvironmental and palaeoclimatological research.
New perspectives on circum-Caribbean paleoclimate were attained in 1999 and 2002 when seismic surveys were completed on Lake Petén Itzá, the largest (∼100 km²) and the deepest lake (z\text{max} > 160 m) in the lowlands of Central America (Hillesheim et al., 2005; Anselmetti et al., 2006) (Fig. 1.1). Because of its great depth, Lake Petén Itzá held water even during the driest periods of the late Pleistocene. Seismic data indicated over 100 m of sediment in some depocentres (Anselmetti et al., 2006). Hence, the basin was shown to contain a sediment record that spans multiple glacial/interglacial cycles, and extends back far beyond the record from nearby Lake Quexil. In addition to containing a long paleoclimate record, the sediments of Lake Petén Itzá possess an ideal archive to study complex interactions among humans, climate, and environment because the area was densely occupied. The region was the cradle of Maya civilization from ∼1000 BC to ∼900 AD (Rice and Rice, 1990). In this context, the main objectives of this thesis are

- To recover continuous, high-quality sediment cores, which can be used to reconstruct the paleoclimatic history of the northern lowland Neotropics on orbital to suborbital time scales emphasizing marine-terrestrial linkages (e.g. comparison with Cariaco Basin and Greenland ice core records).
- To test the hypothesis derived from marine records of the Cariaco Basin that past changes in summer precipitation in the Circum Carribbean area were related to the meridional displacement in the mean position of the Atlantic Intertropical Convergence Zone (ITCZ) (Peterson et al., 2000).
- To infer climate-environment-human interactions during the emergence of ancient Maya culture in the Early Preclassic period (2,000-1,000 BC) in the Maya Lowlands of Petén. Several studies have addressed the importance of severe drought in the “Collapse” of Late Classic lowland Maya culture during the 9th century AD (e.g. Hodell et al., 1995; Haug et al., 2003). Little, however, has been reported about climate-environment-human interactions during the emergence of ancient Maya culture in the Early Preclassic period (2,000-1,000 BC).
- To address the timing of forest recovery and soil stabilization in the region during the past millennium, a period during which there was reduced anthropogenic stress on the sensitive lowland ecosystem after the abandonment of agricultural systems associated with disintegration of Classic Maya polities ca. ∼AD 800-1000.
- To identify the source and major processes responsible for the deposition of the Holocene “Maya Clay”.

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- To identify the source and major processes responsible for the deposition of the Holocene “Maya Clay”.
In spring 2006, Lake Petén Itzá’s sediment record was drilled under the auspices of an International Continental Scientific Drilling Program (ICDP)-project (Figs. 1.2 and 1.3, Table 1.1). Cores were retrieved using the Global Lakes Drilling (GLAD 800; Fig. 1.2) platform operated by DOSECC (Drilling, Observation and Sampling of the Earth’s Continental Crust). The objective of the Lake Petén Itzá Drilling Project was to recover continuous, high-quality sediment cores to infer a long, continuous paleoenvironmental history for the area. In this thesis, the entire drilled sediment record of Lake Petén Itzá is described and interpreted in terms of the Late Quaternary palaeoclimatological, palaeoenvironmental, and sedimentological history of low-latitude Mesoamerica. Seismic data from Lake Petén Itzá (Anselmetti et al., 2006) are integrated with data from the long drill cores to facilitate reconstruction of past conditions. Sedimentological data from Kullenberg cores retrieved in summer 2002 (Hillesheim, 2005) were also investigated. The Kullenberg cores were used to study the late Holocene climate history of the region and determine whether palynologically documented forest decline that began more than 3,000 years ago in Petén, northern Guatemala, was driven exclusively by Maya deforestation, as has been suggested (Deevey et al., 1979; Binford, 1983; Vaughan et al., 1985), or whether it was partly attributable to climate changes. Short gravity
cores from Lake Petén Itzá, retrieved in summer 2005, were used to study tropical forest regeneration and soil stabilization following a protracted period of intense human-mediated deforestation and consequent soil erosion.

Table 1.1: Location, penetration depth (meters below lake floor), and percent recovery of all ICDP-sites drilled in 2006 in Lake Petén Itzá.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Water depth (m)</th>
<th>Penetration Depth (mbed)</th>
<th>Average Recovery</th>
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<tr>
<td>PI-1</td>
<td>16° 59.9760’ N</td>
<td>89° 47.7396’ W</td>
<td>65</td>
<td>94.5</td>
<td>90.3</td>
</tr>
<tr>
<td>PI-2</td>
<td>16° 59.9712’ N</td>
<td>89° 44.6085’ W</td>
<td>54</td>
<td>66.2</td>
<td>41.2</td>
</tr>
<tr>
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<td>17° 0.2018’ N</td>
<td>89° 40.24’ W</td>
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<td>96.9</td>
<td>95.3</td>
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<tr>
<td>PI-4</td>
<td>17° 0.3342’ N</td>
<td>89° 50.772’ W</td>
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<td>67.4</td>
<td>46.3</td>
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<tr>
<td>PI-6</td>
<td>17° 0.0162’ N</td>
<td>89° 47.0866’ W</td>
<td>71</td>
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<td>89° 47.6844’ W</td>
<td>46</td>
<td>133.2</td>
<td>122.8</td>
</tr>
<tr>
<td>PI-9</td>
<td>16° 59.436’ N</td>
<td>89° 47.646’ W</td>
<td>30</td>
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Figure 1.2: Pictures from the Global Lakes Drilling platform GLAD 800 superbarge (RV Kerry Kelts). Lake Petén Itzá’s sediment record was drilled as part of an International Continental Deep Drilling Program (ICDP)-project between 3 February and 11 March 2006. Using the platform GLAD 800, operated by Drilling Observation and Sampling of the Earth’s Continental Crust (DOSECC), a sediment record of over 1300 m was retrieved from Lake Petén Itzá.

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Figure 1.3: Bathymetric map of Lake Petén Itzá showing the locations of all ICDP sites drilled in 2006. This map has been distributed to locals of Petén prior to drilling.
1.2 Site Description

Lake Petén Itzá (~16°55'N, 89°50'W) is the largest and deepest lake in the lowlands of Central America. It is one water body of the Petén Lake District in the Maya Lowlands, northern Guatemala (Fig. 1.1). The Petén Lake District lies in the southern part of the Yucatán Peninsula, which is a limestone platform that ranges in elevation from 0 - 300 m above sea level (Vinson, 1962). Topography is characterized by porous karst hills of Cretaceous and Tertiary age, with extensive dissolution features. Lake Petén Itzá, like the other basins in the Petén Lake District, owes its origin to a combination of two principal processes, tectonism and limestone dissolution. It lies along a tectonic half-graben formed by a series of east-west aligned en-echelon faults (Vinson, 1962).

Lake Petén Itzá consists of a large (area ~100 km²), deep northern basin (z_max > 160 m), and a smaller (area ~20 km²) and generally shallower southern basin (z_max ~10 m) (Fig. 1.3). The larger northern part contains the deepest water-filled basin in lowland Central America. It is a closed-basin lake with no visible outlet, though at higher stage water has been known to drain into underground cavities along the north shore. In closed basins, lake level is sensitive to changes in the ratio of evaporation (E) to precipitation (P). Thus, in times of lower P and/or higher E, the level of Lake Petén Itzá declines, while in times of higher P and/or lower E, lake level rises. Such lake level changes in the order of decimeters are documented for the 20th century and can be associated with mean monthly precipitation records for the periods 1934 to 1942 and 1971 to 1976 in Petén (Deevey et al., 1980). The fact that the lake level is controlled by E/P is also documented by the oxygen isotopic ratio (δ18O) of the lake water, which averages +2.9‰ and is enriched by ~7‰ relative to regional groundwater (~4‰) (Hillesheim et al., 2005).

Lake Petén Itzá’s water is relatively fresh today and has a total dissolved solids concentration of about 408 mg l⁻¹. The pH is ~8. The water is rich in calcium and bicarbonate, with magnesium and sulfate following closely in concentration (Table 1.2, Hillesheim et al., 2005). Lake Petén Itzá is thermally stratified throughout most of the year. The thermocline lies between 20 and 35 m water depth and displays temperature range from about 30.5 to 25.5 °C during the period of maximum heat storage (Hillesheim et al., 2005) (Fig. 1.4). Seismic data document that erosional processes took place at depth generally associated with the metalimnion (Anselmetti et al., 2006). It is speculated that erosion/non-deposition at this water depth may be related to internal progressive currents at the metalimnetic interface (Anselmetti et al., 2006). Side scan sonar data, taken during our short-coring campaign in 2005, confirm this hypothesis. These data show wave ripples along surface sediments in a water depth of ~30 m, suggesting subaqueous currents (Fig. 1.5).
Figure 1.4: Schematic model of the stratification of Lake Petén Itzá with a water temperature profile taken on 13 August 2002 (Hillesheim et al., 2005). The thermocline at ~30 m water depth is associated with an erosional feature due to subaquatic currents (Anselmetti et al., 2006).

Table 1.2: Mean ion concentrations of Petén Itzá lake water after Hillesheim et al. (2005).

<table>
<thead>
<tr>
<th>Ion</th>
<th>Concentration (meq l⁻¹)</th>
<th>Concentration (mg l⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca²⁺</td>
<td>3.15</td>
<td>63.13</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>1.86</td>
<td>22.62</td>
</tr>
<tr>
<td>Na⁺</td>
<td>0.60</td>
<td>13.80</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>0.26</td>
<td>9.22</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>2.11</td>
<td>101.34</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>3.24</td>
<td>197.67</td>
</tr>
<tr>
<td>Total</td>
<td>11.22</td>
<td>407.78</td>
</tr>
</tbody>
</table>

Soils in the Lake Petén Itzá watershed are principally mollisols (calcimorphic rendzinas) that cover approximately 90% of the Petén landscape (Simmons et al., 1959). Minerals of this soil type (mainly calcite and montmorillonite) support tropical, lowland dry forest that includes, among others, Fabaceae, Meliaceae, Sapotaceae, and Moraceae. A member of the latter family, *Brosimum alicastrum*, is the dominant tree in most associations, and contributes 40 - 60% of the modern pollen rain in the Petén Lake District (Vaughan et al., 1985; Leyden, 1987).
1.3 Climate in Petén

Precipitation across the Yucatan Peninsula displays a range from ∼2500 mm yr\(^{-1}\) in the southeast to ∼500 mm yr\(^{-1}\) in the northwest (Wilson, 1984). In Petén, annual precipitation averages 1600 mm (Deevey, 1978). The majority of the rain in Petén falls in the rainy season between June and October. These rainy summer months are often interrupted by a slight rainfall decrease in July and August, which is known as the canícula or “little dry” (Magaña et al., 1999). The rainy season ends by late October and is followed by a pronounced dry season during the winter months (January to May). Rainfall differences throughout the year are largely determined by the seasonal migration of the Intertropical Convergence Zone (ITCZ) and Azores–Bermuda high-pressure system (Hastenrath, 1984). The term “ITCZ” is used loosely to include both the zonally elongated, narrow band of convection as well as other tropical convective activity that is less spatially oriented (Hodell et al., 2008). The rainy summer months are driven by increased convection associated with a northward migration of the ITCZ, whereas the drier winter months are associated with an equatorward (i.e. southward) movement of the...
1.4 Cultural history of the Petén

The Petén region of northern Guatemala was the heartland of ancient Maya civilisation from \( \sim 1000 \) BC to \( \sim 900 \) AD (Rice and Rice, 1990) (Fig. 1.6). The Maya were one of the most populous pre-Columbian civilizations in Mesoamerica. The Maya civilisation developed writing as well as calendrical, mathematical and astronomical systems. The Maya civilization is divided into three time periods. During the Preclassic Period, spanning from 1000 BC to 250 AD, the Maya in Petén developed from nomadic hunter-gatherers into sedentary agriculturalists and urban dwellers (Rice and Rice, 1990). Ceramics dating to that time indicate the earliest human settlement in Petén (Rice, 1976). First examples of writing in the region are dated to the Late Preclassic (Coe, 1999).

During the Classic Period, which spanned from 300 to 900 AD, the Maya civilization became more complex as the population increased and centers in the highlands and the lowlands began to interact with one another. This time was characterized by tremendous development in architecture, writing, and calendrical systems throughout the Maya Lowlands. By late Classic times (550 - 800 AD), population densities up to 300 persons per km\(^2\) were attained in Petén (Rice and Rice, 1990; Rice et al., 1985). For reasons that are still debated, the Maya centers in the southern lowlands went into decline during the 8\(^{th}\) and 9\(^{th}\) centuries AD (Fig. 1.6). This population decline is often referred to in the literature as the “Classic Maya Collapse” (e.g. Rice and Rice, 1990). There is no universally accepted single theory to explain this “collapse”, but several hypotheses, including warfare, disease, earthquakes, soil degradation, and droughts have been proposed to explain the decline (Adams, 1973; Webster, 2002; Hodell et al., 1995; Haug et al., 2003). During the Postclassic Period, from 900 AD to 1525 AD, small, nucleated Maya settlements continued until Spanish contact in 1525 AD and conquest in 1697 AD.

Many palaeoenvironmental and palaeolimnological studies in the Maya Lowlands have investigated human-climate-environment interactions. One focus of these studies has been the impact of prehistoric human land use on the lowland tropical environment using sediment cores from Petén lakes (Deevey et al., 1979; Brenner, 1994; Anselmetti et al., 2007). The general sedimentologic pattern in regional lake basins is a succession of two gyttja units that are intercalated by an inorganic unit that coincides roughly with Maya occupation in the watersheds (Brenner et al., 2002). This inorganic unit is thick
and clay-carbonate-rich. It has been called “Maya Clay” and was interpreted to be the result of widespread Maya deforestation and consequent rapid soil erosion (Deevey et al., 1979; Binford, 1983; Vaughan et al., 1985). Catchment-wide, mean sustained soil erosion values were estimated in the Lake Salpetén basin to be as high as 1000 t/km$^2$ yr$^{-1}$ (Anselmetti et al., 2007), suggesting that soil erosion may have been a major problem for Maya agriculture. Similar patterns of stable soil phases, interrupted by periods of enhanced soil erosion, were also described from excavated sites in the area and document temporally variable impacts of Maya activity on local environments (Beach et al., 2006; Beach, 1998). There is ongoing debate as to whether forest reduction and consequent soil erosion were driven exclusively by anthropogenic deforestation, or whether they were attributable, at least in part, to climate change (Brenner et al., 2002; Hodell et al., 2000; Mueller et al., 2009).

Figure 1.6: A) Generalized archaeological chronology of Maya cultural periods (E-Early, M-Middle, L-Late, T-Terminal) (Rice and Rice, 1990; Anselmetti et al., 2007). B) Human impact on the terrestrial and aquatic environments in Petén as demonstrated by soil erosion rates (gray area) and sedimentation rates (black dashed line) (modified after Binford et al., 1987; Rice, 1996; Anselmetti et al., 2007). C) The Petén Lake District in northern Guatemala. Population density in Petén (Rice and Rice, 1990). D) Vegetation changes in Petén inferred from pollen analysis (Leyden, 1987).
This thesis consists of seven chapters: Chapter 1 provides a general introduction to the thesis. Chapters 2 to 6 represent four, individual peer-reviewed scientific articles that are published, accepted for publication, submitted or in preparation. Main conclusions and ideas for future prospects are summarized in chapter 7.

Chapter 2: “Late Quaternary Palaeoenvironment of Northern Guatemala: Evidence from Deep Drill Cores and Seismic Stratigraphy of Lake Petén Itzá” is accepted for publication in Sedimentology and documents the stratigraphy and sedimentology of all sites drilled by DOSECC between Feb 3 and March 11, 2006 using the Global Lake Drilling platform, GLAD 800. In this chapter, I show that Lake Petén Itzá’s sediment record consists mainly of alternating clay, gypsum and carbonate units, and that it extends back >200 ka. I demonstrate that most of these lithostratigraphic units are traceable throughout the basin along seismic reflections that serve as seismic stratigraphic boundaries, and suggest the lithostratigraphy can be used to infer regional palaeoenvironmental changes. In addition, I show that the integration of lithologic and seismic data led to a revision of the original seismic stratigraphy.

Chapter 3: “An 85-ka record of climate change in lowland Central America” was published in Quaternary Science Reviews and presents results of the sediment lithology, density and magnetic susceptibility. The data are interpreted with respect to climate-related variability in the northern Neotropics of Petén during the last 40 ka. Further, changes in the position of the Atlantic ITCZ and linkages to climate variability in the region (e.g., Cariaco Basin) and elsewhere (e.g., high-latitude North Atlantic) are discussed.

Chapter 4: “Climate drying and associated forest decline in the lowlands of northern Guatemala during the late Holocene” was published in Quaternary Research and presents middle to late Holocene climate conditions in Petén, focusing on the implications for tropical vegetation, in particular on palynologically documented forest decline during the late Holocene. Results presented in this chapter provide evidence that late Holocene tropical forest decline in this area was not exclusively a consequence of anthropogenic deforestation by ancient Maya, as previously suggested, but was partly attributable to a circum-Caribbean climate drying trend.

Chapter 5: “Recovery of the forest ecosystem in the tropical lowlands of northern Guatemala after disintegration of Classic Maya polities” is submitted to Geology. This chapter focuses on the recovery of the tropical environment that followed abandonment of agricultural systems associated with disintegration of Classic Maya polities ca. AD 800-1000. Our results indicate that in the absence of large human populations and extensive farming activities, Petén forests recovered within a span of 80 to 260 years.
Chapter 6: “A comparison between two clay units in the sediment record of Lake Petén Itzá: The Holocene Maya-Clay versus the Late Pleistocene LGM Clay”, compares the clay unit deposited during the Last Glacial Maximum (LGM) between ∼23 and 18 ka, with the late Holocene “Maya Clay”, which has been interpreted to be exclusively an artefact of ancient Maya activities. We provide evidence that the “LGM Clay” represents a natural analogue of the “Maya Clay”. This observation questions the claim that the “Maya Clay” is exclusively of anthropogenic origin. Rather, the “Maya Clay” may be related, in part, to natural climate variability.

Chapter 7 summarizes the most important findings of this thesis and provides future prospects.

Scientific contributions

The work presented in this thesis was supported by scientific contributions of various people as summarized below.

Chapter 1: Written by Andreas D. Mueller (A.D.M.). Side Scan Sonar (SSS) data were collected by A.D.M., Flavio S. Anselmetti (F.S.A.), Daniel Ariztegui (D.A.), Mark Brenner (M.B.) and David A. Hodell (D.A.H.). The SSS data were processed and interpreted by A.D.M. and F.S.A.

Chapter 2: This chapter represents a paper first-authored by A.D.M. who described the sedimentology and summarized the general stratigraphy. Seismic data were processed and interpreted by A.D.M. and F.S.A. Mineralogical analysis was achieved by A.D.M. supervised by Michael L. Plötz (M.L.P.). A.D.M. measured the Inorganic carbon (IC) and Total carbon (TC) content. A.D.M. performed the SEM analyses. F.S.A., D.A., M.B., J.C., Jaime Escobar (J.E.), Adrian Gilli (A.G.), Dustin A. Grzesik (D.A.G.), D.A.H. and A.D.M. provided crucial fieldwork. Cores were logged at the US National Lacustrine Core Repository (LacCore), University of Minnesota, using a GEOTEK multi-sensor core logger. Ash layers have been dated by Steffen Kutterolf (S.K.). Radiocarbon analyses were performed at the Department of Energy on the University of California by Thomas P. Guilderson (T.P.G.).

Chapter 3: This chapter represents a paper first-authored by D.A.H. A.D.M. synthesized the general stratigraphy and sedimentology, defined the lithological units, and produced Fig. 3.5. Seismic data were processed and interpreted by A.D.M. and F.S.A. Crucial fieldwork was provided by F.S.A., D.A., M.B., J.C., J.E., A.G., D.A.G., D.A.H. and A.D.M. Cores were logged at the US National Lacustrine Core Repository (LacCore), University of Minnesota, using a GEOTEK multi-sensor core logger. Mark B. Bush and Alexander Correa-Metrio provided pollen data. Ash layers have been dated by S.K. Radiocarbon analyses were performed at the Department of Energy on the University of California by T.P.G.

Chapter 4: This chapter represents a paper first-authored by F.S.A. who described the general stratigraphy and sedimentology, defined the lithological units, and produced Fig. 4.5. Seismic data were processed and interpreted by A.D.M. and F.S.A. Crucial fieldwork was provided by F.S.A., D.A., M.B., J.C., J.E., A.G., D.A.G., D.A.H. and A.D.M. Cores were logged at the US National Lacustrine Core Repository (LacCore), University of Minnesota, using a GEOTEK multi-sensor core logger. Mark B. Bush and Alexander Correa-Metrio provided pollen data. Ash layers have been dated by S.K. Radiocarbon analyses were performed at the Department of Energy on the University of California by T.P.G.

