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

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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 ¹⁴C 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.

Key words: *ICDP, Petén Itzá, tephrochronology, CAVA, paleoclimate, explosive volcanism*

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 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.

Lake Petén Itzá sediments and paleoclimate

Lake Petén Itzá (16°55'N, 89°50'W, surface area = ~100 km², 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 Itzá's 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 meters 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-¹⁴C 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 ¹⁴C 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 litho-stratigraphic 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.

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 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 magnitude of eruptions (Rose et al., 1999).

During the late Pleistocene and Holocene, arc volcanism formed a number of large caldera volcanoes in the northern sector (Guatemala and El Salvador), which produced numerous, large-magnitude eruptions of highly evolved, mostly silicic magmas (Rose et al., 1999). Ninety-one potentially widespread, well-defined tephra units in the last ~400 ka, of andesitic to rhyolitic composition, that could have impacted the Petén Itzá area, were sourced from the Ayarza, Amatitlán and Atitlán calderas in Guatemala, the Berlin-Chinameca complex, the Ilopango, Apastepeque, Coatepeque, and Ataco calderas in El Salvador, and from larger eruptions of volcanoes in northern Nicaragua (Gonzales Partida et al., 1997; Kutterolf et al., 2008a to d; 2007a; Metzner et al. 2014; Newhall, 1987; Rose et al., 1999; Wundermann and Rose, 1984; Figs. 1 and 2). Using initial provenance studies, and major element compositions (SiO_2 , K_2O , CaO), eruptions of the Atitlán (LCY, WFT; Figs. 1,2) and Amatitlán (LFT, Figs. 1,2) calderas in Guatemala, and Coatepeque Caldera (ACT, CGT; Figs. 1,2) in El Salvador, were suggested as potential sources for some ash beds in the Petén Itzá sediments, probably extending back >191 ka (Mueller et al., 2010; Hodell et al., 2008).

Methods

Sampling and preparation

Detailed descriptions of drilling operations, core recovery and logging are given in Mueller et al. (2010). Cores were split, described and all visible ash horizons (50) were sampled during three sampling efforts between 2007 and 2013 at LacCore, University of Minnesota, Minneapolis (USA). Identification of ash beds was confirmed with smear slide observations. The sampled ashes were sieved and separated with pure water into fractions of 32-63 μm , 63-125 μm and >125 μm , and subsequently embedded with epoxy resin into acrylic tablets with 12 pre-

drilled holes and polished for electron microprobe (EMP) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) analysis. Correlative samples from terrestrial deposits were sampled and analyzed in previous studies and the sampling and preparation procedures are described in Kutterolf et al. (2008a).

Analytical techniques

Glass shards from Petén Itzá ash beds were analyzed by EMP (JEOL JXA 8200 wavelength dispersive electron microprobe at GEOMAR, Kiel, Germany) for major and minor elements following Kutterolf et al. (2011). Basic settings for conducting analyses included: (1) a calibrated measuring program based on international standards, cross-checked by repeated analysis (every 60th single-shard measurement) of well-known natural standards (e.g. *Lipari*; Hunt and Hill 2001), which yielded a deviation of <0.5% for major and <3% for minor elements, (2) a constant accelerating voltage of 15 kV, and (3) a beam defocused to 5 μm , and a beam current of 6 nA for felsic glasses and 10 nA for mafic glasses. All analyses were normalized to 100% to eliminate the effects of variable post-depositional hydration.

Trace element concentrations of glass shards were analyzed by LA-ICP-MS. At the Helmholtz Centre for Ocean Research (GEOMAR), Kiel, Germany, we used in February 2012 a 193-nm Excimer laser ablation system (Coherent, GeoLasPro) coupled to a double-focusing, high-resolution magnetic sector mass spectrometer (Nu Instruments, AttoM) in low resolution mode (300 Res, 10% valley definition). Ablation was done under He carrier gas, with additional Ar carrier gas mixed in prior to the plasma torch. Spot analyses were done by 40-60 s ablation at a laser repetition rate of 5 Hz using spot diameters between 16 and 44 μm and a fluence of 5 J cm^{-2} . Fifty seconds of gas background data were collected prior to each ablation. NISTSRM610 was used for calibration and a MPI-DING glass standard (ATHO-G) as reference material. Element concentration calculations were performed applying the linear regression slope method

(Fietzke et al., 2008). Silicon was used for internal standardization utilizing pre-analyzed data from EMP analyses.

The second set of samples was analyzed in October 2015 at the Institute of Earth Sciences, Academia Sinica in Taipei, Taiwan, which is equipped with a Photon Machines Analyte G2 laser ablation system (Photon Machines, Inc., Redmond, USA) and a New Wave UP213 laser ablation system, both attached to a magnetic sector ICP-MS (ThermoFinnigan Element XR). The Photon Machines Analyte G2 laser ablation system utilizes a 193-nm ArF Excimer laser with 5-ns pulse duration. The New Wave laser ablation system utilizes a 213-nm ArF Excimer laser with 5-ns pulse duration. The instruments feature a HelEx two-volume ablation cell that provides aerosol washout times of <10 s for a signal drop of three orders of magnitude. The carrier gas that transported the ablated sample from the ablation cell was mixed with the Ar gas flow prior to arriving at the plasma torch. Spot analyses were done using a spot diameter of 16-30 μm , at energy densities of 7 J cm^{-2} and 5 Hz repetition rate. International standard glasses (USGS BCR-2G, NISTSRM612, NISTSRM611) were measured every twelve samples to monitor accuracy. Silica and calcium concentrations, measured by EMP, were used as internal standards to normalize the trace element analyses. Average compositions and raw data of Petén Itzá ash beds are given in Supplementary Table 1 and 2. Average precision and accuracy were <10% for most elements. Further descriptions of the LA-ICPMS analytics and a detailed evaluation of the standard deviations are given in Supplementary Table 3 and in Kutterolf et al. (2014).

