Quaternary Science Reviews 150 (2016) 200–220

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A 400-ka tephrochronological framework for Central America from Lake Petén Itzá (Guatemala) sediments

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ARTICLE INFO

Article history:
Received 25 March 2016
Received in revised form
10 August 2016
Accepted 16 August 2016

Keywords:
ICDP
Petén Itzá
Tephrochronology
CAVA
Paleoclimate
Explosive volcanism

ABSTRACT

Lake Petén Itzá, northern Guatemala, lies within a hydrologically closed basin in the south-central area of the Yucatán Peninsula, and was drilled under the auspices of the International Continental Scientific Drilling Program (ICDP) in 2006. At 16°55′N latitude, the lake is ideally located for study of past climate and environmental conditions in the Neotropical lowlands. Because of its great depth (>160 m), Lake Petén Itzá has a record of continuous sediment accumulation that extends well into the late Pleistocene. A key obstacle to obtaining long climate records from the region is the difficulty of establishing a robust chronology beyond ~40 ka, the limit of ^{14}C dating. Tephra layers within the Lake Petén Itzá sediments, however, enable development of age/depth relations beyond 40 ka. Ash beds from large-magnitude, Pleistocene-to-Holocene silicic eruptions of caldera volcanoes along the Central American Volcanic Arc (CAVA) were found throughout drill cores collected from Lake Petén Itzá. These ash beds were used to establish a robust chronology extending back 400 ka. We used major- and trace-element glass composition to establish 12 well-constrained correlations between the lacustrine tephra layers in Lake Petén Itzá sediments and dated deposits at the CAVA source volcanoes, and with their marine equivalents in eastern Pacific Ocean sediments. The data also enabled revision of eight previous determinations of erupted volumes and masses, and initial estimates for another four eruptions, as well as the designation of source areas for 14 previously unknown eruptions. The new and revised sedimentation rates for the older sediment successions identify the interglacial of MIS5a between 84 and 72 ka, followed by a stadial between 72 and 59 ka that corresponds to MIS4. We modified the age models for the Lake Petén Itzá sediment sequences, extended the paleoclimate and paleoecological record for this Neotropical region to ~400 ka, and determined the magnitude and timing of CAVA eruptions.

1. Introduction

In the last couple of decades, retrieval of long sediment cores from the Guatemalan lowlands became a major objective for paleoenvironmental and paleoclimatological studies, initially driven by investigations of late Holocene climate change and its implications for ancient Maya civilization (Anselmetti et al., 2007; Brenner et al., 1990; Hodell et al., 2008; Mueller et al., 2010). Seismic images from Lake Petén Itzá, in northern Guatemala, revealed the huge potential for retrieving a very long Neotropical paleoclimate archive (Anselmetti et al., 2006), extending well beyond the purported 36-ka basal age of a core from nearby Lake

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http://dx.doi.org/10.1016/j.quascirev.2016.08.023
0277-3791/

Quexil (Leyden et al., 1993). The Petén Itzá Lake Drilling Project was thus undertaken with support from the International Continental Scientific Drilling Program (ICDP), to explore a longer sediment history from the region. In 2006, >1300 m of lake sediment were collected at seven sites, with the objective of inferring climate and environmental changes on the tropical Yucatán Peninsula through glacial and interglacial times (Mueller et al., 2010; Hodell et al., 2008, 2006).

Several tephra layers in the Petén Itzá drill cores came from large volcanic eruptions of the Central American Volcanic arc (CAVA), and were documented by Mueller et al. (2010) and Hodell et al. (2008). These layers presented the potential to extend the age model for the Lake Petén Itzá sediments much farther back in time. Preliminary correlation of these tephra layers to well-dated, large explosive eruptions of Central American volcanoes was limited to geochemical fingerprinting using only major elements, but lacked confirmation by trace elements. Moreover, early stratigraphic descriptions of the Petén Itzá cores lacked a well-constrained tephrochronology for the deeper parts of the sediment succession.

Here, we establish correlations between the lacustrine ash beds recovered in the Petén Itzá sediments and their source volcanoes, using a complete set of major and trace element compositions. This enabled development of a complete tephro-chronostratigraphy and revised age models for the drill cores, with implications for paleoclimate research in the Neotropics. Our results were used to constrain estimated eruptive volumes for the respective eruptions.

1.1. Lake Petén Itzá sediments and paleoclimate

Lake Petén Itzá (16°55′N, 89°50′W, surface area = ~100 km^2, z_{max} = ~160 m; Hillesheim et al., 2005) is a closed-basin lake located in the Neotropical lowlands of Petén, northern Guatemala (Fig. 1). The Central Petén Lake District consists of a series of lake basins, oriented E-W along *en-echelon* faults (Vinson, 1962). The lakes are located in the south-central area of the climatically sensitive Yucatán Peninsula, which is characterized by steeply increasing northwest-south rainfall and vegetation gradients, making it an ideal region for paleoclimatological and paleoecological studies. Lake Petén Itzáś modern surface lies ~110 m above sea level and its volume changes in response to shifts in the balance between evaporation and precipitation.