Chapter 5: This chapter represents a paper first-authored by D.A.H. A.D.M. synthesized the general stratigraphy and sedimentology, defined the lithological units, and produced Fig. 5.5. Seismic data were processed and interpreted by A.D.M. and F.S.A. Crucial fieldwork was provided by F.S.A., D.A., M.B., J.C., J.E., A.G., D.A.G., D.A.H. and A.D.M. Cores were logged at the US National Lacustrine Core Repository (LacCore), University of Minnesota, using a GEOTEK multi-sensor core logger. Mark B. Bush and Alexander Correa-Metrio provided pollen data. Ash layers have been dated by S.K. Radiocarbon analyses were performed at the Department of Energy on the University of California by T.P.G.
Chapter 4: This chapter represents a paper first-authored by A.D.M. Lithologic profiles were established by A.D.M. and F.S.A. Pollen data were provided by G.A.I. and interpreted by A.D.M. and G.A.I. Stable isotopic analyses were measured by A.D.M. supervised by D.A.H. and J.C. at the University of Florida. Chemical composition data (IC, TC) and chemical elemental data (X-ray fluorescence) were measured by M.B.H. at the University of Bremen and by A.D.M. and D.A. at the University of Geneva. A.D.M. identified and counted the gastropod content in the superficial samples. D.A.G. measured the inorganic carbon (IC) and total carbon (TC) content. $\delta^{13}$C TOC analyses were performed by Kathryn A. Venz at the University of Florida. Radiocarbon analyses were performed at ETH Zurich by Irka Hajdas (I.H.) and at the Department of Energy on the University of California by T.P.G. Crucial fieldwork to collect Kullenberg cores was provided by M.B., M.B.H. and D.A.H.

Chapter 5: This chapter represents a paper, first-authored by A.D.M. who measured the inorganic carbon (IC), total carbon (TC) and Multi-Sensor Core Logger (MSCL) data. Pollen data were provided by G.A.I. and interpreted by A.D.M. and G.A.I. Doug J. Kennett provided assistance with palaeodemographic data. X-ray fluorescence core scanner data were provided by Yvonne Hamann and Gerald H. Haug at ETH Zurich. Radiocarbon analyses were performed by I.H. at ETH Zurich. F.S.A., D.A., M.B., D.A.H. and A.D.M. provided crucial fieldwork to collect short gravity cores.

Chapter 6: This chapter represents a paper in preparation first-authored by A.D.M. Seismic data were processed and interpreted by A.D.M. and F.S.A. Mineralogical analysis was performed by A.D.M. supervised by M.L.P. A.D.M. measured the Inorganic carbon (IC) and Total carbon (TC) content, and performed the SEM analyses. F.S.A., D.A., M.B., J.C., J.E., A.G., D.A.G., D.A.H. and A.D.M. provided crucial field work. Cores were logged at the US National Lacustrine Core Repository (LacCore), University of Minnesota, using a GEOTEK multi-sensor core logger. Ash layers have been dated by S.K. Radiocarbon analyses were performed at the Department of Energy on the University of California by T.P.G.
Chapter 2

Late Quaternary palaeoenvironment of northern Guatemala: Evidence from deep drill cores and seismic stratigraphy of Lake Petén Itzá

ABSTRACT

Long sediment cores were collected in spring 2006 from several water depths in Lake Petén Itzá, northern Guatemala, in water depths ranging from 30 to 150 metres, as part of an International Continental Scientific Drilling Program (ICDP) project. The sediment records from deep water consist mainly of alternating clay, gypsum and carbonate units, and in at least two drill sites, extend back >200 kyr. Most of the lithostratigraphic units are traceable throughout the basin along seismic reflections that serve as seismic stratigraphic boundaries and suggest that the lithostratigraphy can be used to infer regional palaeoenvironmental changes. A revised seismic stratigraphy was established on the basis of integrated lithological and seismic reflection data from the basin. From ca 200 to ca 85 ka, sediments are dominated by carbonate-clay silt, often interbedded with sandy turbidites, indicating a sediment regime dominated by detrital sedimentation in a relatively humid climate. At ca 85 ka, an exposure horizon consisting of gravels, coarse sand and terrestrial gastropods, marks a lake lowstand or partial basin desiccation, indicating dry climate conditions. From ca 85 to ca 48 ka, transgressive carbonate-clay sediments, overlain by deep-water clays, suggest a lake-level rise and subsequent stabilisation at high stage. From ca 48 ka to present, the lithology is characterized by alternating clay and gypsum units. Gypsum deposition correlates with Heinrich Events (i.e. dry climate), whereas clay units coincide with more humid interstadials.

2.1 Introduction

Palaeoenvironmental studies in the lowlands of Petén, northern Guatemala (Fig. 2.1), began in the 1960s and focused on ancient Maya impact on regional watersheds as well as Holocene climate change and its implications for Maya civilization (Cowgill and Hutchinson, 1966; Deevey et al., 1979; Vaughan et al., 1985; Rice et al., 1985; Binford et al., 1987; Leyden, 1987; Brenner et al., 1990; Islebe et al., 1996; Beach et al., 2006; Anselmetti et al., 2007). By the late 1970s, E.S. Deevey and colleagues had begun searching for Pleistocene-age deposits in the Maya heartland to gain insights into Ice-age climate shifts in the lowland Neotropics (Deevey et al., 1983; Leyden, 1984; Leyden et al., 1993, 1994). Attention was focused on relatively deep lakes, as most shallow basins in the region were shown to have first filled with water in the early Holocene and were evidently dry during glacial times. Recent palaeoenvironmental studies in the region have focused on obtaining even longer sediment records to investigate tropical climate and environmental changes on the Yucatan Peninsula during both glacial and interglacial times, and to explore terrestrial-marine linkages using palaeoclimate records from sites around the Caribbean (e.g. Cariaco Basin, north of Venezuela; Haug et al., 2001). Retrieval of long sediment cores from the Neotropical lowlands became a major objective for palaeoenvironmental and palaeoclimatological studies. Until the present study, the longest lacustrine sediment record taken in the region was a core from relatively deep ($z_{\text{max}} = 32$ m), small (area $= 2.2$ km$^2$) Lake Quexil. Collected in 1980, the core penetrated ca 20 m below the sediment-water interface. Unfortunately, the Pleistocene-age section of the sequence was poorly dated. Pleistocene deposits contained few terrestrial macrofossils, and the estimated basal age of the core (36 ka), was based on extrapolation of a radiocarbon date on an aquatic snail shell (Leyden et al., 1993). For more than two decades, the Quexil core was the longest continental palaeoclimate record from the area.

Seismic reflection surveys of Lake Petén Itzá completed in 1999 and 2002, revealed the potential for obtaining a very old palaeoclimate archive from the lowlands of Guatemala (Anselmetti et al., 2006). Lake Petén Itzá is the largest (ca $\sim 100$ km$^2$) and deepest lake ($z_{\text{max}} \sim 160$ m) in lowland Central America (Hillesheim et al., 2005). Because of its great depth, it held water even during the driest periods of the late Pleistocene. Seismic reflection data indicated over 100 m of sediment in some depocentres (Anselmetti et al., 2006). The Petén Itzá sediment record contains a unique environmental and climate archive that extends back far beyond the record from nearby Lake Quexil. Because of its excellent palaeoenvironmental potential, Lake Petén Itzá’s sediment record was drilled in spring 2006 as part of an International Continental Scientific Drilling Program (ICDP) project, using the Global Lakes Drilling (GLAD 800) platform.

More than 1300 m of lake sediment was recovered from seven locations in Lake Petén.
Itzá (Hodell et al., 2006), hereafter referred to as sites PI-1, PI-2, PI-3, PI-4, PI-6, PI-7, PI-9 (Fig. 2.1, Table 2.1). Results presented in this study document the full sediment record of all drill sites, which extends back >200 kyr. Sediments covering the period from 200 to 85 ka were recovered at only two sites, PI-1 and PI-7. This older succession has less age control and is probably less continuous than the younger section, which was drilled at all sites, allowing detailed palaeoenvironmental interpretations spanning the last 85 kyr (Hodell et al., 2008). Interbedded clay and gypsum deposits at site PI-6 were interpreted to represent alternating humid and dry climate, deposited during high and low lake level stands, respectively (Hodell et al., 2008). Details of the climate reconstruction are presented in (Hodell et al., 2008), but are summarized briefly here. The palaeoclimate history was inferred mainly for the last 40 kyr, the period for which the chronology is well constrained by radiocarbon dates on terrestrial macrofossils. Clay and gypsum alternation from 40 to 23 ka (late MIS 3) appears to correlate with stadial-interstadial

**Figure 2.1:** A) Bathymetric map of Lake Petén Itzá showing the locations of all ICDP sites drilled in 2006, and of all seismic track lines collected in the 2002 airgun seismic reflection survey. Inset on the right displays a map of the Caribbean region showing the Maya Lowlands in northern Guatemala and the location of Lake Petén Itzá. B) Satellite picture of Lake Petén Itzá. Note the shallow water area along the south shore characterized by turquoise colour indicating in situ carbonate production (Mueller et al., 2009).
stages (Dansgaard-Oeschger events; Dansgaard et al., 1993) from Greenland ice cores and North Atlantic marine sediment cores, as well as with precipitation proxies from the Cariaco Basin (Peterson et al., 2000; Haug et al., 2001). Gypsum units are associated with cold stadials, especially those containing Heinrich Events, whereas clay units are related to warm interstadials. An unexpected finding was that sediments deposited in Petén Itzá during the Last Glacial Maximum (LGM), from ca 23 to 18 ka, consist of a thick clay unit. This suggests substantial detrital input and a high lake level, hence, more humid climate conditions during the LGM, compared to the preceding and succeeding periods in Petén (Hodell et al., 2008; Bush et al., 2009). This finding contradicts previous palaeoclimate interpretations that proposed a dry LGM in the lowland Neotropics of Central America. The driest period of the last glaciation was not the LGM, but rather the deglacial period (ca 18 to 11 ka), when lake-level fluctuated between low and intermediate stands, as indicated by alternating gypsum and clay sediments.

Following the preliminary palaeoclimate interpretations of Hodell et al. (2008), a basin-wide stratigraphy of the Lake Petén Itzá sediment record is constructed by integrating data from all drill sites. Furthermore, previously collected seismic reflection data of Anselmetti et al. (2006) are combined with new lithological data from the drill cores to test and improve the proposed depositional model for Lake Petén Itzá. The combination of seismic, sedimentological, geophysical and chronological data (49 AMS-\(^{14}\)C ages and a suite of identified tephra layers) facilitates understanding of the sedimentation processes that generated the lithological succession in Lake Petén Itzá, and provides information about how the lake sediments were affected by climate and environmental changes.

### Table 2.1: Location of drill sites, penetration depth (meters below lake floor), and percent recovery for cores collected in Lake Petén Itzá.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Water depth (m)</th>
<th>Penetration Depth (mmd)</th>
<th>Average Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOLE</td>
<td></td>
<td></td>
<td></td>
<td>HOLE A</td>
<td>HOLE B</td>
</tr>
<tr>
<td>1</td>
<td>16° 59.870’N</td>
<td>89° 47.738’W</td>
<td>65</td>
<td>94.5</td>
<td>90.3</td>
</tr>
<tr>
<td>2</td>
<td>16° 59.871’N</td>
<td>89° 44.685’W</td>
<td>54</td>
<td>66.5</td>
<td>41.2</td>
</tr>
<tr>
<td>3</td>
<td>17° 0.201’N</td>
<td>89° 49.224’W</td>
<td>100</td>
<td>96.9</td>
<td>95.3</td>
</tr>
<tr>
<td>4</td>
<td>17° 0.314’N</td>
<td>89° 50.722’W</td>
<td>150</td>
<td>67.4</td>
<td>46.1</td>
</tr>
<tr>
<td>5</td>
<td>17° 0.016’N</td>
<td>89° 47.080’W</td>
<td>71</td>
<td>75.9</td>
<td>66.4</td>
</tr>
<tr>
<td>6</td>
<td>16° 59.723’N</td>
<td>89° 47.644’W</td>
<td>46</td>
<td>133.2</td>
<td>122.8</td>
</tr>
<tr>
<td>7</td>
<td>16° 59.436’N</td>
<td>89° 47.646’W</td>
<td>30</td>
<td>16.4</td>
<td></td>
</tr>
</tbody>
</table>

Following the preliminary palaeoclimate interpretations of Hodell et al. (2008), a basin-wide stratigraphy of the Lake Petén Itzá sediment record is constructed by integrating data from all drill sites. Furthermore, previously collected seismic reflection data of Anselmetti et al. (2006) are combined with new lithological data from the drill cores to test and improve the proposed depositional model for Lake Petén Itzá. The combination of seismic, sedimentological, geophysical and chronological data (49 AMS-\(^{14}\)C ages and a suite of identified tephra layers) facilitates understanding of the sedimentation processes that generated the lithological succession in Lake Petén Itzá, and provides information about how the lake sediments were affected by climate and environmental changes.
2.2 Study site

The Petén Lake District lies in the Neotropical lowlands of Petén, northern Guatemala, and consists of a series of lake basins oriented E - W along en-echelon faults (Vincent, 1962). The largest and deepest lake is Petén Itzá (~16°55'N, 89°50'W), with its surface area of ca 100 km² and a maximum water depth >160 m (Fig. 2.1). Lake Petén Itzá occupies a closed basin, and its volume changes in response to shifts in the balance between evaporation and precipitation. Lake Petén Itzá has a large, deep northern basin and a small, shallow southern basin. The latter has a mean water depth of only ca 5 m. The north shore is characterized by steep-sloping lower Tertiary limestone. The southern shore is gently sloping and, in places, rimmed by poorly drained seasonal swamps (bajos). Lake Petén Itzá’s water is dilute (11.22 meq l⁻¹, 408 meq l⁻¹) and is dominated by calcium and bicarbonate, with magnesium and sulphate following closely in concentration (Hillesheim et al., 2005). Lake water pH is high (ca 8.0) and is saturated with respect to calcium carbonate. The oxygen isotopic composition (δ¹⁸O) of lake water averages +2.9‰, which is enriched by ca 7% relative to regional rainfall and groundwater (ca -4‰) (Hillesheim et al., 2005). This reflects the importance of evaporation in the lake’s water budget. Thermal stratification persists through most of the year, with hypolimnetic temperatures ca 25.4°C, close to the mean annual air temperature. Surface sediments in Lake Petén Itzá’s littoral zone are rich in gastropods (mainly Tryonia sp. and Cochliopina sp.) and poor in ostracods, whereas sediments in deep water contain few gastropods, but are rich in ostracods (mainly Candona sp. and C. Horvayi). Surficial sediments down to a water depth of ca 23 m consist of shell-rich carbonate (Mueller et al., 2009). Carbonate content decreases in greater water depths where surface sediments contain higher amounts of organic matter and non-carbonate detrital constituents.

2.3 Methods

Two seismic reflection campaigns of the Lake Petén Itzá sediment were undertaken. In 1999 a shallow, high-resolution survey (3.5 kHz pinger) was carried out and in 2002 a deeper, lower-resolution survey (1 in³ airgun) was completed (Anselmetti et al., 2006). Applying a seismic sequence stratigraphic approach (Vail et al., 1977) to these data, two shallow-water sites (PI-9, PI-7), three intermediate-water-depth sites (PI-1, PI-2, and PI-6), and two deep-water sites (PI-3, PI-4) were chosen for drilling (Fig. 2.1, Table 2.1). Seven sites were drilled in early 2006. Multiple holes were drilled at most sites (Table 2.1), and cores were logged in the field for density, p-wave velocity and magnetic susceptibility using a GEOTEK multi-sensor core logger. To verify complete stratigraphic recovery, the software program “Splicer”, which allows alignment of lithological features among holes using core-logging data (i.e. density, magnetic susceptibility), was used.
Depths in the cores are reported in metres below lake floor (mblf), or where established, in metres composite depth (mcd), which represents a complete composite section using cores from multiple holes at the same site.

The chronology for the last 40 kyr of the Lake Petén Itzá sediment record was developed using 21 AMS-14C dates from site PI-6, 10 AMS-14C dates from site PI-3 and 18 AMS-14C dates from site PI-2, all measured on samples of terrestrial organic matter (Table 2.2). The terrestrial material was primarily wood fragments, which are unaffected by hard water dating error (Deevey et al., 1954; Stuiver and Polach, 1977). Dates were converted to calendar years before 1950 (cal yr BP) using the online radiocarbon calibration program of Fairbanks et al. (2005) (http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm). Ages are reported in calibrated thousands of years (ka) before 1950. Sediments older than 40 ka were dated by identification of tephra layers within the Petén Itzá cores that were geochemically fingerprinted (microprobe analysis) and matched with the established onland tephrochronology for Central America after Kutterolf et al. (2007, 2008a) (Table 2.3). The presence of lithological markers, stratigraphic boundaries and tephra layers, as well as the very similar magnetic susceptibility and bulk density records throughout the basin, allowed layer-to-layer correlation between most sites. This correlation enabled extrapolation of dates from site to site, yielding a detailed age-depth model for the entire sediment record of Lake Petén Itzá (Figs 2.2 and 2.3).

Lithological units were defined by sediment types, which were established following the classification scheme of Schnurrenberger et al. (2003). Sediment samples were taken at selected depths for analysis. Smear slides were prepared and studied with scanning electron microscopy (SEM). Grain-size distribution was established using laser diffraction techniques. Mineralogical composition was determined by applying the Rietveld technique to measured X-ray diffraction (XRD) patterns (Young, 2002). The Rietveld-technique is a full pattern-fitting method that consists in the calculation of the X-ray diffractogram and its iterative adjustment to the measured XRD-pattern by refinement of phase specific parameters (Ufer et al., 2008).

### 2.4 Results

#### 2.4.1 Core recovery and sediment chronology

A total of 1327 m of lake sediment was recovered from seven sites, with an average core recovery of 90.6 % (Table 2.1). Samples of terrestrial organic matter in Petén Itzá sediments, dated by radiocarbon, yielded reliable chronologies for deposits younger than 40 ka. Most ages are in depth order (Hodell et al., 2008; Table 2.1, Fig. 2.2). Selected tephra layers in Petén Itzá sediments >40 ka were compared to the existing Central American tephra stratigraphy (Kutterolf, et al., 2008a; Table 2.3). In PI-6, the
CGT Tephra (ca 53 ka) is at 51.3 mcd, the Guasal1 Tephra (ca 55 ka) is at 52.7 mcd, and the ACT Tephra (ca 72 ka) is at 55.3 mcd (Table 2.3). The depth of the ACT tephra suggests a considerable change in sedimentation rate, and was not included in the age-depth model. The age of the base of the PI-6 core is constrained by an ash layer at 70.9 mcd from the ca 84 ka Los Chocoyos (LCY Tephra) eruption of the Atitlán Caldera in the Guatemalan highlands (Rose et al., 1999; Kutterolf et al., 2007). This LCY ash layer occurs at 51.0 mcd in site PI-1 (Fig. 2.2), implying that sediments below this marker horizon in PI-1 are much older than 84 ka. Thus, the PI-1 core contains a much longer record than does PI-6. Indeed, the WFT ash layer, dated at ca 158 ka, was identified at 72.0 mcd in PI-1 (Table 2.3; Fig. 2.2; Rose et al., 1999; Kutterolf et al., 2008a). The same ash layer was also identified in shallow-water core PI-7 at 74.3 mcd (Fig. 2.3). Cores from PI-1 and PI-7 have much older records than do any of the other sites. At 84.2 mcd in site PI-1, ash from the ca 191 ka LFT eruption of Amatitlan was identified (Table 2.3; Fig. 2.2; Rose et al., 1999; Kutterolf et al., 2008a) suggesting a basal age of ca 200 ka. Shallow-water site PI-7, which penetrated to 133.2 m, contains no identifiable ash layer in the 60 m below the WFT tephra. The sedimentation rate, down to an age of ca 53 ka (CGT tephra), averages ca 1.0 mm/a in site PI-6, ca 0.7 mm/a in site PI-1 and ca 1.2 mm/a in site PI-2 (Fig. 2.2). Below the CGT tephra in cores from PI-6 and PI-1, sedimentation rates were somewhat lower, ca 0.6 mm/a and ca 0.4 mm/a, respectively (Fig. 2.2). In site PI-2, the sedimentation rate remained relatively constant throughout, ca 1.2 mm/a.

**Figure 2.2:** Calibrated ages (cal yr BP) versus depth (mcd) of sites PI-6 (A), PI-1 (B), and PI-2 (C) showing linear approximation for sedimentation rates (dashed lines). Ages younger than 40 ka are derived by characteristic tephra layers from volcanic eruptions of known age (Table 2.3). Dating error on all samples is smaller than the plot symbols, except where indicated by an error bar.
### Table 2.2: Radiocarbon dates on terrestrial organic material (woody debris) from sites PI-2, PI-3, PI-6.
All radiocarbon dates were converted to calendar years with the on-line radiocarbon calibration program (Fairbanks et al., 2005): http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm. Reporting of ages follows the convention of Stuiver and Polach (1977).