Major and trace element data acquired by Kutterolf et al. (2008a) characterize the proximal and marine tephras from Central American plinian eruptions, potentially correlative to the Petén Itzá tephras. Published and unpublished data from older Central American eruptions, and marine tephras found in the Pacific (Kutterolf et al. 2008a) are shown in Supplementary Table 4.

Correlation techniques

Ash layer correlations are based on modal and chemical compositions, assisted by structural and textural characteristics of the pyroclasts and stratigraphic relationships. We determined the

shape, vesicularity and vesicle texture of glass shards and pumiceous fragments, as well as the petrography of the ash layers/beds in smear slides under the microscope (Supplementary Table S1). Such observations support correlations, whereas glass chemical composition proved to be the most distinctive and useful characteristic. For each of the Lake Petén Itzá ash layers, 20 EMP analyses and 2-11 LA-ICP-MS analyses of individual glass shards in each sample were carried out. Correlations to eruptive events from the CAVA were based on the glass compositions of the tephra obtained from known CAVA eruptions, which were determined using at least 30 EMP and 5-10 LA-ICP-MS analyses per correlative CAVA tephra layer (Kutterolf et al., 2008a).

Results

General description of Petén Itzá ash beds/layers

We use the term “ash bed” to define a bed or zone in the drilled sediment that is predominantly composed of volcanic ash and found in only one hole. Ash beds that are correlated across different holes at a site or across sites and/or with tephra on land, represent a “tephra layer” (CP1-19). Thus, a tephra layer represents a single volcanic eruption, but it can include multiple ash beds that occur in several holes or sites.

The Lake Petén Itzá sediments contain 48 distinct primary ash beds, ranging in thickness from 0.3 to 24.0 cm (Fig. 3). Glass shard compositional heterogeneities revealed that two potential ash beds were in fact reworked volcanoclastic sand layers. Overall, 33 (69%) are light gray to white felsic ashes, five (10%) are gray ash beds of intermediate composition and ten (21%) are black ash beds of mafic composition. The latter ones compare well with the 20% of widespread mafic ash beds found offshore of El Salvador and Guatemala, in the Pacific (Kutterolf et al., 2008a). Overall, the chemical composition of the analyzed glass shards encompasses basaltic andesite to rhyolite (Fig. 4) and can be associated with different compositional groups in a potassium-versus-silica diagram, following Kutterolf et al. (2007b).

Sediment underlying some ash beds is discolored and hardened, probably reflecting diagenetic interaction of silica or carbonate derived from the ash bed with the background lake sediment. Unconformable and/or inclined bedding of ash beds, caused by erosion, creep or slumping of sediment is rare (Fig. 3A-L). In general, ash beds have a sharp basal contact with underlying lacustrine sediments, but often show normal gradation in grain size and a several-cm-thick gradual transition into the overlying sediment (Fig. 3A,C,F,L).

Felsic ash beds are dominated by transparent volcanic glass with rare but persistent occurrences of plagioclase, plus traces of amphibole, biotite, and quartz. The glassy component is predominantly composed of dense, blocky and commonly cusped, non-vesicular shards, with a fraction of pumiceous particles with elongated and tubular vesicles (Fig. 3M, Supplementary Table 1). Cusped glass shards (Fig. 3N,O) predominate in ash beds 1B-15H-2, 77.2-78.2 cm, 1B-20H-3, 51-60 cm, 1C-21H-1, 131-139 cm, 2C-9H-1, 112.5-114 cm, 6A-24E-2, 48.2-49.2 cm, and 6C-17E-2, 20.7-21.7 cm, and are accompanied by common tubular, vesicular, pumiceous clasts (Supplementary Table 1). The plagioclase, pyroxene, and spinel-bearing mafic ash beds contain a mixture of predominantly blocky, brownish, glass shards and common scoriaceous clasts, with moderate vesicularity and mostly rounded and elliptical bubbles (Fig. 3P-R; Supplementary Table 1). Some mafic ash beds, however, also contain highly vesicular, tubular, brownish glass shards. Median grain sizes in the ash beds range from coarse silt to medium sand, i.e. 32 to 250 μm .

Correlations

Correlations between the 48 lacustrine ash beds of different holes and sites, and to their proximal parental tephra deposits and source volcanoes, are based mainly on glass chemical composition (Figs. 5 and 6), but also rely on modal, lithological and textural observations. Figures 5A to F show examples of glass chemical variation diagrams (major elements; e.g., K_2O

or CaO or TiO₂ or MgO versus SiO₂, K₂O and FeO_t versus CaO), which were most useful for chemical correlation. Because of the wide range of differentiation grade, separate panels were created to show mafic and felsic compositions (mafic in Figs. 5E, F). Diagrams using trace elements and their ratios complement these plots (Figs. 6A to D; e.g. Zr/Nb versus Ba/La, La/Yb or Rb versus Ba/Zr, Zr/Nb versus Ba/Th) to further distinguish tephras and establish robust correlations. Additional diagrams are given in Fig. S1.

Compositional variations of analyzed ash beds are indicated in the figures by grey bars (lacustrine ash beds) or compositional fields (proximal deposits). These variations may stem from primary heterogeneity of the eruption products (e.g. zoned magma chambers, Novarupta 1912; Federman and Scheidegger 1984), incomplete mixing of new magma batches into the magma chamber, or compositional segregation with distance (e.g. Toba eruption, Matthews et al. 2012).