The lake sediment cores retrieved in 2006 were initially thought to extend back >200 ka (Mueller et al., 2010) (Fig. 1). A paleoenvironmental study was completed on the younger deposits from the sites and spans the last 85 ka (Hodell et al., 2008); older successions from sites PI-1 and PI-7, which penetrate to 90 and 132 m below lake floor (mblf), respectively, cover a depth not imaged by the seismic surveys (because of limited seismic penetration), had poor age control, and are likely less continuous than the younger sections.

Chronologies from sites PI-6, PI-3 and PI-2 are constrained by 44 AMS-^{14}C dates (<40 ka) on terrestrial organic matter, and six ash beds (>40 ka) (Hodell et al., 2008; Mueller et al., 2010; Escobar et al., 2011) that were correlated to an established late Pleistocene tephrochronology for Central America (Kutterolf et al., 2008a,b) that is based on ^{14}C and Ar/Ar radiometric ages. Using lithologic markers, stratigraphic boundaries, physical properties (magnetic susceptibility and bulk density) and ash beds, site-to-site correlations were established to yield a preliminary age-depth model for the Lake Petén Itzá sediment record (Mueller et al., 2010).

Mueller et al. (2010) characterized seven main sediment types and several sub-types for the sediment succession in the Petén Itzá cores. These sediment types ([A] clastic lacustrine, [B] precipitated, [C] microbial, [D] pyroclastic, [E] clastic terrestrial, [F] karstic/soil, [G] bedrock) were used to divide the sediment record into 11 lithostratigraphic units (Mueller et al., 2010). Ash beds often interrupt the nearly undisturbed sediment successions, and have characteristic grain sizes, colors and internal structures. Nevertheless, in some cases, especially at deep-water sites, down-slope movement and re-deposition of sediments is evident, e.g. in structures within the sediment succession (Mueller et al., 2010), similar to submarine slides along tephra layers at the Central American forearc (Harders et al., 2010; Kutterolf et al., 2008c).

Nine sedimentary units were distinguished by Mueller et al. (2010) in the drilled Petén Itzá sediments, reflecting sedimentological responses to anthropogenic influences in the late Holocene, and climate and environmental changes in deposits extending back ~100 ka. Holocene deposits are composed of laminated montmorillonite-carbonate mud that overlies alternating gypsum-rich and clay-rich carbonate deposits of the last deglaciation (Brenner, 1994; Rosenmeier et al., 2002; Anselmetti et al., 2007). Deeper deposits are likewise composed of alternating gypsum-rich subunits and clay-rich, carbonate sub-units, which reflect relatively drier and wetter conditions, respectively. Bedrock encountered in the shallower drill sites consists of coarse sediments (Basal Gravel Unit) that range from carbonate sand-silt to limestone gravels embedded in a poorly-sorted, carbonaceous sand matrix. At deeper drill sites PI-1 and PI-7, sediments >85 ka were deposited after a hiatus (Unit IX), and are characterized by alternating sediment packages of finely laminated (mm-scale) carbonate-clay mud and homogenous carbonate mud interrupted by turbidites and structurally overprinted by deformation features. Finally, the bedrock at site PI-1 and the material from the deepest holes at site PI-7 represent carbonate lithology.

Paleoenvironmental interpretations of the Lake Petén Itzá sequences, to date, have been largely based on sedimentological and geochemical proxies, but also on pollen analysis (Correa-Metrio et al., 2012). Gypsum units are associated with cold (dry) stadials, especially those containing Heinrich Events, whereas clay units are related to warm (humid) interstadials (Hodell et al., 2008). Therefore, interbedded clay and gypsum deposits at site PI-6 were interpreted to represent alternating humid and dry climate (interstadial-stadial stages: Dansgaard-Oeschger events; Dansgaard et al., 1993), deposited during high and low lake stands, respectively (Hodell et al., 2008). A surprising outcome from this paleoclimate record is the substantial detrital input associated with relatively humid climate conditions and high lake level during the Last Glacial Maximum (LGM, ~23-18 ka), which contradicts previously inferred dry conditions in the lowland Neotropics of Central America during the last glaciation (Hodell et al., 2008; Escobar et al., 2011). Instead, alternating gypsum and clay sediments during the deglacial period (~18-11 ka), deposited when lake level fluctuated between low and intermediate stands (Pérez et al., 2013), seem to reflect the driest episode in this region.

1.2. Central American volcanism, tephrostratigraphy and preliminary correlations to Lake Petén Itzá sediments

The Central American volcanic arc is associated with subduction of the Cocos plate beneath the Caribbean plate since the Early Miocene, at convergence rates of 70–90 mm a^{-1} (Barckhausen et al., 2001; DeMets, 2001). The resulting CAVA extends ~1400 km from Guatemala in the northwest, to Panama in the southeast, and runs roughly parallel to, and 150–200 km landward from the deep-sea trench. Variations in the nature of the incoming plate (Hoernle et al., 2002), in upper-plate crustal thickness and composition (Carr, 1984) and the tectonic setting, are paralleled by along-arc variations in the composition of the volcanic rocks (Carr et al., 2003, 2007; Carr, 1984; Feigenson and Carr, 1986; Hoernle et al., 2008; Patino et al., 1997, 2000) and the maximum observed