<table>
<thead>
<tr>
<th>Accession #</th>
<th>Sample</th>
<th>Depth (m)</th>
<th>Age 14C ± (yr BP)</th>
<th>Age cal ± (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAMS Site Hole - Core Type - Section Interval</td>
<td></td>
<td></td>
<td>(1σ)</td>
<td>(1σ)</td>
</tr>
<tr>
<td>139342</td>
<td>2B-H2-2 39 cm</td>
<td>10.54</td>
<td>3705</td>
<td>30</td>
</tr>
<tr>
<td>139416</td>
<td>2B-H2-2 39 cm rep</td>
<td>10.54</td>
<td>3775</td>
<td>35</td>
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<td>2B-H1-1 102 cm</td>
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</tr>
</tbody>
</table>

22 Late Quaternary palaeoenvironment of northern Guatemala
22 Late Quaternary palaeoenvironment of northern Guatemala
2.4.2 Sediment types

Seven main sediment types ([A] clastic lacustrine, [B] precipitated, [C] microbial, [D] pyroclastic, [E] clastic terrestrial, [F] karstic/soil, [G] bedrock) were identified, together with several additional sub-types in the case of [A], and [B]. Each sediment type, and its sub-types, was described (Table 2.4) and photographed (Fig. 2.4). Table 2.4 contains the palaeoenvironmental interpretations for the sediment types.

2.4.3 Lithostratigraphic units

The different sediment types (Table 2.4) were used to divide the sediment record of Lake Petén Itzá into 11 lithostratigraphic units, labelled I to IX, BGU (Basal Gravel Unit), MU (Mottled Unit), and into sub-units labelled with lower case letters, e.g. Iva (Fig. 2.3), which overlie the basement of Lake Petén Itzá. Using core-logging data (density and magnetic susceptibility) and characteristic lithological layers in split cores along seismic reflection profiles, most of the lithostratigraphic units can be correlated from site to site throughout the entire basin (Figs 2.3, 2.5, 2.6 and 2.7). In general, the recovered sediment cores provide an undisturbed succession of the depositional history. In some cases, however, especially at deep-water sites, there are structures in the sediment fabric that indicate down-slope movement and re-deposition of sediments into basin areas (Fig. 2.8). Such movements often occur along tephra layers with low shear strength and gliding surfaces (Fig. 2.8). This phenomenon was described previously from the Central American Forearc, where large submarine slides of the last 100 kyr were often associated with tephra layers (Harders et al., 2007; Kutterolf et al., 2008b). These mass movements did not prevent establishment of a stratigraphic framework as they were easily identified in seismic and core data. Here, results are presented in order from youngest to oldest deposits, i.e. from top to bottom.
Figure 2.3: Compiled data set of drill sites of Lake Petén Itzá (for site locations see Fig. 2.1): Each site is documented (from left to right) by ages (in cal ka BP; for errors, see Table 2.2), photographic images, the stratigraphic column, lithological units (Roman numbers indicate lithostratigraphic units; MU = Mottled Unit, BGU = Basal Gravel Unit, BSE = basement), the records of magnetic susceptibility (SI x 10^{-6}) and/or of the bulk density (g/cm^3). Core-to-core correlations along unit boundaries are indicated by black lines, correlations of characteristic tephra layers are delineated by red lines, and dashed lines are assumed correlations. The depth scale for all sites is metres composite depth (mcd) except for site PI-7 where it is metres below lake floor (mblf) as indicated.
### Table 2.4: Lake Petén Itzá sediment types.

<table>
<thead>
<tr>
<th>Sediment type</th>
<th>Dominant mineralogy / composition</th>
<th>Sedimentary structures</th>
<th>Interpretation / depositional environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Clastic sediment types</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1. Gray mud</td>
<td>Montmorillonite, Calcite</td>
<td>Very homogenous, extremely fine-grained clay, sub-massic laminations; Accumulations of removed gastropods; Anti-bioclastic bioclastic micrite;</td>
<td>Dental input of eroded soil and wood detritus in the watered littoral zone.</td>
</tr>
<tr>
<td>A2. White sand</td>
<td>Calcite</td>
<td>Massive to weakly laminated silts;</td>
<td>Dental input from eroded soil and limnetic environment in the watered littoral zone.</td>
</tr>
<tr>
<td>A3. Brown-colored silt</td>
<td>Montmorillonite, Calcite</td>
<td>Gradally increasing opal content from 0.3 mm thick to 1 cm thick; characterized by lower foraminiferal content;</td>
<td>Dental input from eroded soil and limnetic environment in the watered littoral zone.</td>
</tr>
<tr>
<td>A4. Dark green clay mud/silt</td>
<td>Montmorillonite, organic matter</td>
<td>Homogeneous clay with sub-mm laminations; Rich in planktonic diatoms (Acanthocystis sp.);</td>
<td>Dental input from eroded soil and limnetic environment in the watered littoral zone.</td>
</tr>
<tr>
<td>A5. Clay-colored silt</td>
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<td>Massively to weakly laminated silts;</td>
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</tr>
<tr>
<td>A6. Bright, beige mud</td>
<td>Calcite</td>
<td>Fossilized (roosting) mud with some carbonized calcite;</td>
<td>Dental input from eroded soil and limnetic environment in the watered littoral zone.</td>
</tr>
<tr>
<td>A7. Dark brown-greenish mud</td>
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</tr>
<tr>
<td>A8. Beige-greenish silt-sand</td>
<td>Calcite</td>
<td>Poorly sorted carbonate sand;</td>
<td>Dental input from eroded soil and limnetic environment in the watered littoral zone.</td>
</tr>
</tbody>
</table>

| B. Precipitated sediment types|                                   |                        |                                          |
| B1. Precipitated sediment type| Gypsum                           | Co-deep, massive to weakly laminated (co-scale) sequences composed of ooskeleton, large (up to 3 mm) gypsum crystals;                    | Dental input from eroded soil and limnetic environment in the watered littoral zone.|
| B2. Yellowish gypsum nodules  | Gypsum                           | Unidentifiable laminites of gypsum laminae (up to 1 cm long) with concentrations of gypsum nodules;                                 | Dental input from eroded soil and limnetic environment in the watered littoral zone.|

| C. Microfossil sediment type  | Sulfur                            | Cross-cutting bedding of clay and gypsum sediments. Typically occurring as transitions from gypsum to clay units. | Dental input from eroded soil and limnetic environment in the watered littoral zone.|

| D. Phytoplankton sediment type| Montmorillonite, Pyrite           | Stratification, black, yellowish, reddish, fine-grained sediments. Gley-like formation! Formed under wet, anaerobic conditions (morro-flocc) and under the presence of anaerobic micro-organisms. | Dental input from eroded soil and limnetic environment in the watered littoral zone.|
| E. Esoteric sediment type     | Limestone, organic matter         | Sediments deposited during a very low water level cap. Deposited in a beach like environment. | Dental input from eroded soil and limnetic environment in the watered littoral zone.|

| F. Modified sediment type     | Montmorillonite, Calcite, Pyrite  | Stratification, black, yellowish, reddish, fine-grained sediments. Gley-like formation! Formed under wet, anaerobic conditions (morro-flocc) and under the presence of anaerobic micro-organisms. | Dental input from eroded soil and limnetic environment in the watered littoral zone.|

### Table 2.5: Lake Petén Itzá sediment types.

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<tr>
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| B. Precipitated sediment types|                                   |                        |                                          |
| B1. Precipitated sediment type| Gypsum                           | Co-deep, massive to weakly laminated (co-scale) sequences composed of ooskeleton, large (up to 3 mm) gypsum crystals;                    | Dental input from eroded soil and limnetic environment in the watered littoral zone.|
| B2. Yellowish gypsum nodules  | Gypsum                           | Unidentifiable laminites of gypsum laminae (up to 1 cm long) with concentrations of gypsum nodules;                                 | Dental input from eroded soil and limnetic environment in the watered littoral zone.|

| C. Microfossil sediment type  | Sulfur                            | Cross-cutting bedding of clay and gypsum sediments. Typically occurring as transitions from gypsum to clay units. | Dental input from eroded soil and limnetic environment in the watered littoral zone.|

| D. Phytoplankton sediment type| Montmorillonite, Pyrite           | Stratification, black, yellowish, reddish, fine-grained sediments. Gley-like formation! Formed under wet, anaerobic conditions (morro-flocc) and under the presence of anaerobic micro-organisms. | Dental input from eroded soil and limnetic environment in the watered littoral zone.|
| E. Esoteric sediment type     | Limestone, organic matter         | Sediments deposited during a very low water level cap. Deposited in a beach like environment. | Dental input from eroded soil and limnetic environment in the watered littoral zone.|

| F. Modified sediment type     | Montmorillonite, Calcite, Pyrite  | Stratification, black, yellowish, reddish, fine-grained sediments. Gley-like formation! Formed under wet, anaerobic conditions (morro-flocc) and under the presence of anaerobic micro-organisms. | Dental input from eroded soil and limnetic environment in the watered littoral zone.|

Results 25
Figure 2.4: Core photographs showing different sediment types (indicated by capital letters) including a SEM-micrograph of an idiomorphic gypsum crystal (upper right panel). For explanations of the sediment types, see Table 2.4.
Figure 2.5: Seismic-to-core correlation of sites PI-4, PI-3, PI-6, and PI-2 along an E-W basinparallel reflection seismic profile composed of two seismic lines (Air8 and Air9). The seismic sequences are labelled with coloured capital letters: T(urquoise), G(reen), P(ink), R(ed) and B(lue). Sub-sequences are indicated by numerals 1 through 5. Small lake inset map displays the location of seismic tracks Air8 and Air9, and the location of imaged sites. For colour-coding of lithological column see Fig. 2.3.
Figure 2.6: Seismic-to-core correlation of site PI-6 along the cross N-S reflection seismic profile Air11a. The seismic sequences are labelled with coloured capital letters (Turquoise), (Green), (Pink), (Red) and (Blue). Sub-sequences are indicated by numerals 1 through 5. In black capital letters with *: earlier interpretation of Anselmetti et al. (2006). Small lake inset map displays the location of seismic track Air 11a, and the location of site PI-6. Note the occurrence of three stacked palaeoshorelines, each of which corresponds to the top of a gypsum layer in lithological Unit II of site PI-6 deposited during the Late Glacial. For symbol legend see Figure 2.3.
Figure 2.7: Seismic-to-core correlation of sites PI-1 and PI-7 along the cross N-S reflection seismic profile Air10b. Seismic sequences are labelled with coloured capital letters: T(urquoise), G(reen), P(ink), R(ed) and B(lue). Sub-sequences are indicated by numerals 1 through 5. Small lake inset map displays the location of seismic track Air 10b, and the location of sites PI-1 and PI-7. For symbol legend see Figure 2.3.
Unit I (0-10 ka)

Unit I is a thick sediment succession deposited during the last 10 kyr. It consists primarily of grey, sub-millimetre, laminated montmorillonite-carbonate mud [A1], with reworked fragments of gastropods. Minerals such as dolomite, pyrite, quartz and feldspars are scarce or poorly developed and give weak and ambiguous XRD signatures. Unit I sediments include dark and graded calcite-montmorillonite silt-turbidites [A3] (Fig. 2.9) and thin, white, graded carbonates and turbidites [A2]. Magnetic susceptibility values are moderately high, reaching values between 20 and $30 \times 10^{-6}$ SI. Much of this thick detrital clay unit was previously named “Maya Clay,” and is labelled here as sub-unit “I$_{m}$” (site PI-6 in Figs 2.3 and 2.10). This “Maya Clay” has been identified in many Petén lakes, and is attributed to accelerated soil erosion resulting from ancient Maya land clearance between ca. 1.0 and ca. 3.0 ka (Deevey et al., 1979; Binford et al., 1987; Brenner, 1994; Rosenmeier et al., 2002; Anselmetti et al., 2007).

Unit II (10-18 ka)

Sediments of Unit II were deposited during the last deglaciation between 10 and 18 ka. Unit II is sub-divided into three gypsum-rich sub-units [B] IIa (11.5 to 12.8 ka). Unit II is a thick sediment succession deposited during the last 10 kyr. It consists primarily of grey, sub-millimetre, laminated montmorillonite-carbonate mud [A1], with reworked fragments of gastropods. Minerals such as dolomite, pyrite, quartz and feldspars are scarce or poorly developed and give weak and ambiguous XRD signatures. Unit II sediments include dark and graded calcite-montmorillonite silt-turbidites [A3] (Fig. 2.9) and thin, white, graded carbonates and turbidites [A2]. Magnetic susceptibility values are moderately high, reaching values between 20 and $30 \times 10^{-6}$ SI. Much of this thick detrital clay unit was previously named “Maya Clay,” and is labelled here as sub-unit “I$_{m}$” (site PI-6 in Figs 2.3 and 2.10). This “Maya Clay” has been identified in many Petén lakes, and is attributed to accelerated soil erosion resulting from ancient Maya land clearance between ca. 1.0 and ca. 3.0 ka (Deevey et al., 1979; Binford et al., 1987; Brenner, 1994; Rosenmeier et al., 2002; Anselmetti et al., 2007).
Figure 2.9: Physical characteristics of sediment type A3. Top, from left to right: Schematic sketch of a fining upward sequence, colour gradient from dark base to bright top on core photograph, fining upward of particle sizes in grain size analysis, and upcore decreasing density record on X-ray radiograph (light colours = high density); Bottom: XRD diffractogram of sediment type A3.

ka), IIc (13.5 to 14 ka), IIe (15 to 18 ka), and two clay-rich carbonate sub-units (A5) IIb (12.8 to 13.5 ka) and IId (14 to 15 ka) (Fig. 2.3). Gypsum-rich sub-units consist of brown to yellowish massive accumulations of coarse, authigenic gypsum crystals [B1], and/or undulating finely laminated, yellowish nodular gypsum layers [B2].

Clay-rich carbonate sub-units consist of weakly laminated calcite-montmorillonite silt [A5]. Gypsum sequences are generally characterized by low magnetic susceptibility and high density, whereas clay-carbonate sequences are represented by higher magnetic susceptibility and lower density (Fig. 2.3).

Unit III (18 - 23 ka)

Unit III, deposited between 18 and 23 ka, coincides approximately with the LGM (Mix et al., 2001). This unit is characterized by grey, sub-millimetre-scale laminated mud, consisting mainly of montmorillonite and calcite [A1]. Dolomite, pyrite, quartz and feldspar occur as trace minerals. Fragments of reworked gastropods are common in this unit. The finely laminated clay is often interbedded by dark grey, graded silt sequences with irregular and erosive bases [A3]. These graded sequences vary in thickness between 1 and 3 cm. Throughout Unit III, magnetic susceptibility is high (40 to 60 x 10⁻⁶ SI), whereas density is low (<1.5 g/cm³) (Fig. 2.3).
Late Quaternary palaeoenvironment of northern Guatemala

Unit IV (23 - 39 ka)
The sediments of Unit IV accumulated between 23 and 39 ka. Unit IV is sub-divided into four gypsum-rich sub-units: IVa (23 to 25 ka), IVc (30 to 32 ka), IVe (35 to 36 ka), IVg (38 to 39 ka), and three clay-rich carbonate sub-units IVb (25 to 30 ka), IVd (32 to 35 ka) and IVf (36 to 38 ka) (Fig. 2.3). Similar to Unit II, gypsum-rich sub-units consist of coarse, massive brownish-yellowish gypsum sand [B1], and/or undulating, laminated, yellowish nodular gypsum layers [B2]. Clay-rich carbonate units consist of massive, cream-coloured silt [A5]. Gypsum beds are characterized by low magnetic susceptibility and high density, whereas clay has higher magnetic susceptibility and lower density (Fig. 2.3).

Unit V (39 - 49 ka)
Sediments of Unit V (39 to 49 ka) consist of finely laminated, dark greenish clay mud, which is rich in organic matter [A4]. This unit consists of up to 5 cm thick, graded turbidites [A3]. Two sequences of authigenic gypsum crystals [B1, B2] were deposited, peaking at ca 42 and ca 48 ka (Fig. 2.3).

Unit VI (49 - 58 ka)
Sediments of Unit VI, deposited from 49 to 58 ka, are composed of grey, laminated montmorillonite mud [A1], which is partly mottled with dark, diffuse organic-rich spots. This unit is punctuated by graded, dark turbidite sequences of silt [A3]. Sediments of this unit include fragments of reworked gastropods.

Unit VII (58 - 78 ka)
Unit VII consists of sediments that were deposited from ca 58 to ca 78 ka. These sediments are composed of rhythmic alternations between bright-beige sequences of carbonate mud [A6] and darker-brown to greenish, organic-rich sequences of laminated clay-carbonate mud [A7] (2.3). The darker clay bands contain planktonic diatoms (Aulacoseira sp.), whereas the brighter carbonate bands are rich in benthonic diatoms (Mastogloia, Denticula).

Unit VIII (78 - 85 ka)
Sediments of Unit VIII (78 to 85 ka) consist of coarse, beige-greenish, poorly sorted carbonate sand-silt with abundant organic macro-remains and fragments of lacustrine gastropods [A8] (Fig. 2.3). Several distinct white carbonate sand layers, characterized by high density, are intercalated within this silty-sandy unit. The sand is punctuated with
hard, solid pieces of limestone, and it is interbedded by up to 5 mm thick, fining-upward, graded sand turbidites. The petrophysical analysis of this lithological unit revealed a trend of increasing density from \( \text{ca} \ 1.4 \ \text{to} \ 1.8 \ \text{g/cm}^3 \) and magnetic susceptibility from \( \text{ca} \ 50 \to 70 \times 10^{-6} \ \text{SI} \).

**Basal Gravel Unit (BGU)**

Sediments of the BGU at the base of sites PI-3, PI-6 and PI-2 consists of solid, large limestone gravels (up to 4 cm) embedded in a poorly sorted, coarse, beige carbonate sand matrix. The gravels are usually angular, but in some cases are rounded. The sand contains fragments of terrestrial gastropod shells [E]. The petrophysical analysis of this lithological unit revealed high density (\( \text{ca} \ 1.9 \ \text{g/cm}^3 \)) and intermediate to high magnetic susceptibility (\( \text{ca} \ 55 \times 10^{-6} \ \text{SI} \)).

**Mottled Unit MU (85 - ? ka)**

This unit, which only occurs in shallow-water site PI-7, intercalated between overlying Unit VI and underlying Unit IX, consists of a more than 30 m thick, sticky, light-bluish-grey to dark-yellowish-orange, fine-grained mud-silt sequence [F]. The mineralogy of this unit is composed mainly of calcite, montmorillonite and pyrite. The grey sediments of this sequence are often mottled with dark black, diffuse spots. MU is characterized by many cracks, which display a reddish hue, probably associated with sediment oxidation. This section has intermediate magnetic susceptibility, high density, low organic matter (mean \( \text{ca} \ 1\% \)), and high calcium carbonate content (mean \( \text{ca} \ 15\% \)).

**Unit IX (? - 200 ka)**

Unit IX, recovered only at sites PI-1 and PI-7, represents sediments deposited some time before a hiatus that ended \( \text{ca} \ 85 \ \text{ka} \) and at least \( \text{ca} \ 200 \ \text{ka} \). This unit is characterized by alternations of two kinds of packages and is up to 10 m thick: i) dark, brown-greenish, finely laminated (millimetre-scale) carbonate-clay mud [A7], and ii) bright beige, very homogenous carbonate mud [A6]. The darker, clay-rich packages are full of planktonic diatoms (Aulacoseira sp.), whereas the lighter, calcite-rich packages are dominated by benthonic diatoms (Mastogloia, Denticula). Thus, rhythmic alternations between darker and lighter packages suggest fluctuations between higher and lower lake levels, respectively. Sediments of Unit IX are often interbedded with dark, graded turbidites [A3], and they are composed of many millimetre-scale to decimetre-scale deformation structures (Fig. 2.8). Such structures are expressed in the sediment record as i) millimetre-scale folded laminations, or ii) large slump structures, which are visible as prominent deformations of thick turbidites (Fig. 2.8).

**Results**

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2.4.4 Seismic stratigraphy

The initial seismic stratigraphy of Anselmetti et al. (2006) was modified and five major seismic sequences (T, G, P, R, B) and several sub-sequences that overlie the acoustic basement were identified (Figs 2.5, 2.6 and 2.7; Table 2.5). Capital letters indicate the colour used to illustrate the seismic reflection that marks the underlying sequence boundary, i.e. T(urquoise), G(reen), P(ink), R(ed) and B(lue). Sub-sequences are indicated by numerals 1 through 5, or in the case of the “Maya Clay” by “Tm” (Fig. 2.10).

Figure 2.10: High-resolution seismic N-S profile (Pinger line PI 11) documenting seismic subsequence Tm coinciding with lithological sub-unit Im (“Maya Clay”). P/H Boundary = Pleistocene/Holocene transition; PS-G1 = Palaeoshoreline G1.
Table 2.5: Seismic geometries and seismic facies of each seismic sequence in the sediment record of Lake Petén Itzá, described from the top (young sediments) to the bottom (old sediments).