We confirmed the presence of 19 tephra layers through correlation of 41 individual ash beds in the Lake Petén Itzá sediment, either between different holes and sites, and/or to their respective eruption from the source volcano or region (Table 1). Below, these correlated lacustrine tephra layers are labeled CP1 through CP19 (CP= Correlations **P**etén Itzá) in stratigraphic order from young to old. Seven ash beds remain uncorrelated.

Tephra-layer correlation between holes and sites

Fifteen hole-to-hole and site-to-site correlations were established among six drill sites and 15 drill holes. Ash beds from two (PI-7) or three (PI-1, -2, -3, -6) drill holes provided the tie lines required to generate a complete sedimentation history for each site and define composite sections; only site PI-4 had a single drill hole (Supplementary Table 1). More important in terms of paleoclimate and paleoecology research are the correlations between sites, because such correlations link the different sedimentary environments of the lake to one another. Using the

chemical discrimination diagrams in Figures 5 and 6, along with Supplementary Table 1 and Figure S1, CP1 (PI-2, -3, -6), CP2 (PI-2, -3, -6), and CP5 (PI-1, -2, -6) can all be correlated across three sites, and CP3 (PI-3, -6), CP4 (PI-2, -4), CP6, and CP8 to CP10 (PI-1, -6) can be correlated across two sites (Table 1). With the exception of Site PI-7, all sites drilled in Lake Petén Itzá can be linked to one another by at least one tephra layer.

Ash-layer correlations to specific eruptions

Using data from the literature (Kutterolf et al., 2008a; Rabek et al., 1985; Gonzáles Partida et al., 1997) and our own unpublished data, we were also able to establish correlations to specific eruptions from the CAVA by chemical fingerprinting. This enabled us to use the known eruption ages to develop the Petén Itzá sediment chronology. Additionally, these correlations to CAVA eruptions provided new distal outcrops for estimating their respective eruptive volumes. When possible, these correlations were supported by modal, lithological and textural observations. In summary, we were able to correlate 19 ash beds in the lake sediment to 10 distinct eruptions (CP4, CP5, CP7 to CP11, CP13, CP18, CP19). Three additional lacustrine ash beds were correlated to two widespread marine tephra layers found in Pacific sediments (CP6 and CP15). In the following section, we discuss the correlations according to the source volcanic centers, in geographic order from north to south.

Atitlán Caldera

The Atitlán Caldera (Guatemala), ~300 km from Lake Petén Itzá (Fig. 1), formed during three major caldera-forming events within the last ~13 Ma (Rose et al., 1987). The latest Caldera stage (Atitlán III) comprises young deposits D-Fall, F-Fall, and I-Fall (Rose et al., 1987; Fig. 2), the W-Tephra (WFT; containing Fall and Flow units; 158 ± 5 ka, Ar/Ar sanidine age, Rose et al., 1999), and the deposits of the ~84 ka Los Chocoyos Tephra (LCY; fall and flow units; Kutterolf

et al., 2008a). Major element analyses initially suggested that LCY reached the Petén Itzá area (Mueller et al., 2010; Hodell et al., 2008). Using the entire compositional data set of major and trace elements (Figs. 5 and 6, Supplementary Tables 1 and 2, Fig. S1), as well as textural observations (e.g., very characteristic, predominantly cusped and disc-like glass shards) we correlated LCY to CP10 (1-9-cm-thick ash beds in sites PI-1 and PI-6) and also found a correlation to the WFT eruption, represented by two 8-12-cm-thick ash beds of CP11 at Site PI-7. Both CP10 and CP11 are found in the Pacific (Kutterolf et al. 2008a; Drexler et al., 1980; Ledbetter, 1985), but also in the Gulf of Mexico (Rabek et al., 1985; “Y8, D Ash layer” and “W1 Ash layer” - Supplementary Table 4).

Amatitlán Caldera

A sequence of eight tephra deposits (Fig. 2) was identified around Guatemala City by Wundermann and Rose (1984), which originated at the Amatitlán Caldera (Fig. 1). So far, only the 191 ± 11 ka L-Tephra (LFT) was correlated, using major elements, to one tephra bed in PI-1 (Mueller et al., 2010). Here, tephra layer CP13, 10-27 cm thick, is found as individual ash beds in all three holes of site PI-1 and confirms the correlation with LFT, using trace elements (Figs. 5 and 6; Supplementary Tables 1 and 2 and Fig. S1). Additionally we identified corresponding ash beds in the Pacific (Kutterolf et al., 2008a) and the Gulf of Mexico (Rabek et al., 1985; W2 Ash layer; Supplementary Table 3) using compositional data. The glass shards are characteristically highly vesicular and have a tube pumice texture in both the corresponding marine and lacustrine ash beds.

The proximal deposits of the E-Tephra (EFT), estimated to have erupted ~50 ka ago (Kutterolf et al., 2008a) from Amatitlán, occur as a coarse, reversely graded white pumice-fall deposit (Wundermann and Rose 1984). By its compositional fingerprint, it can be traced into the Pacific (Kutterolf et al., 2008a) and correlates to two thin ash beds (0.2, 0.6 cm), in Sites PI-2

and PI-3, representing our CP4 (Figs. 5 and 6, Supplementary Tables 1 and 2, Fig. S1). Additional comparison to data of Rabek et al. (1985; “Y5 Ash layer” - Supplementary Table 4) suggests that this eruption also delivered its products into the Gulf of Mexico.