2.4.5 Core-to-seismic correlation

Core-to-seismic correlation is shown along an E-W seismic reflection profile, and along crossing N-S profiles (Figs 2.5, 2.6 and 2.7). Lithological Unit I spans the Holocene and coincides with uppermost seismic sequence T (Fig. 2.6). The bulk of Unit I was deposited in a relatively short period between ca 1.0 and 3.0 ka, and is represented by the “Maya Clay” sub-unit (Iₘ), and in the seismic reflection data by sub-sequence Tₘ (Fig. 2.10). The lithological boundary from Unit I (clay) to Unit II (gypsum) at ca 10.7 ka is expressed by a prominent increase in bulk density (from ca 1.4 to ca 1.7 g/cm³) and a strong, high-amplitude reflection at seismic boundary T/G (Fig. 2.6). Sediments of Unit II (10 to 18 ka) consist of three gypsum sub-units (Ila, c, e) and two clay sub-units (Ilb, d). The top
of each gypsum sub-unit corresponds to one of three stacked palaeoshorelines (PS) in the seismic record at 75 ms (PS-G1, 56 m), 85 ms (PS-G2, 64 m) and 90 ms (PS-G3, 68 m) (Figs 2.6 and 2.7). Clay-rich sediments of Unit III (18 to 23 ka) are characterized by low bulk densities and are represented seismically by low-amplitude reflections of seismic sequence P. The sedimentological transition from Unit III (clay) to Unit IV (gypsum) at 23 ka is expressed by an increase in density from ca 1.5 to ca 1.9 g/cm$^3$ in the core, which corresponds to a strong, high-amplitude reflection at the P/R sequence boundary. Sediments of Unit IV (23 to 39 ka), consisting of alternating gypsum sub-units (IVa, c, e, g) and clay sub-units (IVb, d, f), are marked by high-frequency variations in bulk density, and coincide approximately with continuous, high-amplitude reflections of sub-sequence R1. Lithological Unit V (39 to 49 ka) correlates to seismic sub-sequence R2. Some areas in sub-sequence R2 show transparent to chaotic seismic facies, indicating local mass movements that are also observed in lithological Unit V as deformed sediments, on metre to millimetre scales (Fig. 2.8). The clay-rich mud of Unit VI (49 to 58 ka) represents the upper part of Sequence B. Banded, clay-rich and carbonate-rich lacustrine sediments of Unit VII (58 to 78 ka) correspond to the middle part of Sequence B. The transition from Unit VIII (78 to 85 ka) to Unit VII at 78 ka corresponds to the lower part of sequence B and is expressed by an up-core decrease in density from ca 1.9 to ca 1.5 g/cm$^3$ (Fig. 2.6). Sediments of MU (Site PI-7) and lithological Unit IX that cover the time span from ca 85 to ca 200 ka in sites PI-1 and PI-7, could not be correlated with the seismic record, as the air-gun source was insufficient to penetrate to this sediment depth (Fig. 2.7). Consequently, recovery of these deposits was unexpected because they were not imaged by the seismic reflection survey.

### 2.5 Discussion

#### 2.5.1 Comparisons with the seismic model of Anselmetti et al. (2006)

The entire sediment record from Lake Petén Itzá was used to evaluate and refine the previous seismic stratigraphic work of Anselmetti et al. (2006). In general the earlier study shows good agreement with the observations presented in this study (Fig. 2.6). Nonetheless, there are some significant differences between the findings of this study and the interpretations of Anselmetti et al. (2006):

- Whereas Anselmetti et al. (2006) defined four seismic sequences (T, G, R and B), an additional major seismic sequence P was defined in this study. Sequence P spans the LGM, from 18 to 23 ka. This sequence was added because Unit III (“LGM-Clay”) stands out, not only with respect to its lithological signature, but because...
its seismic facies is characterized by very low reflection amplitudes that contrast sharply with overlying and underlying seismic sequences.

- Sequence G, defined in Anselmetti et al. (2006) as containing two sub-sequences, was sub-divided into three sub-sequences G1, G2 and G3. New evaluation revealed that the three-fold succession of gypsum sediments in Unit II (or sequence G) matches three seismically identified, stacked palaeoshorelines (Figs 2.6 and 2.7) that were not recognized before. The three palaeoshorelines, at -68 m, -64 m and -56 m, thus indicate a stepwise increase in palaeolake water levels after lowstands during the arid, last deglaciation phase (11 to 18 ka).

- At sites PI-1 and PI-7, drilling penetrated significantly beyond predictions made using seismic reflection data, i.e. below the apparent "acoustic basement." This underestimation was caused in part by high-impedance values of the BGU in contrast to the overlying units. Furthermore, large limestone clasts in the BGU scatter the acoustic signal, thereby inhibiting deeper acoustic penetration. Interpretation of the seismic reflection data predicted accurately the sub-surface depth down to the base of Unit VIII and BGU, which appeared as acoustic basement in the deeper-water sections. The occurrence of sediments in Unit IX, below the acoustic basement, which were undetected seismically, is likely limited to the deeper-water depocenters of the lake. In shallow-water areas in contrast, the seismically-mapped acoustic basement may well represent “true” basement, as it is exposed nearby on the lake shores.

2.5.2 Lake level and sedimentation history of Lake Petén Itzá

Eleven lithological units (Units I to IX, MU and BGU) were defined in the stratigraphic record overlying the basement (BSE) of Lake Petén Itzá, and represent at least 11 distinct phases of the lake’s palaeoenvironmental history. Stratigraphic correlation of these lithological unit boundaries (Fig. 2.3) and seismic reflections (Fig. 2.5) throughout the basin indicates that the lithology can be used as a reliable proxy for palaeolimnological and palaeoclimate inferences. Sedimentological results are interpreted and discussed with respect to past lake and environmental changes, from oldest to youngest deposits (Fig. 2.11).

Lake Petén Itzá’s oldest lacustrine sediments, which overlie the basement, are represented by lithological Unit IX in sites PI-1 and PI-7 and reach a basal age of ca 200 ka, corresponding to the transition from MIS 7 to MIS 6. This rather young age does not necessarily represent the age of the initial lake formation. Older sediments may have been eroded and redeposited in the deeper parts of the bedrock topography. Due to the low energy of the acoustic signal produced by the airgun source used in the seismic reflection
survey, seismic energy did not penetrate to bedrock in these deeper areas; therefore continuous mapping of the bedrock surface was not possible. In marginal areas of the lake, where the bedrock surface can be traced with seismic reflection data, the morphology suggests a half graben geometry, with a steep northern border fault and a gently dipping southern graben shoulder. Both appear to be enhanced by karstic dissolution processes,
which contributed to lake basin formation (Anselmetti et al., 2006). Observed sediment deformation and the slumping and sliding of entire sediment packages (Fig. 2.8) may be the result of ongoing tectonic activity. They may also be a consequence of sediment “overloading,” produced by lake-level changes that altered geotechnical properties and decreased slope stabilities, or alternatively as a consequence of distant seismic events. No evidence of faults (e.g. with surface ruptures) were observed in the seismic reflection data. Thus, there is no direct evidence of ongoing tectonic activity in the sub-surface of Lake Petén Itzá.

Sandy to silty carbonates [A8], interbedded by numerous dark, clay-sand turbidites [A3] in unit IX, overlie basement and indicate high runoff and detrital input from the watershed into the lake. This would imply relatively humid conditions during the initial transgression and lake-filling phase. Nevertheless, if the lake basin and catchment morphology were very different from that of today, perhaps as a consequence of tectono-karstic alterations, the hydrology of the system may have also differed. A hydrologically “open” system would not have been as susceptible to evaporite formation as the lake is today. Hence, the rather uniform lithologies could have been produced in an open system that was relatively insensitive to E/P changes. The lack of major lithological changes in this unit, however, is remarkable, especially considering the large glacial-interglacial changes and variations in precessionally-driven insolation that occurred during this period.

At shallow-water Site PI-7, Unit IX is overlain by MU (“Mottled Unit”), which is composed of a peculiar, >30 m thick succession of bluish-yellowish, carbonate-clay-pyrite mud [F] that lacks visible layering. The mottled bluish lithology is reminiscent of gleyed soil, which usually forms under low-oxygen, high soil-moisture conditions followed by flooding (Gambrell and Patrick, 1978; Reddy et al., 1986). Sediments overlying Unit IX in deep-water areas (e.g. sites PI-2, PI-3, and PI-6) are represented by the BGU. These BGU sediments represent a partially exposed beach gravel horizon formed during a low lake stand before 85 ka, when soil formation, represented by MU (“Mottled Unit”), was taking place at shallow water site PI-7. Because seismic information below the BGU horizon is lacking, it is not possible to determine whether only sites PI-1 and PI-7 contain a pre-85 ka section such as Unit IX, or whether Unit IX is restricted to narrow depressions in the tectono-karstic substrate of Lake Petén Itzá. A seismic reflection survey, using a stronger acoustic source, might provide the answer. Because Site PI-4, located near the greatest water depth of the modern lake, was not drilled to bedrock, it is also uncertain if the BGU horizon develops into a conformable succession at greater water depth. In any case, this horizon represents a major lake-level lowering around 90 ka, most likely caused by a significant increase in E/P. In this regard it is noteworthy that lake-level lowstands (i.e. climate drying) around this time have also been inferred for low-latitude African lakes (e.g. Lakes Malawi, Bosumtwi,

Discussion 39

which contributed to lake basin formation (Anselmetti et al., 2006). Observed sediment deformation and the slumping and sliding of entire sediment packages (Fig. 2.8) may be the result of ongoing tectonic activity. They may also be a consequence of sediment “overloading,” produced by lake-level changes that altered geotechnical properties and decreased slope stabilities, or alternatively as a consequence of distant seismic events. No evidence of faults (e.g. with surface ruptures) were observed in the seismic reflection data. Thus, there is no direct evidence of ongoing tectonic activity in the sub-surface of Lake Petén Itzá.

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and Tanganyika (Scholz et al., 2007).

After deposition of the BGU between 85 and 78 ka (ca MIS 5a), a rise in lake level and transgression are indicated by coarse carbonate sand with large gastropods in Unit VIII [A8]. This lithology represents a shallow, transgressive depositional environment with high energy during the flooding phase. Because site PI-7 was drilled in shallow water, it was flooded by this transgression at a later date, during deposition of Unit VI.

The sequence spanning ca 78 to ca 58 ka (ca MIS 4) includes shallower-water and deeper-water sediments (Unit VII) [A6, A7], representing alternating dry and humid climate conditions. Phases of lower lake level were not sufficiently low or persistent enough to reach CaSO₄ saturation, which is required to precipitate gypsum. Nonetheless, alternating lake levels are documented in the sediment record (Unit VII) by intercalated bright-beige carbonate [A6], and dark brown to greenish, carbonate-clay beds [A7]. The brighter carbonate-rich bands represent shallow-water conditions containing bentonic, shallow-water diatoms (Mastogloia, Denticula), whereas the darker clay beds represent deep-water conditions containing planktonic diatoms (Aulacoseira sp.).

The time between 58 and 49 ka (early MIS 3) was characterized by relatively humid conditions (i.e. high lake level) as indicated by the high detrital clay content [A1] Unit VI, suggesting high runoff and detrital input from the watershed during times of greater rainfall.

Between 49 and 39 ka (mid MIS 3), high lake-level stands and humid conditions continued as indicated by high organic matter content in the detrital sediments of Unit V [A4], suggesting higher autochthonous organic matter production during a period of less saline conditions. This overall humid period was interrupted by two short, but pronounced lake-level drops during dry events at ca 48 and ca 42 ka. During these two dry events, Lake Petén Itzá’s volume was reduced significantly and lake waters were more saline than today, causing the first episodes of authigenic gypsum precipitation [B].

The time between 39 and 23 ka (late MIS 3) was characterized by fluctuating high and low lake levels. In Unit IV, stage variations are documented by gypsum layers [B] during low stands that alternate with cream-coloured, carbonate-clay silt [A5] deposits during high stands. Four low stands, at ca 38.5, ca 35.5, ca 31 and ca 24 ka occur between three phases of higher lake level. The timing of clay-gypsum oscillations during the middle and later part of MIS 3 indicates that clay units correlate with warmer interstadial (IS) events documented in Greenland ice cores, whereas gypsum units are associated with cold stadials in the North Atlantic, especially those containing Heinrich Events H4, H3 and H2 (Bond et al., 1992; Hodell et al., 2008) (Fig. 2.11). Similarly, alternating clay-gypsum units during MIS 3 correlate closely with other circum-Caribbean palaeoclimate records, for instance, the marine Cariaco Basin record off northern Venezuela (ODP Hole 1002C, Peterson et al., 2000; Hodell et al., 2008). These Dansgaard-Oeschger climate cycles (Dansgaard et al., 1993) are also represented in the seismic data by high-amplitude

and Tanganyika (Scholz et al., 2007).

After deposition of the BGU between 85 and 78 ka (ca MIS 5a), a rise in lake level and transgression are indicated by coarse carbonate sand with large gastropods in Unit VIII [A8]. This lithology represents a shallow, transgressive depositional environment with high energy during the flooding phase. Because site PI-7 was drilled in shallow water, it was flooded by this transgression at a later date, during deposition of Unit VI.

The sequence spanning ca 78 to ca 58 ka (ca MIS 4) includes shallower-water and deeper-water sediments (Unit VII) [A6, A7], representing alternating dry and humid climate conditions. Phases of lower lake level were not sufficiently low or persistent enough to reach CaSO₄ saturation, which is required to precipitate gypsum. Nonetheless, alternating lake levels are documented in the sediment record (Unit VII) by intercalated bright-beige carbonate [A6], and dark brown to greenish, carbonate-clay beds [A7]. The brighter carbonate-rich bands represent shallow-water conditions containing bentonic, shallow-water diatoms (Mastogloia, Denticula), whereas the darker clay beds represent deep-water conditions containing planktonic diatoms (Aulacoseira sp.).

The time between 58 and 49 ka (early MIS 3) was characterized by relatively humid conditions (i.e. high lake level) as indicated by the high detrital clay content [A1] Unit VI, suggesting high runoff and detrital input from the watershed during times of greater rainfall.

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reflections within Sequence R1 (Fig. 2.6), which are produced by lithological differences between low-density clay and high-density gypsum sediments.

From 23 to 18 ka, i.e. during the LGM (Mix et al., 2001) (early MIS 2), high lake level (i.e. humid climate) and enhanced erosion are indicated by several lines of evidence. First, the sediment is dominated by montmorillonitic clays (Unit III). As montmorillonite is the principal weathering product of tropical soils in Petén (Coggill and Hutchinson, 1966; Curtis et al., 1998), it suggests humid climate and pronounced erosion in the watershed. Second, the dark-coloured turbidites [A3] represent individual heavy precipitation events. Third, high magnetic susceptibility values indicate high deposition of clastic material in the lake. Lastly, the base of sequence P onlaps onto underlying sequence R1 and there is a basinward-thickening wedge of seismic sequence P seen on seismic reflection data (Fig. 2.7), with the depocentre of this sequence coincident with the greatest water depths. These findings are consistent with enhanced detrital input, suggesting sediment focusing into deeper parts of the basin (i.e. high-density turbidites from underflows). These sedimentological characteristics all indicate humid climate during the LGM, which contradicts previous palaeoclimate results from Petén that proposed the lowlands of Central America were dry at that time (Leyden et al., 1993, 1994). Previous inferences, however, were based on the poorly dated sequence from Lake Quexil. Climate mechanisms that may have produced a humid climate in Petén during the LGM are discussed in Hodell et al. (2008) and Bush et al. (2009).

During the last deglaciation from 18 to 11 ka (late MIS 2, early MIS 1), lake levels fluctuated between low and intermediate stands as indicated in Unit II by alternating gypsum [B] and cream-coloured, clay-carbonate units [A5]. The lithology suggests a generally arid late Glacial. In the seismic record, effective moisture cycles are recognized by the increased frequency of high-amplitude reflections in seismic sequence G. Three dry events, i.e. lake-level lowstands, are recorded by three gypsum units at ca 16.5, ca 14 and ca 11.5 ka, all of which have a palaeoshoreline in the lake margin areas (PS-G1-3, Figs 2.6, 2.7 and 2.11). The elevations of these shorelines increase successively from 68 m (90 ms) to 64 m (85 ms) and finally to 56 m (75 ms) below the modern lake level (Figs 2.6, 2.7 and 2.11), showing a stepwise increase in the level of the lowstands during the late Glacial.

About 11 ka, at the termination of the arid last glacial period in early MIS 1, the lake level was ca 56 m below the modern stage, as indicated by a palaeosol in shallow-water cores (Hillesheim et al., 2005; Anselmetti et al., 2006) and by autochthonous gypsum crystals in deep-water cores (Hillesheim et al., 2005; Anselmetti et al., 2006). At that time, the volume of Lake Petén Itzá was reduced to only about 13% of its present volume, the lake was moderately saline, and waters were saturated with respect to gypsum (Hillesheim et al., 2005). After this lowstand, lake-levels rose, as documented in shallow-water cores by transgressive, gastropod-rich lacustrine sediments, which overlie reflections within Sequence R1 (Fig. 2.6), which are produced by lithological differences between low-density clay and high-density gypsum sediments.

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a late Pleistocene palaeosol (Curtis et al., 1998; Hillesheim et al., 2005). In deep-water cores, the transition from arid late Pleistocene to moist Holocene conditions is marked by a shift from gypsum [B] to organic-rich, deeper-water, clay-rich sediments of Unit I [A4]. Onlapping bedding geometries in seismic sequence T clearly illustrate this lake transgression (Fig. 2.6). After this early Holocene rise, lake levels remained high except for minor phases of lowered levels, in particular between 4.5 and 3.0 ka (Mueller et al., 2009). During the last 3 kyr, environmental conditions in Petén watersheds and sedimentology in the lakes have been strongly controlled by human activities (Deevey et al., 1979; Binford et al., 1987; Brenner, 1994; Rosenmeier et al., 2002; Anselmetti et al., 2009). During the last 3 kyr, environmental conditions in Petén watersheds and sedimentology in the lakes have been strongly controlled by human activities (Deevey et al., 1979; Binford et al., 1987; Brenner, 1994; Rosenmeier et al., 2002; Anselmetti et al., 2007). For instance, forest clearance by the ancient Maya, which began about 3000 years ago, led to high erosion rates in Petén watersheds. This is expressed in the Lake Petén Itzá sediment record by the “Maya Clay” subunit (I_m) (Fig. 2.10). Following the demise of Classic Maya culture around 1.0 ka, rapid clay deposition was replaced by slower sedimentation of organic-rich clay and silt deposits, reflecting tropical forest recovery in the watershed and reduced supply of detrital material to the lake basin (Islebe et al., 1996).

### 2.6 Conclusions

Lake Petén Itzá sediments are sensitive recorders of past environmental changes during the last 200 kyr. Seismic stratigraphy, together with sediment core analysis, enabled comprehensive reconstruction of past environmental changes in the region.

1) Radiocarbon dates and tephrachronology reveal that Lake Petén Itzá’s oldest sediments were deposited ca 200 ka (MIS 7a). These samples were recovered from sections below the zone of deepest seismic imaging; accordingly deeper basins in the bedrock morphology may exist, and the age of the sampled sediments may underestimate the age of tectono-karstic basin formation.

2) Eleven lithostratigraphic units (Units I to IX, MU and BGU) overlying the basement were defined in the Petén Itzá sediment record. They represent at least 11 distinct phases of the lake’s palaeoenvironmental history. These lithostratigraphic units are laterally traceable throughout the Lake Petén Itzá basin. This observation justifies the use of the lithological succession as a regional palaeoenvironmental proxy, as suggested by previous studies (Hodell et al., 2008).

3) The sediment succession in cores from the seven drill sites allowed testing and refinement of the seismic stratigraphy proposed prior to drilling. The predictions of stratigraphic boundaries, in general, were accurate. Seismic data penetration was not sufficient to image deep sediment in some sections. In two cases,
reflections interpreted as acoustic basement were instead a gravel-bearing horizon and sediments were much thicker than anticipated.

4) Sediment deposited between *ca* 200 and 85 ka was encountered at only two sites, probably because of irregular basin morphology with narrow depressions in the tectono-karstic basement. These oldest sediments are characterized by lithologies that reflect deposition during an initial transgression, followed by clay and carbonate-rich sediments without major gypsum units, reflecting rather sustained humid conditions resulting in high runoff and high detrital constituents.

5) Before 85 ka, the sediment record is characterized by a gravel-bearing and sand-bearing unit that forms an unconformity indicative of a major lake-level lowstand (i.e. dry climate). Dry climate around this time was also inferred by study of sediments from low-latitude African lakes.

6) During the last *ca* 50 kyr, lithological units are characterized by alternating clay and gypsum units. Gypsum units are associated with low lake levels (i.e. dry climate) and clay units with high lake levels (i.e. humid climate). Stacked palaeoshorelines at -68 m, -64 m and -56 m coincide with gypsum units that indicate a stepwise increase in water levels from the lowstands during the arid, last deglaciation, 18 to 11 ka.

7) The Holocene lacks gypsum deposits, and was thus characterized by relatively high lake levels and humid climate. Human impact during the Maya epoch (*ca* 3.0 to 1.0 ka) is reflected by rapid clay deposition.

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Chapter 3

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

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.

3.1 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 δ¹⁸O 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 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. 3.1). 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 - 40m shallower than today, indicating climate conditions significantly more arid than present.

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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 $\sim 11$ 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. 3.1). It is the largest (100 km$^2$) and deepest ($z_{\text{max}} = 160$ m) lake in the Petén Lake District, considerably deeper than Lakes Quexil ($z_{\text{max}} = 32$ m) and Salpetén ($z_{\text{max}} = 32$ 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
3.2 Modern limnology and climate

Lake Petén Itzá is located at ∼16°55′N, 89°50′W in the Department of Petén, northern Guatemala (Fig. 3.1). 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 3.1). 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 CaSO₄ 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$^{-1}$ with a regional mean of $\sim$1601 mm yr$^{-1}$ (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 yr$^{-1}$ along the northwest coast near Progreso ($\sim$21°N) to $>2000$ mm yr$^{-1}$ in southern Petén, Guatemala ($\sim$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. 3.2; 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 north-ward over the western Gulf of Mexico bringing moisture to the Yucatan Peninsula, northern Mexico, and the central US (Fig. 3.2). 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.

During winter, the NASH dominates in the Intra-Americas Sea and moisture transport is shifted south of the Yucatan Peninsula (Fig. 3.2). The atmosphere over the Yucatan Peninsula is marked by subsidence related to the descending limb of the Hadley cell, which is centered at $\sim$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 $\sim$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

### Table 3.1: Mean ion concentrations of Petén Itzá lakewater (n=24). After Hillesheim et al. (2005)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Concentration (meq t$^{-1}$)</th>
<th>Concentration (mg t$^{-1}$)</th>
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<tr>
<td>Ca$^{2+}$</td>
<td>3.15</td>
<td>63.13</td>
</tr>
<tr>
<td>Mg$^{2+}$</td>
<td>1.86</td>
<td>22.62</td>
</tr>
<tr>
<td>Na$^+$</td>
<td>0.60</td>
<td>13.80</td>
</tr>
<tr>
<td>Cl$^-$</td>
<td>0.26</td>
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<td>HCO$_3^-$</td>
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<td>Total</td>
<td>11.22</td>
<td>407.78</td>
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</tbody>
</table>

Mean ion concentrations of Petén Itzá lakewater (n=24). After Hillesheim et al. (2005) to 2500 mm yr$^{-1}$ with a regional mean of $\sim$1601 mm yr$^{-1}$ (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 yr$^{-1}$ along the northwest coast near Progreso ($\sim$21°N) to $>2000$ mm yr$^{-1}$ in southern Petén, Guatemala ($\sim$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. 3.2; 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 north-ward over the western Gulf of Mexico bringing moisture to the Yucatan Peninsula, northern Mexico, and the central US (Fig. 3.2). 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.

During winter, the NASH dominates in the Intra-Americas Sea and moisture transport is shifted south of the Yucatan Peninsula (Fig. 3.2). The atmosphere over the Yucatan Peninsula is marked by subsidence related to the descending limb of the Hadley cell, which is centered at $\sim$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 $\sim$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
Figure 3.2: 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 U.S. 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).

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$^{-1}$), which caused high lake levels and flooding, as commemorated by a plaque marking the 1938 high water mark.

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in Flores (Fig. 3.1B). In contrast, the early to mid-1970s were dry (1415 mm yr\(^{-1}\)) 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 \(\sim 56\) 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).

### 3.3 Methods

#### 3.3.1 Composite sections

Three holes were drilled at both Sites PI-3 and PI-6 to ensure complete recovery of the stratigraphic section (Table 3.2). 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, 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 \(\sim 75.9\) 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.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Water depth (m)</th>
<th>Penetration Depth (mblf)</th>
<th>Average % Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI-3</td>
<td>17° 0.2016' N</td>
<td>89° 49.24' W</td>
<td>100</td>
<td>96.9, 95.3, 90</td>
<td>92.9</td>
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<tr>
<td>PI-6</td>
<td>17° 0.0162' N</td>
<td>89° 47.0868' W</td>
<td>71</td>
<td>75.9, 66.4, 66.8</td>
<td>94.9</td>
</tr>
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</table>

#### 3.3.2 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 aluminium 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 uchannel samples (1.8 cm x 1.9 cm plastic channels cut to length; Tauxe et al., 1983) from the center of cores along the spliced composite section and remeasured magnetic susceptibility using a custombuilt instrument in the Paleomagnetic Laboratory at the University of Florida (Thomas et al., 2003). The 3.3 cm² 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.

### 3.4 Results

#### 3.4.1 Chronology

We obtained AMS-¹⁴C dates at 21 stratigraphic depths in core PI-6 and seven depths in core PI-3 (Fig. 3.3A, Tables 3.3 and 3.4). With few exceptions, radiocarbon dates are in stratigraphic order and yield a mean sedimentation rate of ~1 m ka⁻¹ (1 mm yr⁻¹). 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. 3.4). This correlation enables use of radiocarbon dates from both sites to produce a detailed age-depth model (Fig. 3.3B, Table 3.5). 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, 2008a). Four ash layers have been identified: Congo Tephra (CGT; 53 ± 3 ka; dated by ¹³C; 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).

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Figure 3.3: 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 kyrs). Green dot represents the position of the Los Chocoyos (LC) ash in PI-6 dated at 84 ka (Ledbetter, 1984). 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 Figure 3.4. Age model (line) was derived using a weighted fit through selected age-depth points from Sites PI-3 and PI-6.

Figure 3.4: (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.
Table 3.3: Radiocarbon dates on terrestrial organic material from Site PI-6. 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 Suiker and Polach (1977). No reservoir correction was applied to radiocarbon dates because the material dated was terrestrial organic matter and assumed to reflect atmospheric CO₂.

<table>
<thead>
<tr>
<th>Accession #</th>
<th>Sample</th>
<th>Depth (mod)</th>
<th>Age 14C (yr BP)</th>
<th>± (1σ)</th>
<th>Age cal (yr)</th>
<th>± (1σ)</th>
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Table 3.4: Radiocarbon dates on terrestrial organic material from Site PI-3. 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 Suiker and Polach (1977). No reservoir correction was applied to radiocarbon dates because the material dated was terrestrial organic matter and assumed to reflect atmospheric CO₂.

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3.4.2 Lithostratigraphy

The lithostratigraphy of Sites PI-3 and PI-6 is very similar to a depth of ~38 mcd (Fig. 3.5). 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 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.

Table 3.6: Density and magnetic susceptibility of common minerals found in Petén Itzá’s sediment. Source: Hunt et al. (1995).

<table>
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<th>Mineral</th>
<th>Density (g cm$^{-3}$)</th>
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<tr>
<td>Gypsum</td>
<td>2.34</td>
<td>-13 to -29</td>
</tr>
<tr>
<td>Calcite</td>
<td>2.71</td>
<td>-7.5 to -39</td>
</tr>
<tr>
<td>Clay</td>
<td>1.70</td>
<td>170 to 250</td>
</tr>
</tbody>
</table>

3.4.3 **Density and magnetic susceptibility**

Variations in magnetic susceptibility and density reflect changes in sediment lithology (Fig. 3.5). Magnetic susceptibility of Petén Itzá’s sediment is generally low (<60 SI x 10$^{-6}$) 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 SI x 10$^{-6}$) in sediments that are rich in gypsum or calcite, reflecting the different susceptibilities of these minerals (Table 3.6). 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.

3.5 **Discussion**

3.5.1 **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$^\circ$ N) is influenced by the same seasonal variations in the ITCZ and NASH as the Cariaco Basin (11$^\circ$ 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.

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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 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

Figure 3.5: 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).
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, 2001b,a).

3.5.3 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

3.5.2 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.

3.5.3 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. 3.3). 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.

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. 3.6). 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. 3.6). 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 the glacial cycle.

Figure 3.6: Magnetic susceptibility (red) and density (blue) of Site PI-6 for the last 85 ka.

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Figure 3.6: Magnetic susceptibility (red) and density (blue) of Site PI-6 for the last 85 ka.
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 \( \sim 48 \text{ ka} \) 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).

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. 3.7). 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 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. 3.7; 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. 3.7; 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. 3.8). 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. 3.8), 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 also marked by growth phases during Heinrich events, indicating wet climate (Wang et al., 2004).

**23-18 ka (LGM Chronozone)**

Clay-rich sediments accumulated between ~23 and 18 ka (Figs. 3.6 and 3.7), 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

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**Figure 3.7:** 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 in Cariaco Basin Site 1002 (green; Peterson et al., 2000), 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.
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. 3.9; Bush et al., 2009). 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 PI-6 also contains mesic tropical elements (Fig. 3.9; Bush et al., 2009), 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 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 (21000 ± 2000 cal yr BP) was a rather mild period in the subtropical North Atlantic, with SST on the order of ~13 °C (Fig. 3.7), 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

Figure 3.9: Pollen accumulation rates, charcoal concentration, and magnetic susceptibility from Site PI-6 in Lake Petén Itzá (Bush et al., 2009), color reflectance from Site 1002 in the Cariaco Basin (Peterson et al., 2000), and δ18O of the Greenland Ice Core (Grootes et al., 1993).
more frequent and intense during the LGM (Bush et al., 2004, 2009). 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., 2009). 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.

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. 3.10; 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 $^{230}$Th/Th (McManus et al., 2004). This event was also associated with an abrupt cooling in both Greenland (Fig. 3.7) and sea surface temperature records from the subtropical North Atlantic (Fig. 3.10). The ITCZ was located at a far southerly position (Leduc et al., 2000) 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. 3.10). 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. 3.7) 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 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. 3.10). This finding is more frequent and intense during the LGM (Bush et al., 2004, 2009). 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).

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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. 3.10). 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. 3.10).

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., 2009). 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. 3.9).

### 3.6 Conclusion

Cores from Site PI-6 in Lake Petén Itzá, Guatemala, comprise a complete, spliced stratigraphic section to 75.9m 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.

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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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Chapter 4

Climate drying and associated forest decline in the lowlands of northern Guatemala during the late Holocene

ABSTRACT

Palynological studies document forest disappearance during the late Holocene in the tropical Maya lowlands of northern Guatemala. The question remains as to whether this vegetation change was driven exclusively by anthropogenic deforestation, as previously suggested, or whether it was partly attributable to climate changes. We report multiple palaeoclimate and palaeoenvironment proxies (pollen, geochemical, sedimentological) from sediment cores collected in Lake Petén Itzá, northern Guatemala. Our data indicate that the earliest phase of late Holocene tropical forest reduction in this area started at ~4500 cal yr BP, simultaneous with the onset of a circum-Caribbean drying trend that lasted for ~1500 yr. This forest decline preceded the appearance of anthropogenically associated Zea mays pollen. We conclude that vegetation changes in Petén during the period from ~4500 to ~3000 cal yr BP were largely a consequence of dry climate conditions. Furthermore, palaeoclimate data from low latitudes in North Africa point to teleconnective linkages of this drying trend on both sides of the Atlantic Ocean.


Chapter 4

Climate drying and associated forest decline in the lowlands of northern Guatemala during the late Holocene

ABSTRACT

Palynological studies document forest disappearance during the late Holocene in the tropical Maya lowlands of northern Guatemala. The question remains as to whether this vegetation change was driven exclusively by anthropogenic deforestation, as previously suggested, or whether it was partly attributable to climate changes. We report multiple palaeoclimate and palaeoenvironment proxies (pollen, geochemical, sedimentological) from sediment cores collected in Lake Petén Itzá, northern Guatemala. Our data indicate that the earliest phase of late Holocene tropical forest reduction in this area started at ~4500 cal yr BP, simultaneous with the onset of a circum-Caribbean drying trend that lasted for ~1500 yr. This forest decline preceded the appearance of anthropogenically associated Zea mays pollen. We conclude that vegetation changes in Petén during the period from ~4500 to ~3000 cal yr BP were largely a consequence of dry climate conditions. Furthermore, palaeoclimate data from low latitudes in North Africa point to teleconnective linkages of this drying trend on both sides of the Atlantic Ocean.

4.1 Introduction

Late Holocene tropical forest reduction in the Maya lowlands of northern Guatemala has been documented in palaeoenvironmental studies that investigated pollen records in lacustrine sediment archives (Vaughan et al., 1985; Islebe et al., 1996; Leyden, 2002). This vegetation change was generally interpreted as being exclusively a consequence of ancient Maya activities (e.g. forest clearance, slash and burn agriculture) (Deevey et al., 1979; Binford, 1983; Vaughan et al., 1985; Brenner, 1994). In some cases, however, it was not possible to distinguish the relative significance of human- versus climate-induced vegetation change (Islebe et al., 1996; Curtis et al., 1998). The question remains, whether the forest decline was driven solely by anthropogenic deforestation or whether it was partly attributable to climate changes (Hodell et al., 2000; Brenner et al., 2002). Here we address this issue and present multiple palaeoclimate and palaeoenvironment proxies (pollen, geochemistry, sedimentology) from sediment cores collected in Lake Petén Itzá in Petén, northern Guatemala (Fig. 4.1).

Lake Petén Itzá is a closed basin, so that its water level varies in response to the changing ratio between evaporation and precipitation (E/P) (Curtis et al., 1998; Hillesheim et al., 2005; Anselmetti et al., 2006; Hodell et al., 2008). Its sediment record preserves an archive of past climate changes and is an ideal repository of information to investigate the complex interactions among climate, environment and ancient Maya culture during the Holocene. In this study, we focus on the time window from ~8000 to ~1000 cal yr BP to study the palynologically documented middle to late Holocene tropical forest decline in the Petén. In particular, we investigate the relation between vegetation changes and climate changes during the late Holocene in this lowland tropical area. To assess the regional or even extra-regional scale of our findings from Lake Petén Itzá, we compare them with palaeoclimatic data from other sites in the circum-Caribbean region. We also discuss the potential role of the changing mean position of the Atlantic Intertropical Convergence Zone (ITCZ) as a driving mechanism for the observed climate change.

4.2 Study site

Lake Petén Itzá (~16°55' N, 89°50' W) is the deepest lake (maximum water depth [wd] ~160 m) in the lowlands of Central America. It is located in the Department of Petén, in the Maya lowlands of northern Guatemala (Fig. 4.1). Lake Petén Itzá is composed of two connected basins. The deeper, northern basin occupies a large half-graben formed by a series of east-west-aligned en-echelon faults (Vinson, 1962), whereas the smaller
southern basin is much shallower, averaging only \( \sim 5 \) m in water depth. Presently, the water of Lake Petén Itzá is dilute (11.22 meq l\(^{-1}\)) and dominated by calcium and bicarbonate, with magnesium and sulfate following closely in concentration (Hillesheim et al., 2005). Lake water pH is high (\( \sim 8.0 \)) and is saturated with respect to calcium carbonate. Thermal stratification persists in the lake throughout most of the year, with hypolimnetic temperatures averaging \( \sim 25.4^\circ \)C, close to the mean annual air temperature. Lake Petén Itzá is situated in a climatically sensitive region where the amount of rainfall is related to the seasonal migration of the ITCZ and the Azores-Bermuda high-pressure system (Hastenrath, 1984). Heavy rains between June and October are associated with the northward migration of the ITCZ and the Azores-Bermuda high-pressure system. This period is characterized by weak trade winds and warm sea surface temperatures in the Atlantic between about 10° and 20°N. The rainy season is followed by a pronounced dry season during the winter (January to May) as the ITCZ and the Azores-Bermuda high move equatorward (i.e. southward) and strong trade winds become predominant in the Caribbean Sea region and in the Gulf of Mexico.

4.3 Materials and methods

In June 2002, we retrieved six piston sediment cores from Lake Petén Itzá along a north-south water depth transect from 9.7 to 63.2 m using a Kullenberg-type piston corer (Hillesheim et al., 2005; Anselmetti et al., 2006). This study focuses primarily on cores
Past changes in the ratio of E/P were reconstructed using a geochemical proxy (elemental geochemistry, stable oxygen isotope geochemistry) applied to down-core and surface sediments. Inorganic carbon (IC) was determined by coulometric titration using a UIC/ Coulometrics 501I coulometer coupled with a UIC 5240-TIC carbonate autosampler. Weight percent calcium carbonate (CaCO$_3$) was calculated by multiplying IC by 8.33. Total weight percent carbon (TC) was measured using a Carlo Erba NA 1500 CNS elemental analyzer with autosampler. Weight percent organic carbon (OC) was estimated by subtracting IC from TC, weight percent organic matter (OM%) was estimated by multiplying OC by 2.2, and weight percent inorganic clay was estimated by subtracting the sum of CaCO$_3$ and OM from 100%. Oxygen isotopic ratios in the sediment of core 11C were measured on gastropod shells (Cochliopina sp.). Sediment samples were disaggregated in 3% H$_2$O$_2$ and washed through a 63-μm sieve. Coarse material (>63 μm) was dried at 60°C. Gastropod shells were picked from the dried samples, soaked in 15% H$_2$O$_2$, cleaned ultrasonically in deionized water, and rinsed with methanol before drying. Approximately 15 gastropod shells were used to constitute a sample, which was ground to a fine powder. A fraction of this powder was analyzed from each sample. Samples were reacted in 100% orthophosphoric acid at 90°C using a Thermo Finnigan Kiel III automated preparation system. Isotopic ratios of purified CO$_2$ gas were measured online with a ThermoFinnigan-MAT 252 mass spectrometer. All isotopic values are reported in standard delta (δ) notation relative to the VPDB standard. Relative elemental concentrations in the sediments of core 11B were measured at high resolution (2 mm), using an Avaatech X-ray fluorescence (XRF) core-scanner at the University of Bremen (Hillesheim, 2005). Core 11B was scanned at 10 kV when amperage was set at 1.0 mA. Past vegetation changes in the watershed of Lake Petén Itzá were inferred using shifts in fossil pollen assemblages and changes in the carbon isotope signature (δ$^{13}$C) of terrestrial derived, long-chain n-alkanes (C31 and C33) in the sediment record.
Table 4.1: Accelerator mass spectrometry (AMS) radiocarbon dates and calibrated ages of terrestrial organic matter for samples from Lake Petén Itzá cores PI 8-VI-02 11A (11A), PI 5-VI-02 11B (11B) and PI 9-VI-02 11C (11C). Radiocarbon ages were measured at the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory, and at the AMS Facilities ETH/PSI, Zurich. All radiocarbon dates were converted to calendar years with the program OxCal version 3.10 (Bronk Ramsey, 2005) using atmospheric data from Reimer et al. (2004). All radiocarbon ages were corrected to $\delta^{13}C$ values of -25 permil using stable isotope measurements. Samples indicated with # were too small for $\delta^{13}C$ analysis and were assumed to be -25 permil.

<table>
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<tr>
<th>Core</th>
<th>Accession number</th>
<th>Material</th>
<th>Depth in core</th>
<th>Depth (m)</th>
<th>$\delta^{13}C$</th>
<th>Radiocarbon age</th>
<th>Calibrated age</th>
<th>Projected-depletion$^{(2)}$ to core 11A, 11B, and/or 11C</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>(mm)</td>
<td>(mm)</td>
<td>($%$)</td>
<td>(14C, $\mu$eR)</td>
<td>(14C, yr BP)</td>
<td>(14C, yr BP)</td>
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<td>1605 ± 87</td>
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<td>248.0</td>
<td>#</td>
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<td>2628 ± 138</td>
<td>2168 (core 11B)</td>
</tr>
<tr>
<td>11A</td>
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<td>298.0</td>
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<td>7470 ± 53</td>
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<td>Wood</td>
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<td>8520 ± 80</td>
<td>9510 ± 160</td>
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</tr>
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<td>9665 ± 45</td>
<td>11500 ± 168</td>
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</tbody>
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(1) Depth below lake floor (hbf)
(2) Radiocarbon ages, which have been published by Hillelshiem et al. (2005) but recalibrated for this study with OxCal version 3.10 (Bronk Ramsey, 2005).
(3) Calibrated ages are reported in cal yr B.P. (before 1950).

Samples for pollen analysis were processed using 1-2 cm$^3$ of sediment taken from core 11C at 3-cm intervals. Pollen samples were prepared with standard laboratory procedures, i.e. KOH, HCL and acetolysis. Exotic Lycopodium spores were added to every sample.