Coatepeque, and Concepción de Ataco Calderas

In northern El Salvador, several nested calderas produced large explosive eruptions in the Pleistocene (Figs. 1 and 2). Only the youngest one, the Coatepeque Caldera, has been studied and dated in detail (Rose et al., 1999; Kutterolf et al., 2008a). It revealed a tephra succession of four eruptions within the last 77 ka. Silicic activity at Coatepeque Caldera began with the Bellavista eruption at 77 ± 2 ka, followed by the eruptions of the 72 ± 3 ka Arce Tephra, the 53 ± 3 ka Congo Tephra and the ~ 51 ka Conacaste Tephra (Ar/Ar sanidine ages and ^{14}C ages; Rose et al., 1999; Kutterolf et al., 2008a).

The largest deposit of the Coatepeque Caldera is the 72 ± 3 ka (Rose et al., 1999) Arce Tephra (ACT), including plinian fall beds and ignimbrites that are also found in marine sediments offshore of El Salvador (Kutterolf et al., 2008a). In contrast to Mueller et al. (2010) and Hodell et al. (2008), who suggested a correlation of only two ash beds in PI-1 and PI-6 to ACT, we are now able to distinguish between a 1.4-2.5-cm-thick lower, and a 0.3-0.4-cm-thick upper Arce tephra layer, associated with CP8 and CP9, respectively (Figs. 5 and 6, Supplementary Table 1 and 2, Fig. S1). The 53 ± 3 ka Congo Tephra (CGT) is a complex succession of plinian fall, ignimbrite and surge deposits, with highly vesicular pumice clasts in the proximal area as well as characteristic angular and cusate glass shards in distal marine deposits of the Pacific (Kutterolf et al., 2008a). We chemically correlated 1.3- to >2 -cm-thick tephra layer CP5 in sites PI-1, PI-2, and PI-6 with CGT (Figs. 5 and 6; Supplementary Table 1 and 2, Fig. S1). These correlations are supported by textural observations (predominantly cusate glass shards). Comparison to major element data of Rabek et al. (1985; “Y6 Ash layer” - Supplementary Table 4) suggests that the

Congo eruption also delivered its pyroclasts into the Gulf of Mexico, although this correlation lacks trace element fingerprinting.

The older explosive history in this region is not well documented. González Partida et al. (1997) provided an overview for the Plio-Pleistocene volcanic history of the Concepción de Ataco Caldera, including a ~400-ka-long series (Siebert et al., 2010; González Partida et al., 1997) of fallout (i.e. Lower, Middle, and Upper Ataco tephra) and several flow units (e.g., Chilamatal Ignimbrite), which we sampled during fieldwork in 2009 and 2013. The 5.5-cm-thick CP18 corresponds to the thickest and lowermost pumice layer, the Lower Ataco tephra. Additionally, the 5-cm-thick tephra layer CP19 correlates to the widespread Chilamatal Ignimbrite. Stratigraphic relationships in the proximal area are not well constrained, but the stratigraphic succession in Hole A of Site PI-7 clearly shows that the Chilamatal Ignimbrite is older than the Ataco Pumice layers.

Cosigüina Caldera

Cosigüina Peninsula at the Gulf of Fonseca is the northernmost volcano of Nicaragua (Fig. 1). In addition to its famous Plinian eruption in AD 1835 that was studied in detail by Self (1989), Scott et al. (2006) and Longpré et al. (2014), mafic and felsic fall deposits of older, undated eruptions have been observed and sampled during our fieldwork in 2002 and 2003. Although the thick lower and upper Cosigüina Pumice layers (LCO and UCO, Fig. 2) appear to be widespread plinian deposits, only a mafic tephra (MCO1) can be correlated to marine tephra in nearby Pacific sites by chemical fingerprinting (Kutterolf et al., 2008a). Nevertheless, compositional data provided for these older deposits by Kutterolf et al. (2008a) facilitate the correlation of the lower Cosigüina tephra layer to a 1.2-cm-thick lacustrine tephra layer CP7 in the sediments of Site PI-1 (Figs. 5 and 6, Supplementary Tables 1 and 2, Fig. S1).

Correlation to tephra layers in the Pacific Ocean

We also established a compositional correlation (CP6 in Figs. 5 and 6) between two 1.5- to 1.8-cm-thick mafic ash beds in PI-1 and PI-6 and a ~55-ka-old mafic marine tephra layer presented in Kutterolf et al. (2008a,c) and summarized therein as their marine correlation “C24” (Figs. 5 and 6, Supplementary Tables 1 and 2, Fig. S1). Additionally, correlation CP15 (labeled AOT in Figs. 5 and 6) can be made between a 5-cm-thick ash bed in PI-7 and a ~306-ka-old marine tephra layer (“C26”; Kutterolf et al., 2008a,c) in Pacific cores offshore of Guatemala (Figs. 5 and 6, Supplementary Table 1, Supplementary Fig. 1).

Tephra-layer correlations to source volcanoes and along the arc

Seven felsic and mafic ash beds and eight tephra layers (CP1-3, CP6, CP12, CP14, CP16, and CP17; Fig. 5 and 6) in the Lake Petén Itzá sediments cannot be correlated with individual source tephras. Further constraints on the source regions for these tephra layers and ash beds, however, can be achieved by comparison with systematic along-arc variations of bulk-rock and glass trace-element characteristics (Fig. 7; see supplement for methods) of the Central American (CENTAM data base; Carr and Rose, 1987; Carr et al., 2003, 2007; Patino et al., 2007) and Mexican (MEXPET data base; Luhr et al., 2006) arc rocks, valid for both, felsic and mafic tephras (Kutterolf et al., 2015). We therefore plotted glass compositions of the eight tephra layers and seven ash beds in Fig. 7 by projecting the Petén Itzá location onto the arc, along the subduction vector (see supplement methods). If the along-arc comparison is ambiguous, we favor the source area closest to Lake Petén Itzá.