Materials and methods

Table 4.1: Accelerator mass spectrometry (AMS) radiocarbon dates and calibrated ages of terrestrial organic matter for samples from Lake Petén Itzá cores PI 8-VI-02 11A (11A), PI 5-VI-02 11B (11B) and PI 9-VI-02 11C (11C). Radiocarbon ages were measured at the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory, and at the AMS Facilities ETH/PSI, Zurich. All radiocarbon dates were converted to calendar years with the program OxCal version 3.10 (Bronk Ramsey, 2005) using atmospheric data from Reimer et al. (2004). All radiocarbon ages were corrected to $\delta^{13}C$ values of -25 permil using stable isotope measurements. Samples indicated with # were too small for $\delta^{13}C$ analysis and were assumed to be -25 permil.

Materials and methods
before chemical processing. All residues were mounted in glycerine jelly. Pollen taxa were identified using Roubik and Moreno (1991), and the reference collection of the Ecosur Herbarium. A pollen sum of 200, excluding aquatic taxa, ferns and fungal spores, was targeted. Some samples had pollen of few taxa. Taxa were grouped by ecological preference: tropical forest, pine and temperate taxa, and disturbance taxa. Alkane extraction and isolation methods followed the procedures of Newell (2005). Lipids were extracted from 3-5 g of dry sediment using 2:1 methylene chloride/ methanol in a Dionex Accelerated Solvent Extractor 300. After solvent exchange, samples were eluted through a 1 cm x 29 cm glass column filled with 2.5 g of 5% deactivated silica gel to separate the non nalkane fraction. Samples were urea adducted to obtain straight chain n-alkanes. Purity and concentration were checked with a Perkin Elmer 8500 Gas Chromatograph (GC). The dilutions for GC-IRMS analysis were calculated and samples were transferred to glass autosampler vials. Carbon isotopic analyses were performed using an Agilent 6890 GC connected to a Thermo Finnigan Delta+XL Mass Spectrometer via a GC-C III interface.

Figure 4.2: Photographic images and schematic divisions of lithologic and lithostratigraphic Units of Kullenberg cores PI 9-VI-02 11C, PI 5-VI-02 11B, and PI 8-VI-02 11A collected in Lake Petén Itzá (Hillesheim et al., 2005). Correlation of sedimentologic features and C-14 ages among cores is indicated by black solid lines. Boundaries of lithostratigraphic Units are shown by red dashed lines. Missing uppermost sections in core 11B, and 11C are indicated at the top of the photographic image.
4.4 Proxy indicators of environmental changes

To reconstruct past changes in the ratio of E/P, we use a geochemical proxy. We assume that lower rainfall (higher E/P) reduces the delivery of detrital elements Ti, Fe and Al to the lake. Higher E/P also concentrates dissolved substances in the water column, thereby causing increased precipitation of authigenic carbonate (CaCO₃). Thus, we inferred past changes in E/P from the shifting ratio of Ca/(∑ Ti, Fe, Al) in the sediment record. Higher ratios reflect dry conditions and lower ratios reflect wet conditions. We also explored past changes in E/P by measuring stratigraphic variations in the oxygen isotope composition (δ¹⁸O) of gastropod shells. Lower values reflect moister conditions and greater values reflect drier conditions (Hodell et al., 1991). In addition, past changes in the water level of Lake Petén Itzá (i.e., shifts in E/P) were inferred by first establishing modern relationships between surface sediment composition (% CaCO₃, % organic matter OM, % clay, and gastropod content) and lake water depth, and then applying these relationships to the composition of sediments in core 11C. Vegetation changes in the Lake Peten Itza catchment were reconstructed from fossil pollen assemblages and from shifts in carbon isotopic ratios (δ¹³C) of terrestrially derived long-chain nalkanes (C₃₁ and C₃₃). The latter measure reflects changes in the relative abundance of C₃ plants (e.g., trees and shrubs) and C₄ plants (e.g., tropical grasses) in the watershed (Huang et al., 2001). Increasing δ¹³C values reflect a relative increase of C₄ to C₃ plant biomass in the watershed.
4.5Results

4.5.1 Lithostratigraphy and chronology

The Holocene sediment record from Lake Petén Itzá reveals five lithostratigraphic Units (U5-U1), each of which is characterized by a lithology that is also seen in surface sediments collected along the transect from modern shallow-water to deep-water depositional environments (Fig. 4.4). Sediments in Unit U5 (latest Pleistocene), in the lower part of Unit U4 (early Holocene), and in Unit U1 (∼1000 cal yr BP to present) fall outside our time window of interest, and are not described in detail.

Sediments of Unit U5 (late Pleistocene to ∼11,000 cal yr BP) in cores 11A and 11B are characterized by autochthonous gypsum deposits (Figs. 4.2 and 4.4) (Hillesheim et al., 2005b; Anselmetti et al., 2006).
Results 77

2005; Anselmetti et al., 2006). The landward equivalent of Unit U5 is marked by an organic-rich paleosol in core 11C (Figs. 4.2 and 4.4). The lower part of overlying Unit U4 (∼11,000 to ∼8000 cal yr BP) is marked in all the cores (11A, 11B, and 11C) by carbonate-rich sediments. The upper part of Unit U4 (∼8000 to ∼4500 cal yr BP) in each core consists of dark green, mm-scale laminated, organic-rich clay. The CaCO₃ content in Unit U4 of core 11C, and the Ca/(Ti, Fe, Al) ratio in core 11B display low and unchanging values (Fig. 4.5). Accumulation of these sediment was slow (0.03 cm yr⁻¹ in 11A and 11B, and 0.01 cm yr⁻¹ in 11C) (Fig. 4.3). The lithologic transition from Unit U3 to Unit U4 at ∼4500 cal yr BP is expressed in core 11C by a shift from finely laminated clay to gastropod-rich (Pyrgophorus sp., Cochliopina sp., and Tryonia sp.) carbonate silt, and by an increase in carbonate content from 10% to 70%, which peaks at ∼3500 cal yr BP (Fig. 4.5a). In deep-water cores 11A and 11B, this transition is marked by greater amounts of authigenic calcite crystals, expressed as an increase in the ratio of Ca/∑(Ti, Fe, Al), which also reaches a maximum at ∼3500 cal yr BP (Fig. 4.5b). Sedimentation rates in Unit U3 increased to 0.06 and 0.05 cm yr⁻¹ in cores 11A and 11B, respectively, and remained constant in core 11C (0.01 cm yr⁻¹). Sediment of Unit U2 (∼3000 to ∼1000 cal yr BP) in all cores consists of a thick, detrital inorganic clay unit. This lithology has been identified in other Petén lakes and was designated “Maya Clay” (Deevey et al., 1979; Anselmetti et al., 2007). The sedimentation rate increased in the “Maya Clay” zone to 0.15 cm yr⁻¹ in 11A, to 0.10 cm yr⁻¹ in 11B, and to 0.02 cm yr⁻¹ in 11C. Uppermost sediments of Lake Petén Itzá (Unit U1) are composed of organic-rich silt, often referred to as “Post-Mayan gyttja” Brenner et al. (2002). Due to the Kullenberg coring technique and the high water content of these sediments, we did not recover Unit U1 in cores 11A and 11B, and only the lower part of this Unit was collected in core 11B (Fig. 4.2). The oxygen isotope composition (δ¹⁸O) of gastropod shells in core 11C displays a gradual decrease from ∼2.75‰ at the bottom of Unit U4, ∼8000 cal yr BP, to ∼1.0‰ at the top of Unit U2, ∼1300 cal yr BP (Fig. 4.5a).
The pollen assemblage of U4 in core 11C is dominated by tropical moist forest taxa such as *Brosimum* and other Moraceae (Figs. 4.5a and 4.6). At the transition from U4 to U3, a change from dense vegetation to a more open, savanna-like landscape is indicated by a decline in the relative abundance of tropical forest taxa and an increase in *Pinus* (pine), *Quercus* (oak), Poaceae (grasses), and secondary taxa. Remains of the alga *Botryococcus* are also abundant in U3. Sediments of U2 are characterized by an increase in pollen of disturbance taxa such as *Asteraceae*, *Ambrosia*, and *Chenopodiaceae*, and by the first appearance of *Zea mays* pollen. Carbon isotope values (δ^{13}C) of C31 and C33 n-alkanes show a gradual increase from the base of U4 (-36‰) to the top of U2 (-28‰), indicating a relative increase of C4 plant biomass in the watershed (Fig. 4.5a).
4.5.3 Modern sedimentology of Lake Petén Itzá

Surface sediment samples from the shoreline to a water depth of ~23 m (shallow-water zone) in Lake Petén Itzá (Fig. 4.7) are characterized by gastropod-rich carbonate silt, with low organic matter and clay content (>60% CaCO$_3$; <5% OM; <20% Clay; gastropods: Pyrgophorus sp., Cochliopina sp., and Tryonia sp.). In contrast, surface sediments deposited in water >23 m deep (deep-water zone), are characterized by low carbonate content, no gastropods, but high amounts of organic matter and clay (10-20% OM; >80% Clay; <10% CaCO$_3$).

4.6 Discussion

4.6.1 Palaeoenvironmental interpretation

Gypsum of Unit U5 was deposited during a lake-level lowering of 58 m in the Late Glacial period (Hillesheim et al., 2005; Anselmetti et al., 2006). A prominent palaeoshoreline marks the transition between the lacustrine gypsum deposits lakeward and the paleosol horizon landward, which was formed in subaerially exposed areas (Fig. 4.4).
subsequent lake level rise is recorded at the base of Unit U4 by carbonate-rich transgressional sediments (Fig. 4.4). The finely laminated, organic-rich clay of U4 (from ~8000 to ~4500 cal yr BP) and the high concentration of tropical moist forest taxa in the pollen record during this time indicate deposition in deeper water under wet climate conditions of the middle Holocene. This interpretation is consistent with the Holocene thermal maximum, a wet phase observed in several other palaeoclimate records from the circum-Caribbean region (e.g. Hodell et al., 1991; Haug et al., 2001). The prominent lithologic transition in core 11C from laminated clay (U4) to the overlying gastropod-rich carbonate silt (U3) indicates a lake level lowering that reflects an increase in the ratio of E/P caused by the onset of climatic drying. The modern water depth at site 11C is ~30 m, or ~7 m deeper than the modern, maximum water depth for deposition of the shallow-water facies (i.e., <~23 m; Fig. 4.7).

We thus conclude that a lake level lowering relative to the modern stage of at least 7 m was required to deposit shallow-water facies at the site of core 11C. Lake level lowering beginning at ~4500 cal yr BP is also inferred from the upcore increase in $\text{Ca}_{\text{Ti, Fe, Al}}$ at the U3-U4 transition in deep-water core 11B (Fig. 4.5b). It reflects elevated amounts of authigenic carbonates that indicate higher ion concentrations in the water, and therefore increasing E/P. Furthermore, lake level decline at this time is also registered by the high concentrations of *Botryococcus* in U3 of core 11C (Fig. 4.6), which indicate an algal response to lower water level and associated higher nutrient concentration in the lake water (Batten and Grenfell, 1996). The $\text{CaCO}_3$ record of core 11C and the $\text{Ca}_{\text{Ti, Fe, Al}}$ record of core 11B both suggest that the drying trend in Petén began at ~4500 cal yr BP, peaked at ~3500 cal yr BP, and terminated at ~3000 cal yr BP (Fig. 4.5). The oxygen isotope record from Lake Petén Itzá, however, does not record an increase in $\delta^{18}O$ values at ~4500 cal yr BP, as might be expected with increasing E/P (Fig. 4.5a). We suggest that this lack of response in the oxygen isotope data may reflect low sensitivity of this climate proxy in this large-volume lake (Curtis et al., 1999). The pollen record in Unit U3 of core 11C reveals a late Holocene decline in tropical moist forest and expansion of an open, savanna-like landscape in Petén that coincided with this drying trend. The question remains as to whether this palynologically documented forest decline during the middle to late Holocene was attributable to climate changes, human disturbance, or both. The shift from the “Maya Clay” (U2) to the overlying organic-rich silt of U1 was interpreted previously to be the result of forest
recovery after human pressure declined following the Maya Classic period (Vaughan et al., 1985; Brenner et al., 2002; Leyden, 2002). Coincidence of water level lowering in Lake Petén Itzá with tropical forest reduction at ~4500 cal yr BP suggests that the vegetation shift in Petén was driven, at least in part, by climatic drying. This suggestion is further supported by the absence of Zea mays pollen in Unit U3 (Fig. 4.6). The first Zea mays pollen do not appear before the deposition of the “Maya Clay” (Unit U2) at ~3000 cal yr BP in the record of 11C (Figs. 4.5a and 4.6) indicating that initial vegetation changes preceded substantial early Maya agricultural activity in the Petén Itzá catchment. In contrast, other studies provide the earliest evidence for Zea mays pollen at ~4500 cal yr BP in the Mirador Basin of northern Guatemala (Wahl et al., 2006), prior to ~5000 cal yr BP in the Pulltrouser Swamp in Belize and coastal Guatemala (Jones, 1994; Pohl et al., 1996; Neff et al., 2006), and more than ~7000 years ago in the Gulf Coast lowlands (Pope et al., 2001; Pohl et al., 2007). This pattern indicates that adoption of maize agriculture varied across the Maya lowlands and adjacent regions. Thus, the relative contributions of climate change and human land use as drivers of recovery after human pressure declined following the Maya Classic period (Vaughan et al., 1985; Brenner et al., 2002; Leyden, 2002). Coincidence of water level lowering in Lake Petén Itzá with tropical forest reduction at ~4500 cal yr BP suggests that the vegetation shift in Petén was driven, at least in part, by climatic drying. This suggestion is further supported by the absence of Zea mays pollen in Unit U3 (Fig. 4.6). The first Zea mays pollen do not appear before the deposition of the “Maya Clay” (Unit U2) at ~3000 cal yr BP in the record of 11C (Figs. 4.5a and 4.6) indicating that initial vegetation changes preceded substantial early Maya agricultural activity in the Petén Itzá catchment. In contrast, other studies provide the earliest evidence for Zea mays pollen at ~4500 cal yr BP in the Mirador Basin of northern Guatemala (Wahl et al., 2006), prior to ~5000 cal yr BP in the Pulltrouser Swamp in Belize and coastal Guatemala (Jones, 1994; Pohl et al., 1996; Neff et al., 2006), and more than ~7000 years ago in the Gulf Coast lowlands (Pope et al., 2001; Pohl et al., 2007). This pattern indicates that adoption of maize agriculture varied across the Maya lowlands and adjacent regions. Thus, the relative contributions of climate change and human land use as drivers of
vegetation change in the late Holocene may have differed across the region. In some areas, Maya agricultural systems might have played an important role in initial forest decline, whereas elsewhere, significant human-induced biotic alterations related to more intensive agricultural systems may have followed climatically induced deforestation.

The palynological and sedimentological record from Lake Petén Itzá suggests that dry conditions in lowland Guatemala were partly responsible for late Holocene vegetation changes. However, if the initial spread of savanna in Petén between ~4500 and ~3000 cal yr BP was caused by dry climate conditions, simultaneous drying should also be evident in other palaeoclimate records from the circum-Caribbean. Indeed, several other circum-Caribbean palaeoclimatic records are consistent with the inferences for dry climate conditions in Petén between ~4500 and ~3000 cal yr BP that peaked at ~3500 cal yr BP. For instance, low metal concentrations (Ti, Fe) and high oxygen isotopic values in a marine record off northern Venezuela (Cariaco, ODP Hole 1002C) are interpreted to record dry conditions at ~3500 cal yr BP (Haug et al., 2001; Tedesco and Thunell, 2003) (Fig. 4.8). Similarly, high oxygen isotopic values in lacustrine
sediments from Lake Miragoane, Haiti (Hodell et al., 1991), and from Lake Valencia, northern Venezuela (Curtis et al., 1999) are interpreted to document dry conditions and/or less rainfall around 3500 cal yr BP. Furthermore, a drying trend around this time apparently occurred in the northern hemisphere tropics on both sides of the Atlantic Ocean (Fig. 4.9). Sediments from Lake Bosumtwi, Ghana indicate a major lake level decline at ∼3200 cal yr BP (Russell et al., 2003) and several other lakes in the northern hemisphere African tropics display evidence of water-level low stands around this time (Fig. 4.9), e.g., Bahr-el-Ghazal, Chad and Lake Abbé, Ethiopia (Gasse, 2000). Temporal coincidence of dry conditions in the northern hemisphere tropics across America and Africa ∼3500 cal yr BP indicates teleconnective linkages and suggests global-scale forcing. In contrast to the drying that is documented in the northern hemisphere tropics at 3500 cal yr BP, palaeoclimate records from the southern Hemisphere in South America (e.g., Lake Titicaca, Peru; Baker et al., 2001) and in Africa (e.g., Lake Malawi, Malawi; Johnson et al., 2002) indicate increased humidity at this time (Fig. 4.9). This out-of-phase pattern is consistent with a southward migration of the mean meridional position of the Atlantic ITCZ (Hodell et al., 1991; Haug et al., 2001; Peterson and Haug, 2006) and suggests it is a potential explanation for the observed drying trend beginning ∼4500 cal yr BP in the Petén. Southerly migration of the mean position of the Atlantic ITCZ is controlled by different forcing mechanisms, such as i) reduction of the Atlantic Meridional Overturning Circulation (AMOC), which decreases the cross-equatorial heat flux from the South to North Atlantic and strengthens the northeast trade winds (Timmermann et al., 2005; Cheng et al., 2007), ii) decreasing latitudinal gradients of the sea surface temperature (SST), associated with cooling of SST in the North Atlantic (Chiang and Bitz, 2005; Peterson and Haug, 2006), iii) increasing intensity of the annual cycle in the southern hemisphere tropics, associated with the ∼21,000-year precessional component of Milankovitch forcing (Hodell et al., 1991; Haug et al., 2001), iv) increasing land-sea ice cover in the Northern Hemisphere (Chiang and Bitz, 2005), v) weakening of the Caribbean Low-Level Jet (CLLJ) (Mestas-Nunez et al., 2007), vi) increased ENSO-variability in the tropical Pacific (Haug et al., 2001), vii) weakening of the Walker circulation (Stott et al., 2002), and/or viii) changes in the seasonal distribution of the North Atlantic Oscillation (NAO) (Giannini et al., 2001a). Regardless of the forcing mechanisms that dominated and ultimately caused the inferred climate shifts, we note that the drying trend registered in the Petén, and more broadly in equatorial regions of the Northern Hemisphere, parallels an increased commitment to maize-based food production and the emergence of hierarchically organized societies on the Pacific and Gulf Coasts of Mexico (Clark and Blake, 1994; Pope et al., 2001; Kennett et al., 2006) that later influenced similar cultural developments in the Maya lowlands (Rice, 1976; Rice and Rice, 1990; Neff et al., 2006).
84 Climate drying and associated forest decline in the lowlands of northern Guatemala

Figure 4.9: Map of sea surface temperatures (SST) (http://atlas.snet.gob.sv) in degrees Celsius (°C) in the Atlantic Ocean (June 1985-1997) showing sites discussed in this study. The colors represent climate conditions around 3500 cal yr BP at each site (yellow: dry, blue: humid): 1, Lake Petén Itzá, northern Guatemala (this study); 2, Lake Miragoane, Haiti (Hodell et al., 1991); 3, Cariaco Basin, offshore northern Venezuela (Haug et al., 2001); 4, Lake Valencia, Venezuela (Curtis et al., 1999); 5, Lake Bosumtwi, Ghana (Russell et al., 2003); 6, Bahr-el-Ghazal, Chad (Gasse, 2000); 7, Lake Abbé, Ethiopia (Gasse, 2000); 8, Lake Malawi, Malawi (Johnson et al., 2002); and 9, Lake Titicaca, Peru/Bolivia (Baker et al., 2001).

4.7 Conclusions

Our sedimentological, geochemical, and pollen data from Lake Petén Itzá provide new insights into the palynologically documented, late Holocene forest decline in the lowland Neotropics of northern Guatemala. First, the earliest phase of tropical forest reduction in Petén coincided with a water-level decline in Lake Petén Itzá (i.e. dry conditions) between ~4500 and ~3000 cal yr BP. Second, the onset of late Holocene forest reduction at ~4500 cal yr BP preceded the first appearance of Zea mays pollen in the sediments of Lake Petén Itzá, suggesting that initial forest reduction preceded substantial agricultural activity in the watershed. Third, comparison of results from Lake Petén Itzá with other palaeoclimate data shows that forest loss in Petén coincided with a widespread drying trend. We conclude that the late Holocene vegetation change in the Maya lowlands was not associated solely with human activity, as previously suggested, but that its earliest phase was driven largely by climatic drying. Temporal correlations between climate drying, associated environmental changes in agricultural intensification and the early emergence of hierarchically organized complex societies merit further investigation by archaeologists and palaeoclimatologists.
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Chapter 5

Recovery of the forest ecosystem in the tropical lowlands of northern Guatemala after disintegration of Classic Maya polities

ABSTRACT

We employed paleolimnological methods to investigate tropical forest recovery and soil stabilization that followed abandonment of agricultural systems associated with disintegration of Classic Maya polities ca. ∼AD 800-1000. We used lithological, geochemical, magnetic, and palynological data from sediment cores of Lake Petén Itzá, in the Maya Lowlands of northern Guatemala. Sediment core chronology was developed using radiocarbon dates on terrestrial wood and charcoal fragments. Our results indicate that in the absence of large human populations and extensive farming activities, Petén forests recovered under humid climate conditions within a span of 80 to 260 years. Soil stabilization postdates pollen evidence of forest re-growth stratigraphically, and required between 120 and 280 years. We conclude that the tropical forest ecosystem in the watershed of Lake Petén Itzá had been re-established by the early Postclassic period (AD 1000-1200).

5.1 Introduction

Ancient Maya population decline during the terminal Classic period (~AD 800 - 1000) in lowland Guatemala (Fig. 5.1) was associated with abandonment of regional agricultural systems. This demographic decline occurred following a long episode of sustained occupation that began ~1000 BC, and initiated regional forest recovery and soil stabilization. Several paleolimnological studies in the Maya Lowlands found evidence of environmental recovery associated with decreased anthropogenic pressure, but the exact timing and dynamics of forest re-growth and soil stabilization remained elusive, due to the difficulty of establishing reliable sediment core chronologies and to spatial and temporal variations of human impact on the landscape (Wiseman, 1985; Leyden, 1987; Brenner et al., 1990, 2002; Islebe et al., 1996; Johnston et al., 2001; Rue et al., 2002; Wahl et al., 2006). Dating lake sediment records from the region is challenging because radiocarbon dates on bulk sediments are confounded by hard-water-lake error (Deevey and Stuiver, 1964). The problem arises because “old carbon” from local limestone bedrock and soils can enter lake water as dissolved bicarbonate and be incorporated into lacustrine organic matter. Aside from challenge of developing reliable core chronologies it remained unclear whether reforestation after the Classic Maya Period (~AD 250 - 1000) was exclusively a consequence of reduced anthropogenic stress, as some have suggested (Deevey et al., 1979; Wiseman, 1985), or if it was associated, in part, with increasing regional rainfall (Hodell et al., 2000; Brenner et al., 2002). We investigated these complex interactions among climate, environment and humans in the Maya Lowlands using a well-dated sediment record from Lake Petén Itzá that spans roughly the last 1000 years.

Previous studies throughout the Maya Lowlands (Fig. 5.1) displayed considerable variability with respect to the apparent timing of forest recovery and soil stabilization after the Classic Period. Forest recovery is indicated in regional pollen records by a transition from a savanna-like landscape to a closed-canopy forest that appears similar to early Holocene, “pre-Maya” vegetation. Soil stabilization is marked by a reduction in inorganic detrital input, i.e. the end of rapid watershed soil erosion. Pollen studies from the shallow southern basin of Lake Petén Itzá (Islebe et al., 1996; Curtis et al., 1998) and from the Mirador Basin (Wahl et al., 2006) point to rapid forest recovery and soil stabilization within 150 years after the disintegration of Maya political systems between AD 800 and 1000. Studies from the Petapilla Swamp, Honduras (Rue, 1987; Rue et al., 2002) and from Laguna Las Pozas in the Río de la Pasión drainage, Guatemala (Johnston et al., 2001) suggested that forest regeneration began after AD 1200, long after the decline of Classic Maya populations. Poorly dated pollen records from small, shallow lakes in the Petén savannas (Brenner et al., 1990) even suggested that forest re-growth in Petén was delayed until the Spanish conquest in the 16th century AD.
5.2 Study site

Lake Petén Itzá (16°55′N, 89°50′W) is the deepest and largest lake in the lowland Neotropics of Central America (maximum depth ~160 m, area ~100 km²) (Fig. 5.1). It is located in the Department of Petén, northern Guatemala, in the heart of the Maya Lowlands. Lake Petén Itzá occupies a closed basin and its water level varies in response to the changing ratio between evaporation and precipitation (Hillesheim et al., 2005; Hodell et al., 2008). Lake Petén Itzá is located in a climatically sensitive region where rainfall is highly seasonal and related to the migration of the Intertropical Convergence Zone (ITCZ) and the Azores-Bermuda high-pressure system (Hastenrath, 1984).

Figure 5.1: A) Bathymetric map of Lake Petén Itzá, with the location of sediment core 7C along seismic line PI7. Inset shows the map of the circum-Caribbean region with sites from the Maya Lowlands mentioned in this study: 1: Lake Petén Itzá (this study), 2: Mirador Basin (Wahl et al., 2006), 3: Laguna Las Pozas (Johnston et al., 2001), 4: Petapilla Swamp (Rue, 1987), 5: Aguada X’caamal (Hodell et al., 2005), 6: Cariaco Basin (Haug et al., 2001, 2003). B) Bulk density with scan of core 7C superimposed on a seismic image collected along seismic line PI7 (Anselmetti et al., 2006), for location, see A. The density contrast at the transition from clay to gyttja results in a high-amplitude reflection in the seismic record.

5.3 Methods

In August 2005, short sediment cores were retrieved from Lake Petén Itzá with a gravity corer. Core locations were selected based on high-resolution seismic data collected in 1999 (Anselmetti et al., 2006). In this study we focused on core PI VIII-05 7C, hereafter referred to as core 7C. Core 7C was 106 cm long and was collected in ~60 m of water (Fig. 5.1). The chronology for core 7C was based on 14C ages of terrestrial wood and charcoal samples (Table 5.1) thereby avoiding dating problems associated with hard-water-lake error (Deevey and Stuiver, 1964). Radiocarbon ages were measured using
Past climate and environmental change was inferred from multiple variables, including sedimentology, elemental geochemistry, magnetic susceptibility and pollen from the late Holocene sediment archive. Total carbon (TC) and total inorganic carbon (TIC) were measured by coulometry with a UIC, Inc. system. For the TC measurement, samples were combusted at 950 °C to convert all forms of carbon into CO$_2$. Samples were acidified to convert carbonate to CO$_2$. Total organic carbon content (TOC) was calculated as TC minus TIC. Weight percent calcium carbonate (CaCO$_3$ %) was calculated by multiplying TIC by 8.33. Weight percent organic matter (OM %) was estimated by multiplying TOC by 2.2. Ca elemental concentrations in bulk sediment were measured at high resolution (1 mm) using an Avaatech X-ray fluorescence (XRF) core-scanner at ETH Zurich.

Late Holocene vegetation changes in the region were inferred from shifts in fossil pollen assemblages throughout the sediment record. Pollen data were grouped by ecological preference: tropical forest elements, pine temperate elements, disturbance elements, spores and algae. Pollen analysis was completed at 3-cm intervals. Samples of 1-2 cm$^3$ were processed with standard laboratory procedures, using KOH, HCL and acetolysis. A known amount of exotic Lycopodium spores was added to each sample to enable calculation of absolute pollen concentration. Residues were mounted in glycerine jelly and pollen grains were identified using (Roubik and Moreno, 1991; Palacios C. P.

The accelerator mass spectrometry (AMS) facility at ETH, Zurich. An age-depth model was developed using a depositional P Sequence model (k=3) of the OxCal 4.1 calibration program. The approach assumes depositional processes are random and incorporates “a priori” information on sample stratigraphic position, following a Bayesian mathematical approach (Bronk-Ramsey, 2008). All dates are reported in calibrated calendar years BC/AD (2 - error ranges).

### Table 5.1: Accelerator mass spectrometry (AMS) radiocarbon dates and calibrated ages of terrestrial organic material in Lake Petén Itzá core PI VIII-05 7C. Radiocarbon ages were measured using the accelerator mass spectrometry (AMS) facility at ETH, Zurich. Radiocarbon ages were corrected to δ$^{13}$C values of -25%. All radiocarbon dates were calibrated using a depositional P Sequence model (k=3) of the OxCal 4.1 calibration program (Bronk-Ramsey, 2008).
and the reference collection of the Ecosur Herbarium. A pollen sum of 200 was targeted, as some samples had few pollen elements, excluding aquatic elements, ferns and fungal spores. Diagrams were constructed with Palaeo Data Plotter (Juggins, 2002). Pollen was grouped by ecological preference: tropical forest elements, pine temperate elements, disturbance elements, spores and algae.

5.4 Results

The calibrated calendar age at the base of core 7C (106 cm) is estimated to be between AD 880 and 1140 (Fig. 5.2, Table 5.1). This indicates that the core represents deposition over a time span of 810 to 1070 years. The average sedimentation rate in core 7C was ∼1 mm/yr. Sedimentological and geochemical characteristics were used to divide core 7C into four lithologic units, I to IV, from bottom to top (Fig. 5.3). Lithologic units, variations in organic matter and carbonate content, changes in magnetic susceptibility, and shifts in calcium concentration are shown in Figure 5.3. The date on basal sediments of unit I (106-96 cm) has a range from AD 880 to 1140, and the date at the top of unit I falls between AD 1020 and 1180. Sediments at the base of unit II (96-66 cm) were dated to between AD 1020 and 1180, which uppermost sediment in unit II was dated to between AD 1280 and 1410. Assuming a constant sedimentation rate, bottom sediments of unit III (66-28 cm) date to between AD 1280 and 1410, and topmost sediments date to between AD 1700 and 1760. Lowermost sediments of unit IV (< 28 cm) were deposited between AD 1700 and 1760, whereas the youngest sediments at the top of unit IV are assumed to represent modern deposits.

Pollen results from core 7C are shown as percentage diagrams (Figs. 5.2D and 5.4). The pollen diagrams were divided into four zones from bottom (1) to top (4) on the basis of plant ecological preferences. Sediments at the base of pollen zone 1 (106-98 cm) date to between AD 880 and 1140 while those at 98 cm date to between AD 980 and 1160. Pollen was rare in this zone and relative abundances could not be calculated. Pollen zone 2 (98-79 cm) ranges from its lower boundary, dated to between AD 980 and 1160, to its upper boundary, dated to between AD 1160 and 1270. This zone is dominated by tropical, moist forest elements such as Brosimum alicastrum, Moraceae, Ficus, Fabaceae, Euphorbiaceae, Guettarda combsii, Myrtaceae, Meliaceae, Myrica and Sapotaceae. Local elements like fungal spores and Cyperaceae also occur in pollen zone 2. Pollen zone 3 (80-43 cm) has a lower boundary dated to between AD 1160 and 1270, and an upper boundary dated to between AD 1540 and 1630. In this zone, a change from dense forest vegetation to a more open, savanna-like landscape is indicated by a decline in relative abundance of tropical forest elements Moraceae and Brosimum, and

Results 91

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Figure 5.2: A) Calibrated 14C ages (cal yr BC/AD) measured on terrestrial organic matter (2 - error ranges) versus depth for Lake Petén Itzá core PI VIII-05 7C. The OxCal 4.1 depositional P Sequence model (k=3) after Bronk-Ramsay (2008) was used to build the age-depth model for the core. B) Stratigraphic column with lithologic units, with range of ages (cal yr BP) of the boundaries, and with a photographic scan of core 7C. C) Generalized archaeological chronology (dates are from Rice and Rice, 1990, 2004; Demarest et al., 2004; Adams and MacLeod, 2000; Sharer and Traxler, 2006). D) Pollen zones and pollen percentage diagram of core 7C (for a detailed pollen diagram, see Fig. 5.4).

Figure 5.3: Lithologic, geochemical and magnetic susceptibility data for Lake Petén Itzá Core PI VIII-05 7C versus age in calibrated years AD. From left to right: Stratigraphic column with lithologic units, weight percent organic matter (OM, %), magnetic susceptibility MS (cgs), weight percent calcium carbonate (CaCO₃, %), and calcium elemental (Ca) concentration (cts*10⁴)
a coincident increase in *Pinus* (pine), *Quercus* (oak), *Alnus*, Asteraceae and Poaceae (grasses). Melastomataceae, typical in disturbance vegetation, have values between 1 and 6%. Other disturbance elements with low values in pollen zone 3 are *Croton*, *Celtis*, *Cecropia*, *Trema* and Solanaceae. Pollen grains of Ulmus were detected in the sample at 56 cm depth. Pollen zone 4 (43-0 cm) is characterized by tropical, lowland dry forest taxa that are typical of recent vegetation in Petén, with abundant *Brosimum alicastrum* and other Moraceae. Minor forest disturbance is indicated by *Cecropia*, *Celtis* and *Ceiba*.

**Figure 5.4:** Pollen percentage diagram for Lake Petén Itzá, core PI VIII-05 7C. Elements were grouped by ecological preference: tropical forest elements, pine temperate elements, disturbance elements, spores and algae.
5.5 Discussion

5.5.1 Human ecology in Petén at the Terminal Classic to Early Postclassic Transition

Major economic, political, and demographic changes are evident in the archaeological record of the Petén Lakes region during the Terminal Classic (AD 800 - 1000) and Early Postclassic (AD 1000 - 1200) periods (Rice and Rice, 1990, 2004; Demarest et al., 2004; Adams and MacLeod, 2000; Sharer and Traxler, 2006). These changes occurred at the end of a protracted, ~750-year episode of population growth and political integration in the southern Maya Lowlands that was associated with the expansion of agriculture, which involved slash-and-burn clearance of tropical forest (Lentz and Hockaday, 2009). Such deforestation promoted increased soil erosion, leading to a characteristic inorganic detrital deposit in most lakes and wetlands in Petén termed “Maya Clay” (Doevey, 1979; Brenner et al., 1990; Beach et al., 2006; Anselmetti et al., 2007; Mueller et al., 2009).

Sediments of bottommost unit I, deposited between about AD 880 (minimum) and AD 1180 (maximum), possess characteristics of the “Maya Clay.” This clay unit thus indicates high detrital input into the lake, coinciding roughly with the Terminal Classic (Fig. 5.2). Hence, continued rapid clay deposition following the Classic Maya Period (AD 250 - 1000) indicates sustained, unstable soil conditions, reflecting persistent open vegetation around Lake Petén Itzá during this period. This is in accord with the low pollen concentrations in unit I, as high detrital input further diluted the low influx of pollen grains in pollen zone 1 deposited between AD 880 (minimum) and AD 1160 AD (maximum).

Open vegetation suggests persistent human disturbance around Lake Petén Itzá during the Terminal Classic. This finding is consistent with archaeological data that indicate people moved from the nearby Petexbatún and Río Pasión River areas into the Petén Lakes region during the Terminal Classic (Rice and Rice, 2004), and suggests that the Petén Lakes area was more politically stable and environmentally favorable than adjacent regions. Open vegetation in the Terminal Classic period may, however, simply reflect delayed ecosystem recovery after widespread anthropogenic deforestation during the Classic Maya period.

The transition from pollen zone 1 to zone 2 is dated between AD 980 and 1160, and represents the re-establishment of closed tropical vegetation, beginning in the Early Postclassic. The shift is characterized by tropical forest elements such as Moraceae, Brosimum alicastrum, and Ficus. The lithologic transition from unit I to unit II is dated between AD 1020 and 1180, representing the end of the phase of high detrital input, i.e. the end of rapid soil erosion in the Petén Itzá watershed, as indicated by decreasing magnetic susceptibility values (Fig. 5.3). Consequently we suggest that since ~AD 900, in the absence of large human populations and extensive agricultural activity i) Petén
forests recovered within a span of 80 to 260 years, and ii) soil stabilization required between 120 and 280 years, stratigraphically postdating pollen evidence for forest recovery. This small discrepancy between the apparent timing of forest re-growth and soil stabilization may be a consequence of pollen rain reflecting regional vegetation shifts, while sedimentological and geochemical data reflect local, watershed-specific erosion intensity. Pollen assemblages of zone 2, deposited during the Early Postclassic, represent the period of re-establishment of closed tropical vegetation containing high percentages of *Brosimum alicastrum*, Moraceae, *Ficus*, *Guettarda combsii*, and Sapotaceae, suggesting moist climate conditions. Local elements like fungal spores and Cyperaceae in zone 2 indicate marsh-like shore vegetation, supporting the inference for wetter conditions at that time. Thus, we suggest that reduced forest clearance, combined with more humid climate conditions, promoted rapid forest regeneration around Lake Petén Itzá at the beginning of the Early Postclassic Period (∼AD 1000). This differs from the conclusions of several previous studies, which suggested vegetation re-growth in Petén was attributable exclusively to reduced anthropogenic stress (Deevey et al., 1979; Wiseman, 1985). Our findings support the hypothesis proposed in some earlier studies, that climate, too, contributed to the reforestation process (Rue 1987; Brenner et al., 1990, 2002; Hodell et al., 1995, 2000; Curtis et al., 1996). Increased humidity after AD 1000 has also been documented in other paleoclimate records from the circum-Caribbean region, and is associated with the phase referred to as the “Medieval Warm Period,” from ∼AD 950 to 1300 (Haug et al., 2001, 2003).

**5.6 Conclusions**

We used lithological, geochemical, magnetic, and palynological data from a ∼1000-year-long sediment core taken in Lake Petén Itzá to reconstruct the dynamics of environmental recovery in the Guatemalan lowlands associated with demographic and political changes at the end of the Maya Classic Period. The pollen record indicates that tropical forest in Petén recovered within 80 to 260 years after major demographic decline and abandonment of regional agricultural systems. Reforestation occurred during a relatively moist period, implying a climate contribution to the recovery process. Soil stabilization stratigraphically postdates pollen documented forest re-growth, and required between 120 and 280 years. We conclude that regional tropical vegetation had been re-established and that soils were stabilized in the Petén Itzá watershed by the Early Postclassic (AD 1000 to 1200). The timing of “post-Maya” reforestation and soil stabilization in the Maya Lowlands probably varied somewhat across the landscape, depending upon the earlier intensity of human occupation and environmental characteristics such as...
Recovery of the tropical ecosystem after disintegration of Classic Maya polities

water availability, topography, geology, and soil type. Nonetheless, this study provides important insights into tropical forest ecosystem recovery following a prolonged period of human vegetation disturbance.

Acknowledgments

Many thanks to Ursi Brupbacher, Urs Gerber, Nuria Torrescano, and David, Rosita, Kelsey Kuhn. This work was supported by ETH Research Grant TH-1/04-1, the Swiss National Science Foundation, and the US National Science Foundation (ATM-0502030).
Chapter 6

A comparison between the Holocene Maya-Clay and the Pleistocene LGM-Clay from Lake Petén Itzá, Guatemala

ABSTRACT

The “Maya-Clay”, a thick detrital clay unit in the late Holocene sediments from lakes in the Petén Lake District of northern Guatemala, has been interpreted to be a consequence of soil erosion generated exclusively by ancient Maya deforestation and land use practices. In this study we compare sedimentologic and seismic characteristics of the Maya-Clay with a prominent clay unit that was deposited during the Last Glacial Maximum, termed “LGM-Clay”, in the sediment record of Lake Petén Itzá. Both, the Maya-Clay and the LGM-Clay, are composed of numerous similar sedimentologic and seismic characteristics such as high sedimentation rates, a lithology composed of montmorillonite clay interbedded by sandy turbidits, and seismic sequences with wedging-out geometries. These similarities suggest comparable depositional processes for both units, in particular underflows of high-density turbidite currents during strong runoff and flood events. Although differences in the pollen and oxygen isotope ratios exist, we suggest that the LGM-Clay represents a natural analog to the human-induced Maya-Clay.

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6.1 Introduction

The objective of this study is to compare sedimentological and petrophysical characteristics of the late Holocene “Maya-Clay” with a thick, prominent clay unit that was deposited during the Last Glacial Maximum (LGM), termed “LGM-Clay” in Lake Petén Itzá (Hodell et al., 2008). The Maya-Clay is a thick, distinct, inorganic clay-rich unit that has traditionally been interpreted to be a consequence of soil erosion brought about exclusively by ancient Maya deforestation and land use practices such as slash and burn agriculture (Deevey, 1978; Deevey et al., 1979; Brenner, 1994; Brenner et al., 2002; Binford et al., 1987; Beach et al., 2006; Anselmetti et al., 2007). The LGM-Clay was discovered in 2006 when long sediment cores were recovered from Lake Petén Itzá (Fig. 6.1) as part of an International Continental Scientific Drilling Program (ICDP) - project (Hodell et al., 2008). The LGM-Clay is a thick, prominent clay unit that has been interpreted to be the result of rather wet climate conditions during the LGM in Petén (Hodell et al., 2008). The Maya-Clay and the LGM-Clay units are macroscopically very similar to each other. Such a similarity, that encompasses mineralogy, depositional mechanisms, sedimentary structures, and seismic geometries, implies that the pre-Holocene LGM-Clay may serve as a sedimentological analog to the late Holocene Maya-Clay.
6.2 Study site

The Petén Lake District in the Department of Petén, northern Guatemala has been the focus of palaeoenvironmental study for over 30 years. Most investigations explored Holocene palaeoecology, especially the impact of Maya civilization on the lowland tropical environment (Deevey, 1978; Deevey et al., 1979; Brenner, 1994; Brenner et al., 2002; Binford et al., 1987; Rice and Rice, 2004; Beach et al., 2006; Anselmetti et al., 2007). The Petén Lake District comprises a series of lake basins oriented E-W along enechelon faults. The basins in this area owe their origin to a combination of two principal processes, tectonism and limestone dissolution. The largest and deepest lake in this region is the closed-basin Lake Petén Itzá (16°55’ N, 89°50’ W), with a surface area of ~100 km² and a water depth of >160 m.