CP1 and CP3 (low Ba/Zr, La/Yb and Rb/Hf; intermediate U/Th) are derived from a source ~320 km along the arc, in northern El Salvador (Fig. 7, Table 1, Supplementary Table 1 and 2, Fig. S2). Stratigraphic position below ~50 ka EFT (CP4) and 53 ka CGT (CP5), as well as the

mafic composition of CP1 and CP3, further suggest St. Anna Volcano in North El Salvador (319.4 km) as a possible source volcano. From our field observations, it is the only candidate in the area that features thicker (1-2 meter) mafic deposits in the proximal area within the last 50 ka, that potentially was transported into distal regions.

CP6, hereafter referred to as Old Pacayal tephra (OPT), was also correlated with marine cores in the Pacific (Kutterolf et al. 2008a) and displays unique trace element ratios that match exclusively to a region 450 to 470 km along the arc in southern El Salvador, equivalent to either the Pacayal or San Miguel volcano. Our field work in the proximal area indicated numerous outcrops that contain thick pyroclastic sequences that may correlate to this tephra layer, but hitherto these mafic sequences were not characterized compositionally or stratigraphically. Surprisingly, we can also establish a correlation (CP12; PI-7) to the Nicaraguan Masaya/Las Sierras caldera system, ~740 km along the arc, which also has a unique compositional signal (very high Ba/La, Ba/Th, U/Th; Fig. 7, Supplementary Table 1 and 2, Fig. S2), reflecting the increased involvement of slab fluids because of a steep subduction angle (e.g. Carr et al. 2007; Kutterolf et al., 2007a, 2008a, 2015).

The remaining seven uncorrelated Petén Itzá ash beds and tephra layers CP2, CP14, CP16, and CP17 can be assigned to either a southern (~-300 to -450 km) or central (-600 to -700 km) Mexican volcanic provenance (high La/Yb, low to medium Ba/Zr, U/Th, Rb/Hf), or to an origin from northern Guatemala, most probably a pre-Atitlán-III caldera phase (Fig. 7, Supplementary Table 1 and 2, Fig. S2). Further discrimination is, so far, not possible because of the lack of information for these older tephra sequences.

Discussion

New and extended age models for Lake Petén Itzá sediments

In addition to errors associated with the dating methods (e.g. excess argon and ^{14}C reservoir effects) one key problem for developing long-term paleoclimate records is the limitations of the methods (radiocarbon dating <50 ka, quantity and quality of datable material for Ar/Ar analysis). Tephra layers within the Lake Petén Itzá sediments now provide excellent age constraints for deposits well beyond 50 ka. We used robust correlations between tephras in Lake Petén Itzá and radiogenically dated proximal deposits at the CAVA source, as well as their tephras in sediments of the Pacific Ocean, to constrain time markers >40 ka and formulate new Petén Itzá sediment age/depth models. As a novel and key outcome of this study, the age range in our cores now extends to ~400 ka, the time marked by the distal ash of the Lower Ataco Tephra (ACT3; Fig. 2; Fig.8), thus effectively doubling the previously assumed maximum age of ~200 ka (Hodell et al., 2008; Mueller et al., 2010). Additionally, the ages of nine, still undated tephra layers (CP1, CP2, CP3, CP7, CP12, CP14, CP16, CP17, CP19) and seven single ash beds were estimated. Previous age estimates (Kutterolf et al. 2008a) for two more tephra layers (CP4, CP6), based on marine sedimentation rates offshore of Guatemala, were revised using their relative positions between known time markers and linear interpolation, and assuming that sedimentation rate remained constant within the intervening time interval (Fig. 8).

PI-1 contains the 191 ka L-Fall Tephra (CP13), the 84 ka Los Chocoyos Tephra (CP10), the 72 ± 3 ka Arce tephras, and the 53 ± 3 ka Congo Tephra (CP5) as well-dated horizons (Fig. 8). The tephras were used to calculate sedimentation rates for the lower sediment succession. The rates are low ($13.5 \text{ cm k.y.}^{-1}$) between 72 and 50 ka (43 – 40 mblf), but much higher ($\sim 88 \text{ cm k.y.}^{-1}$) between 84 and 72 ka, after having been relatively constant ($\sim 24 \text{ cm k.y.}^{-1}$) from the beginning of the sediment succession at ~90 mblf (~225 ka). Using the depth of tephra layer CP7 in this site and the determined sedimentation rates enabled us to estimate an age of ~62 ka for the Lower Cosigüina eruption. CP6, estimated to be ~55 ka old from its occurrence in Pacific marine cores offshore of Central America (Kutterolf et al. 2008a), was confirmed to have an age of 59.3 ka using the Petén Itzá sedimentation rates.

The previously estimated age of CP6 (~ 55 ka based on its occurrence in Pacific marine cores offshore of Central America; Kutterolf et al. 2008) is consistent with our new estimate of 59 ka from the Petén Itzá sedimentation rates. Sedimentation rates in the short time interval spanning CP6 and CP7 were low. Therefore the new age estimates provide good first-order approximate values, since higher sedimentation rates during longer time intervals may be more variable, and consequently introduce larger errors into the age estimates.

Shallower drill sites PI-2 (62 mblf) and PI-3 (52 mblf) possess a high number of ^{14}C ages (Mueller et al., 2010) that constrain the age models in Figure 8. They also contain the 53 ± 3 ka Congo Tephra (CP5) and the ~51 ka E-Fall Tephra (CP4). The latter age, derived from marine sedimentation rates in the Pacific (Kutterolf et al. 2008a), is consistent with that estimated here using Petén Itzá sedimentation rates (49 ka). Sedimentation rate at PI-2 is relatively high near the base (~200 cm k.y.⁻¹), whereas accumulation rate in the bottom part of PI-3 is relatively constant, at ~87 cm k.y.⁻¹. Between ~38 and ~25 ka, sedimentation rates at both sites were fairly constant, between 60 and 80 cm k.y.⁻¹. The age models for both sites show relatively high sedimentation rates (PI-2 = 129-260 cm k.y.⁻¹; PI-3 = 94-199 cm k.y.⁻¹) in the last 25 ka. Lower sedimentation rates were, however, recorded between 11 and 6 ka, with values of 14 cm k.y.⁻¹ (PI-2) and 46 cm k.y.⁻¹ (PI-3), respectively.

Well-dated tephtras from site PI-6 are the 84 ka Los Chocoyos Tephra (CP10), the 72 ± 3 ka Arce tephtras, and the 53 ± 3 ka Congo Tephra (CP5). The younger sediment sequence is also well dated by numerous ^{14}C dates (Mueller et al., 2010). Consequently, the age model is very well constrained and starts with a high sedimentation rate of ~123 cm k.y.⁻¹ from the bottom of the record at 72 mblf (84 ka). Similar to PI-1, sedimentation rate drops to ~16 cm k.y.⁻¹ between 72 ka and 60 ka (55 mblf), then remains constant at ~80 cm k.y.⁻¹, from ~60 to 20 ka (~20 mblf). Likewise to PI-2 and PI-3, the sedimentation history is then characterized by high sedimentation rates of ~185 to 265 cm k.y.⁻¹ in the last ~20 ka of the record, with the same shift to lower sedimentation rates (~66 cm k.y.⁻¹) between ~13 and ~5 ka (Fig. 8). The age of CP6, determined

from the Petén Itzá sedimentation rates (59.3 ka) is close to that estimated from marine sedimentation rates (~55 ka), and is in almost perfect agreement with the age of CP6 in the core from site PI-1 (59.4 ka).

The longest and oldest drilled sediment record is from site PI-7 and contains the ~400 ka Lower Ataco Tephra (CP18), the ~306 ka “old” Atitlan Tephra (CP15), the age of which was determined by marine sedimentation rates, and the 158 ± 3 ka WFT (CP11) as age markers (Fig. 8). In the absence of ^{14}C ages for the younger sediments, sedimentation rates were calculated only for the lower sediment succession. From the last age tie point of ~306 ka (CP15) at 103.6 m, derived from a lacustrine/marine correlation, until 75 mblf, where the 158 ka old WFT tephra (CP11) was found, sedimentation rates, assuming they were constant, were on average 19.5 cm k.y.^{-1} . Extrapolation of this sedimentation rate to the bottom of the hole revealed the oldest tephra layer (CP19) at ~126 mblf has an age of ~406 ka. Applying this sedimentation rate also to CP18, correlated to the ~400 ka old Lower Ataco eruption (González Partida et al., 1997), reveals an age of 400.5 ka.

Using the new age models for PI-1, PI-2, PI-3 and PI-6, ages of ~49 ka for EFT (CP4) and ~59 ka for OPT (CP6; 59.4 ka at PI-1 and 59.3 ka at PI-6) were estimated and support the preliminary age estimates presented by Kutterolf et al. (2008a), of ~51 and ~55 ka, respectively. The consistent ages derived for OPI (CP6) at two different site locations, and therefore different depositional environments, and the fact that both the CP6 and CP15 ages are supported independently by marine ages, suggest that sedimentation rates, at least in Lake Petén Itzá, can be used to determine the eruption ages for as yet undated tephtras.

Using linear interpolation, we can also estimate the length of time between deposition of the Lower and Upper Arce ash layers (CP8 and CP9) in the Petén Itzá sediments at sites PI-1 and PI-6 and therefore the time interval between the two eruptions. Assuming constant sedimentation rate between the two ash layers at each site, the intervening lake mud interval between CP8 and CP9 of 3.2 cm at PI-1 and 4.2 cm at PI-6 would represent time intervals of ~460 and ~120 years,

respectively, between eruptions. The difference may be a consequence of different local depositional conditions or different amounts of reworked, dispersed ash that was incorporated into the background sediment immediately after the eruptions. Nevertheless, it provides possible time ranges for the interval between the eruptions, which cannot be resolved by radiometric age dating, given the typical errors on such dates (e.g. 72 ± 3 ka for Arce given by Rose et al., 1999).

Age models for the several Petén Itzá drill sites show similar sedimentation rate trends through time. Before rapid erosion of the “Maya Clay” led to high sedimentation rates, particularly between 3 and 1 ka, lower sedimentation rates were recorded between ~13 and ~6 ka in PI-2, PI-3 and PI-6, and may represent a tropical response to the aftermath of a stadial that corresponded to the time of the Younger Dryas (Fig. 9). A short, 4-ka period of higher sedimentation rates at sites PI-2 and PI-6, between 17 and 13 ka, is not observed in PI-3. This may be a consequence of limited ^{14}C samples, which preclude high-resolution estimation of sedimentation rates, or spatial differences in sedimentation, which reflect the shallow locations of sites PI-2 and 6 (high gypsum sand sedimentation), versus the deeper and more central location of Site PI-3 (less gypsum sand, but more clay) to the west (see Figure 1 in this manuscript and Figure 3 in Mueller et al., 2010). The same effect may be responsible for the short pulse of high sedimentation between 40 and 38 ka in PI-2, if the ages are correct. Another shift in sedimentation rate is observed between ~72 and ~59 ka and coincides with cold Marine isotope stage 4 (MIS4), inferred by Mueller et al. 2010 to have been a time of fluctuating lake level, perhaps causing lower sediment accumulation (Fig. 9). Earlier high sedimentation rates, between 84 ka and 72 ka, correspond to a warmer interglacial (MIS5). Below that, sedimentation rates were relatively constant at both deeper sites (PI-1, PI-7), amounting to ~19 to 24 cm k.y.⁻¹, similar to the sedimentation rates recorded during earlier glacial times (e.g. PI-1, 2, 6).