6.3 Methods

Two seismic investigations of Lake Petén Itzá were undertaken in 1999 and 2002 including a shallow, high-resolution survey (3.5 kHz pinger) and a deeper, low-resolution survey (1 in.³ airgun) (Anselmetti et al., 2006). The pinger survey provided seismic stratigraphic information for shallow subsurface sediments (< 40 m), whereas the airgun survey provided images of deeper sediments and bedrock morphology for most of the lake basin.

Multiple seismic transects provided a quasi-three-dimensional (3D) image of the sediment architecture so that sediment volumes could be quantified throughout the basin. To calculate the sediment volumes and sedimentation rates of the Maya-Clay and the LGM-Clay, sediment thicknesses were interpolated throughout the basin using KingdomSuite™ seismic interpretation software. Between Feb 3 and March 11, 2006, the complete sediment record of Lake Petén Itzá was drilled using the Global Lakes Drilling Platform GLAD800. In addition to sedimentological data from the drill cores, data from Kullenberg cores, retrieved in summer 2002 (Hillesheim et al., 2005), were also investigated. The LGM-Clay and the Maya-Clay were compared using i) a Geotek core scanner with magnetic susceptibility loop and a gamma-ray source-detector system for bulk density measurements, ii) a Bruker AXSD Advance-XRD instrument to analyze mineralogy, iii) a laser-optical Malvern Mastersizer for grain size analysis, iv) smear slides for lithologic analysis, v) macroscopic descriptions of sedimentary structures, and vi) seismic reflection data. The chronology for these two units was established using AMS-¹⁴C dates on terrestrial organic matter fragments (wood and charcoal). Past vegetation changes in the watershed of Lake Petén Itzá were inferred using shifts in fossil pollen assemblages. Climate changes are established by the analysis of stable oxygen isotope geochemistry (Escobar et al., in prep).
6.4 Results

6.4.1 Maya-Clay (~3.0 to 1.0 ka BP)

The Maya-Clay deposited from ~3.0 to ~1.0 cal ka BP (Hillesheim et al., 2005) (Fig. 6.2), is characterized by high sedimentation rates, with highest values in the deep-water zone (> 3 mm yr⁻¹) (Fig. 6.3). Sediments of the Maya-Clay are composed of gray, finely laminated (mm-scale) clay with few reworked gastropod fragments. Graded silt turbidites, up to 5 cm thick, are common and are characterized by i) fining-upward sequences, ii) color gradients from a dark gray base to a light gray top, iii) upward decreasing density gradients, and iv) sharp contacts at their base. XRD analysis of the Maya-Clay shows that its mineralogical composition is mostly montmorillonite clay (Fig. 6.5) with calcite as dominant non-clay mineral. Other minerals - dolomite, pyrite, quartz, and feldspar are scarce or poorly ordered and give ambiguous x-ray traces (Fig. 6.5). The Maya-Clay is characterized by high magnetic susceptibility values (~60 SI x 10⁻⁶), low organic carbon content (<5%), and high carbonate content (30-40%) (Fig. 6.6). The Maya-Clay has very low pollen abundances dominated by disturbance taxa (grasses and weeds) and by zea mays pollen (Iselebe et al., 1996; Curtis et al., 1998). The oxygen isotope signatures in the Maya-Clay are subject of further investigations (Escobar et al., in prep).

Detailed analyses of high-resolution seismic profiles showed that the Maya-Clay can be identified as its own seismic sequence Tₘ (Fig. 6.7). The sequence Tₘ is internally characterized by both, high and low amplitude reflections, and reveals a geometry that wedges out consistently at a water depth of ~40 ms. The thickest part of sequence Tₘ is ~7 meters, and is found in the area of maximum water depth (Fig. 6.3).

Figure 6.2: Calibrated ages (cal yr BP) versus depth for Lake Petén Itzá sediment core 11A (Hillesheim et al., 2005). Dating error on all samples is smaller than the plot symbols, except where indicated by an error bar.
Figure 6.3: A) Bathymetric map of Lake Petén Itzá showing the locations of ICDP sites drilled in 2006, and the locations of Kullenberg cores 11A and 11B, retrieved in summer 2002 (Hillesheim, 2005). B) Thickness and sedimentation rate of the Maya-Clay. C) Thickness and sedimentation rate of the LGM-Clay.
6.4.2 LGM Clay (~23.0 to 18.0 ka BP)

The LGM-Clay deposited between ~23 and 18 ka BP (Hodell et al., 2008) (Fig. 6.4), displays highest sedimentation rates in (2.5 mm yr$^{-1}$) in the deep-water zone (Fig. 6.3). This unit consists of dark gray, to greenish, laminated (mm-scale) clay. Fragments of gastropods are common throughout the LGM-Clay. Sedimentary structures recognized in this unit are composed of several fining-upwards, silty turbidites, varying in thickness between 1 and 5 cm. The sediments contain predominantly montmorillonite and calcite. Dolomite, pyrite, quartz, and feldspar also occur as trace minerals, but yield ambiguous x-ray traces on the XRD diffractogram (Fig. 6.5). The LGM-Clay is characterized by high magnetic susceptibility ($\sim$60 SI x 10$^{-6}$), relatively low organic carbon content (2-5 %), and relatively high carbonate content (averaging 30 %) (Fig. 6.6). The Pollen record in the LGM Clay was dominated by a pine-oak assemblage (Bush et al., 2009). The oxygen isotope ratios in the LGM-Clay are subject of further investigations (Escobar et al., in prep).

The LGM-Clay is expressed in the seismic record by low-amplitude reflections of sequence P (Fig. 6.7). Sequence P consistently wedges out at 85 ms (two-way travel time). The depocenter of Sequence P, where this unit reaches a maximal vertical thickness of 12 m, is found at maximum water depth (Fig. 6.3).

![Figure 6.4: Calibrated ages (cal yr BP) versus depth for Lake Petén Itzá Sites PI-6 and PI-3. Ages younger than 40 ka are from radiocarbon dates on terrestrial organic matter. Ages older than 40 ka are from tephra layers of known age (CGT: Congo Tephra, Guasal1: Guatemala-El Salvador Tephra 1, LCY: Los Chocoyos Tephra).](image-url)
Figure 6.5: XRD diffractograms of the Maya-Clay and of the LGM-Clay documenting the mineralogical predominance of montmorillonite and calcite in both lithologies.

Figure 6.6: Comparison of lithologic properties of the Maya-Clay and of the LGM-Clay versus age in the sediment record of site PI-6 from Lake Petén Itzá. From left to right: Scan, magnetic susceptibility (SI x 10^{-6}), density (g cm^{-3}), enlarged window of the Maya-Clay and LGM-Clay, respectively: Scan, sedimentary structures (turbidites), mineralogy (%), and grain size (μm).
Figure 6.7: Top: Seismic-to-core correlation of site PI-6 along the cross north-south reflection low-resolution seismic profile Air 11a. Note the wedging out geometry of sequence P, which represents the LGM-Clay. Coloured capital letters represent seismic sequences defined in (Mueller et al., 2013). Bottom: Seismic-to-core correlation of Kullenberg core 11B along north-south, high-resolution seismic profile PI 11. Note the wedging out geometry of sequence T_{\text{ms}}, which represents the Maya-Clay.
6.5 Discussion

There are numerous sedimentological similarities between the Holocene Maya-Clay and the Pleistocene LGM-Clay: The Maya-Clay displays sedimentation rates with highest values in the deep-water zone ($> 3.00$ mm yr$^{-1}$). Similarly, the LGM-Clay has its highest sedimentation rates in the deep water zone ($\sim 2.5$ mm yr$^{-1}$) (Fig. 6.3). Both units reveal numerous graded turbidites within finely laminated clay. The mineralogy of both units is dominated by montmorillonite. Because montmorillonite is the dominant constituent of soils in the Lake District, it is interpreted to be the residue of long-term dissolution of the regional limestone (Cowgill and Hutchinson, 1963; Curtis et al., 1998) and points to a detrital nature of the two units. In addition, a detrital nature of both units can be confirmed by high magnetic susceptibility values and a high abundance of reworked gastropod fragments. On the seismic data both clay units can be recognized as own seismic sequences that both provide very similar sediment geometries as they focused in the deep-water parts of the basin (Figs 6.3 and 6.7). Another similarity is that both sequences provide a wedge-shaped geometry: the Maya-Clay wedges out at 40 ms, and the LGM-Clay at 85 ms twt, respectively. This observation is consistent with a nature of high detrital input as such sediment-focusing is caused by lateral particle transport through underflows of high-density turbidite currents, which accumulate preferentially in deep-water areas.

There are also some differences between the Holocene Maya-Clay and the Pleistocene LGM-Clay: For instance, the pollen record indicates that the vegetation was entirely different during the late Holocene and the last glacial maximum: Whereas the LGM-Clay is dominated by a pine-oak assemblage, the Maya-Clay has very low pollen abundances dominated by disturbance taxa and is characterized by the occurrence of Zea mays pollen. This clearly shows that the Maya-Clay is associated with anthropogenic impact, whereas the LGM-Clay was generated without human impact. Another significant difference between the LGM- and Maya-Clay is the completely different oxygen isotope ratio throughout the two clay units (Escobar et al., in prep). Climatic and vegetation implications from the oxygen isotope ratios and from the pollen record are not the focus of this paper, but were discussed in (Hodell et al., 2008) and will be addressed in detail in Escobar et al. (in prep).

6.6 Conclusion

The comparison between the Maya-Clay and the LGM-Clay points to a similar sedimentological nature for these two units, in particular underflows of high-density turbidite
A comparison between the Maya-Clay and the LGM-Clay currents caused by strong runoff during flood events. That means that the depositional mechanism of the pre-Holocene LGM-Clay might be analogous to the late Holocene Maya-Clay. We conclude that a clay unit similar to the Maya-Clay can be deposited also without human disturbance in Petén lakes. As a consequence, rather than being an exclusive consequence of deforestation and agricultural practices of the ancient Maya, we suggest that the late Holocene Maya-Clay may have been to some degree also caused by natural climate variability affecting erosional and runoff processes in the catchment. However, different environmental conditions, i.e. the changes in the interplay between climate conditions and soil characteristics, could have lead to similar deposits in the sediment sink of the lakes. In any case, without the buffering effect of a dense forest cover, precipitation may lead to flood events that can cause a dramatic increase in soil erosion. This erosion is expressed in the sediments of Lake Petén Itzá by the Maya-Clay and the LGM-Clay. To further identify environmental and climatic patterns of the two periods, results of stable isotopic analyses (Escobar et al., in prep) will be used to test the preliminary palaeoclimatic interpretations inferred from seismic and sedimentological investigations. However, considering the fact that there are no gypsum deposits in both clay units, we propose that the climate was dominated by rather humid conditions and rather high lake levels.

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We are grateful to the staff at La Casa de Don David (David, Rosita & Kelsey Kuhn). We also thank Urs Gerber, and Sandra Herrmann. This work was supported by ETH Research Grant TH-1/04-1, the Swiss National Science Foundation, and the US National Science Foundation (ATM-0502030).
Chapter 7

Conclusions and Future Prospects

The main objective of this thesis was to recover and interpret long, continuous, sediment cores from Lake Petén Itzá that span multiple glacial-interglacial cycles. Under the auspices of the International Continental Scientific Drilling Program (ICDP), the sediment record of Lake Petén Itzá was drilled in spring 2006. In this thesis, the complete sediment record is described and interpreted to explore Late Quaternary palaeoclimate and palaeoenvironment of low-latitude, low-altitude Mesoamerica, and the sedimentological history of Lake Petén Itzá. Previously collected seismic data from Lake Petén Itzá (Anselmetti et al., 2006) are integrated with the new sediment core data. Furthermore, data from Kullenberg cores retrieved from Lake Petén Itzá in summer 2002 (Hillesheim et al., 2005), and from short gravity cores retrieved in summer 2005 are investigated. These shorter cores are used to focus on climate-environment-human interactions during the late Holocene.

Section 6.1 contains the main conclusions from this research project. In section 6.2, I discuss potential future prospects.

7.1 Conclusions

The most important findings from this thesis are listed below:

- The sediment record of Lake Petén Itzá provides an excellent and sensitive archive to reconstruct past environmental changes extending back >200 kyr. The sediment record is composed mainly of alternating clay, gypsum and carbonate units. Clay units are associated with high lake level stands (i.e. wet climate), gypsum units are related to low lake level stands (i.e. dry climate), whereas carbonate units are related to detrital input (reflecting high runoff under wet climate) or authigenic precipitation (reflecting rather low lake levels under dry climate). These lithological variations provide crucial insights into past climatic conditions and environmental changes in the region.

- The record from Lake Petén Itzá also reveals significant human impacts during the late Holocene, such as changes in land use and deforestation. These findings highlight the importance of combining sedimentological data with archaeological evidence to understand the complex interactions between climate, environment, and human societies.

- Micropaleontological and geochemical analyses provide additional evidence for the sensitivity of the lake system to climate change. For instance, the occurrence of certain benthic foraminiferal species is a key indicator of past lake levels and environmental conditions, while geochemical proxies like organic carbon and nitrogen isotopes offer insights into the source and nutrient dynamics of the lake.

- The sedimentary record from Lake Petén Itzá allows for a detailed reconstruction of past climatic events, such as glacial advances and retreats, drought episodes, and the Holocene warm period. This information is crucial for understanding the regional and global climate system and for projecting future changes.

These findings underscore the importance of long-term, high-resolution sedimentary records in addressing key questions related to palaeoclimate, palaeoenvironment, and the impact of human activities on natural systems.
units can be tracked throughout the basin along stratigraphic boundaries that can be mapped on seismic reflections, suggesting that the lithology can be used as a valuable proxy to infer palaeoenvironmental changes on a regional scale. Eleven lithologic units were defined in the entire stratigraphic record of Lake Petén Itzá, representing at least eleven distinct phases of the lake’s palaeoenvironmental history.

- The chronology for the last 40 ka of the Lake Petén Itzá sediment record was developed using >30 $^{14}$C dates on terrestrial organic matter. Sediments older than 40 ka were dated by identification of tephra layers that were matched with the established tephrochronology for Central America (Kuttlerolf et al., 2007, 2008a). Lithologic markers, stratigraphic boundaries, and tephra layers, as well as magnetic susceptibility and bulk density records, allowed layer-to-layer correlation among most sites throughout the basin. This correlation enabled extrapolation of dates from site to site, yielding a detailed age-depth model for the entire sediment record of Lake Petén Itzá.

- From $\sim$200 to $\sim$85 cal ka BP, sediments are dominated by carbonaceous clay, often interbedded with turbidites, indicating a detritally-dominated sediment regime under relatively wet climate.

- At $\sim$85 cal ka BP, an exposure horizon marks a lake low stand or partial basin desiccation, indicating dry climate conditions.

- From $\sim$85 to $\sim$48 cal ka BP, transgressive carbonate-clay sediments, overlain by deep-water clays, suggest a lake level rise and subsequent stabilization at high stage.

- Alternating clay-gypsum oscillations in the Lake Petén Itzá sediment record during late MIS 3 (from 48 to 23 cal ka BP) correlate well with stadial-interstadial stages (Dansgaard-Oeschger events) found in Greenland ice cores and in North Atlantic marine sediment cores. Clay units correlate to the warmer interstadial (IS) events, whereas gypsum units are associated with cold stadials, especially those related to Heinrich Events H4 to H1. Tight linkages of these clay-gypsum alternations during MIS 3 are also observed in comparison with precipitation proxies from the marine Cariaco basin record off northern Venezuela. It is suggested that this oscillating pattern was controlled by migration of the meridional position of the Atlantic ITCZ. The ITCZ was located farther south during cold periods when arid conditions prevailed in the northern Neotropics, especially during Heinrich Events when AMOC was reduced (Hodell et al., 2008).

- Sediments deposited during the Last Glacial Maximum (LGM), from 23 to 18 cal ka BP, consist of a thick prominent clay unit. This “LGM Clay” has two major
implications. First, it suggests high detrital input and high lake level, hence, wet climate conditions during the LGM in Petén, northern Guatemala. It is unlikely that the source of moisture during the LGM in Petén was increased summer precipitation because the mean position of the ITCZ is thought to have been far south during the LGM (Chiang et al., 2003). Rather, the major source of moisture during the LGM in Petén was increased winter precipitation when the Laurentide Ice Sheet (LIS) was at its southernmost extent and polar outbreaks (“nortes”) were more frequent and intense than today (Hodell et al., 2008). Second, similarity between the sedimentological and seismic signature of the “LGM Clay” and late Holocene “Maya Clay” points to a similar sedimentological nature for these two units, in particular underflows of high-density turbidite currents caused by strong runoff during flood events.

- During the last deglaciation, from 18 to 11 cal ka BP, three low stands of Lake Petén Itzá occurred. Each is documented by a prominent gypsum unit at \( \sim 16.5, \sim 14, \) and \( \sim 11.5 \) cal ka BP and a corresponding paleoshoreline in the seismic record.

- Late Holocene tropical forest decline in Petén was not exclusively a consequence of anthropogenic deforestation by ancient Maya, as previously suggested, but was partly attributable to a circum-Caribbean climate drying trend between 4.6 and 3 cal ka BP. Furthermore, palaeoclimate data from low latitudes in North Africa point to teleconnective linkages of dry climate conditions at \( \sim 4.6 \) cal ka BP on both sides of the Atlantic Ocean.

- Following abandonment of agricultural systems associated with disintegration of Classic Maya polities ca. \( \sim AD 800-1000, \) Petén forests recovered under humid climate conditions within a span of 80 to 260 years. Soil stabilization postdates pollen evidence of forest re-growth stratigraphically, and required between 120 and 280 years. We conclude that the tropical forest ecosystem in the watershed of Lake Petén Itzá had been re-established by the early Postclassic period (AD 1000-1200).

### 7.2 Future Prospects

This thesis answered many questions, but also raised some new ones. I propose to investigate the following major themes in potential future projects:

- Further studies of climate proxies such as high resolution XRF-records, detailed pollen analyses, and stable isotopic analyses can be used to test the preliminary

### 7.2 Future Prospects

This thesis answered many questions, but also raised some new ones. I propose to investigate the following major themes in potential future projects:

- Further studies of climate proxies such as high resolution XRF-records, detailed pollen analyses, and stable isotopic analyses can be used to test the preliminary
paleoclimatic interpretations inferred here mainly on the basis of a sedimentary facies model.

- Drilling at sites PI-1 and PI-7 penetrated deeper than was expected from the seismic images collected in 2002. The “acoustic basement” identified as from airgun data captured at these drill sites, was erroneously thought to represent bedrock (Anselmetti et al., 2006), but clearly underestimated the lacustrine sediment thickness. This misinterpretation of the seismic images was caused in part by the fact that the “acoustic basement” is represented in the lithology by large limestone clasts (BGU-unit), which i) have high impedance values compared to overlying sediments, and ii) scatter the acoustic signal, thereby inhibiting deeper sound penetration. A seismic survey that employs a stronger acoustic source and a multichannel-technique will be required to seismically image the true “bedrock”.

- Comparisons between the Petén record and other long, high-resolution lacustrine records from Africa and Asia (e.g. Lakes Bosumtwi, Malawi, Van) are required to understand climate variability on a transatlantic and pan-tropical scale during the late Pleistocene.

- The temporal correlations among climate drying, environmental changes, agricultural intensification, and early emergence of the Maya civilization merit further investigation by archaeologists and palaeoclimatologists. Future research to understand these highly complex human-climate-environment interactions during the emergence of ancient Maya culture must include archaeologists in cross-disciplinary studies. Furthermore, given the broad area affected by drying beginning $\sim$4.6 cal ka BP, it would be interesting to explore the implications of such climate shifts not only with respect to the emergence of ancient Maya civilization, but to other cultural developments in ancient Mesoamerica.

- Reforestation and soil stabilization after major demographic decline and abandonment of regional agricultural systems at $\sim$900 AD probably varied across space and time. Results from this study may only apply to the Petén Lake District, rather than to the entire Maya Lowlands. Further palynological studies of well-dated lacustrine sediment cores throughout the Maya Lowlands will be required to evaluate the extent and timing of forest and soil recovery across the broader landscape.
Bibliography


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# Curriculum Vitae

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## Education

<table>
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<th>Year</th>
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| 2004 - 2009 | Doctoral studies at Dep. of Earth Sciences, ETH Zürich, Switzerland            | ETH Zürich  | PhD Dissertation at the Geological Institute in the Climate Geology Group  
|            | Title: “Late Quaternary Environmental Change in the Lowland Neotropics:       |             | The Petén Itzá Scientific Drilling Project, Guatemala”                  |
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