Tephro-chronostratigraphy for Lake Petén Itzá sediments

The entire Lake Petén Itzá tephro-chronostratigraphy, compiled for each drill site from established hole-to-hole and site-to-site correlations, and the resulting age constraints from lacustrine to proximal tephra correlations, is summarized in Fig. 10. The new correlations produce more detailed stratigraphic links and time markers between the successions than before, yielding a consistent tephro-chronostratigraphy for the entire Petén Itzá area. Well correlated tephra layers CP1, CP2, and CP5, and to some extent CP3, CP4, CP6, CP8, CP9, and CP10, facilitate widespread correlations between sites and the projection of time lines down to 84 ka in the drill cores from Lake Petén Itzá, enabling construction of a stratigraphic framework for paleoclimate research. Established correlations in PI-7 (CP11, CP15, CP18) and PI-1 (CP13) to older Central American eruptions allow the extension of the paleoclimate archives to ~400 ka and >191 ka, respectively.

Recalculated eruptive volumes and masses for Central American tephras

We used the correlated tephra layers to extend published isopach maps from proximal and marine areas (González Partida et al., 1997; Kutterolf et al., 2008b; Rose et al., 1987; Wundermann and Rose, 1984; Ledbetter, 1985), in some cases for the first time, to better constrain erupted volumes of the widespread tephra layers and estimate the magnitudes of the large eruptions that occurred at the CAVA during the past 400 ka (Fig. 11). Because distal thickness data are sometimes sparse, the shape of the distal isopachs can only be estimated crudely, which introduces significant error into the volume calculations (Klawonn et al., 2014). If less than 20 data points were considered, errors may be >10 % (Engwell et al. 2013), but it is the only way to obtain a first-order estimate of minimum eruptive volume. Fortunately, isopachs of only five of the eruptions are based on <10 data points and the previously published proximal and distal isopachs for all other deposits are based on 50-238 data points (Koch and McLean 1975; Kutterolf et al., 2008b; Ledbetter 1985; Rabek et al. 1985; Rose et al. 1987; Wundermann and Rose 1984).

The environment in the lowlands of Guatemala is different from that in volcaniclastic-dominated lakes near hilly or mountainous terrains like the Andes or cryptotephra-rich lake sediments very distant from the volcanic source, which are often prone to extensive reworking and erosion (Bertrand et al. 2014; Pyne-O'Donnell, 2011). This and 100% pure glass shard chemistries in the analysed, macroscopically visible ash beds precludes substantial reworking or gain of material within the studied ash beds. If at all, ash bed thicknesses vary locally and only slightly among sites and holes at Petén Itzá, and are typically complete and display normal gradation from a medium ash into volcanic dust that is incorporated into the background sediment (Fig. 3). Often a single ash bed per tephra layer provides the complete thickness, which is then used as thickness of the deposit. If all ash beds show incomplete thickness, we used the thickest value as the preferred isopach thickness, if an increase in thickness from secondary flow processes could be ruled out.

Approximations of total tephra volumes are obtained by using the exponential decay model and fitting straight lines to data on plots of $\ln$ [isopach thickness] versus square root [isopach area], following Pyle (1989) and Fierstein and Nathenson (1992), and integrating to infinity. In most cases, the data required two straight-line segments to fit proximal to medial and distal data, separately. We used the point of intersection of these line segments to distinguish between the volume contributions from proximal to medial and distal facies.

Several models are introduced to better estimate tephra volumes from sparse data. For example, Green et al. (2016) applied a Bayesian statistical approach on sparse proximal and distal deposits and Sulpizio (2005) presented and tested three empirical methods to calculate distal tephra-fall volumes; all of them are compared, tested or partly incorporate the model of Legros (2000). With ash distributions constrained by <10 data points, we followed Legros (2000) to test the possible error with sparse data (<10 data points; LCO, AOT, AC3, CMT), and used this simple model that yields minimum estimates. Applying Legros (2000), we calculated a minimum tephra volume by assuming the thickness at the farthest site lies on the dispersal axis,

constructing a tear-drop shaped isopach with aperture angles of 30°, 45°, and 60° (average angles for Pleistocene eruptions; e.g. Kutterolf et al. [2007a, 2008b]), and accounting for exponential thickness decrease.

We subsequently used the approach of Kutterolf et al. (2008b) to convert tephra volume to magma mass over proximal to medial and distal regions, using measured densities of 600 kg/m³ for felsic and 800 kg/m³ for mafic proximal tephra, and 2100 kg/m³ for felsic and 2400 kg/m³ for mafic distal ash beds. These values account for a reduction caused by inter-particle pore space, i.e. space between pumice clasts or glass shards, and lithic contents, and an increase caused by gradation of ash beds into the background sediment.

Isopach maps and ln (thickness) versus square root (isopach area) variations are shown in Figures 11 and 12. Single tephra volumes and respective maximum distribution areas are summarized in Table 1. The calculated volumes and masses of each tephra are discussed below from north to south, with respect to the source volcanic centers and previous estimates, and represent minima if distal outcrops are limited to the Petén Itzá area only; masses are also given in volumetric dense rock equivalents (DRE).

Apart from providing first estimates for the 306 ka “Old Atitlán Tephra” (1.9 x 10⁵ km² area, 93 km³ tephra volume; 65 km³ DRE; ~1.4 x 10¹⁴ kg erupted magma mass), we revised previous estimates of erupted masses and volumes for WFT and LCY using the distal outcrops at Petén Itzá (CP10, CP11, CP15) and data from offshore of Guatemala in the Pacific Ocean (Drexler et al., 1980; Bowles et al., 1973; Ledbetter et al. 1985; Kutterolf et al. 2008a,b) and Caribbean Sea (Rabek et al., 1985; Figs. 11 and 12, Table 1). Previous volumes and mass estimates of WFT and the LCY eruptions (WFT: 23.3 km³ tephra, 16 km³ DRE, ~3.3 x 10¹³ kg; LCY: 593 km³ tephra, 280 km³ DRE, ~4.6 x 10¹⁴ kg; Kutterolf et al., 2008b) increase by a factor of 6.5 and 1.9, and yield erupted tephra volumes of 151.5 km³ and 1108 km³ (82.5 km³ DRE and 511 km³ DRE) or ~1.7 x 10¹⁴ kg and ~1.3 x 10¹⁵ kg magma mass, respectively, corresponding to a tephra distribution of the 3-cm isopach to areas of ~1 x 10⁶ km² and ~6.2 x 10⁶ km², respectively

With the correlations (CP4, CP13) to EFT and LFT from the Amatitlán Caldera in Guatemala, complemented by correlations to tephra layers in cores from the Gulf of Mexico (Rabek et al., 1985), we revised the distribution area (LFT: $7 \times 10^5 \text{ km}^2$; EFT: $6.3 \times 10^5 \text{ km}^2$), erupted volumes (LFT: 63.2 km^3 , 42 km^3 DRE; EFT: 45 km^3 , 34 km^3 DRE) and masses (LFT: $7.5 \times 10^{13} \text{ kg}$; EFT: $6 \times 10^{13} \text{ kg}$) presented in Kutterolf et al. (2008b). The new estimates for LFT and EFT yield increased tephra volumes of 328.3 km^3 (217.3 km^3 DRE) and 55.8 km^3 (36.3 km^3 DRE), corresponding to magma masses of $\sim 4.6 \times 10^{14} \text{ kg}$ and $\sim 7.6 \times 10^{13} \text{ kg}$, over distribution areas of $4.2 \times 10^6 \text{ km}^2$ (2-cm isopach) and $6.3 \times 10^5 \text{ km}^2$ (2-cm isopach), respectively (Figs. 11 and 12, Table1).

Five tephra layers in the Petén Itzá sediments (CP5, CP8, CP9, CP18, CP19) are correlated to the younger (<77 ka) Coatepeque (ACT, CGT) and older (~400 ka) Ataco Calderas (ACT3, CMT) in northern El Salvador. Using our new data, and in the case of the Congo Tephra the correlative material in cores from the Gulf of Mexico (Rabek et al., 1985), previous estimates of erupted volumes and masses (ACT: 16.2 km^3 Tephra, 9.8 km^3 DRE; CGT: 18.1 km^3 Tephra, 10.5 km^3 DRE) by Kutterolf et al. (2008b) can be revised by a factor of 2.4 to 6.4 (ACT: 39.6 km^3 tephra, 20.4 km^3 DRE, $4.4 \times 10^{13} \text{ kg}$; CGT: 112.8 km^3 tephra, 74.6 km^3 DRE, $1.6 \times 10^{14} \text{ kg}$), respectively (Figs. 11 and 12, Table 1). For simplicity and comparability, we considered the total Arce tephra volume with SW and N directed distribution fans. Although there were probably two eruptions involved, the proximal outcrops have been summarized into a single tephra unit. From our field observations, we apply two distribution fans for the Congo tephra to account for the main deposit direction to the west, which reached the Pacific (Kutterolf et al. 2008b), and the second one distributed to the northwest, covering the direction of ignimbrite flow to the north and NW, and the outcrops in the Gulf of Mexico, eventually associated with co-ignimbrite fallout.

From the Ataco Caldera, only rough total tephra volume estimates of $\sim 27 \text{ km}^3$ and $\sim 32 \text{ km}^3$ exist for proximal pyroclastic flows and medial fallouts (González Partida et al., 1997). Using

our distal Petén Itzá data we were able to come up with a rough estimate for the Chilamatal tephra and the lower Ataco Tephra, yielding eruptive volumes of $\sim 29 \text{ km}^3$ (15 km^3 DRE) and $\sim 83 \text{ km}^3$ (43 km^3 DRE), eruptive masses of $3 \times 10^{13} \text{ kg}$ and $9 \times 10^{13} \text{ kg}$ at a maximum distribution of $5 \times 10^4 \text{ km}^2$ and $3 \times 10^4 \text{ km}^2$ for the 5-cm isopach, respectively (Figs. 11 and 12, Table 1).

Using the thickness distribution in the Pacific sediments (Kutterolf et al., 2008a), together with the ash bed thicknesses in the Petén Itzá sediments, we were also able to provide first rough tephra volumes and mass estimates of $\sim 132 \text{ km}^3$ (77 km^3 DRE) and $1.6 \times 10^{14} \text{ kg}$ for the widespread mafic tephra layer of CP6 from Pacayal volcano, and for the Lower Cosigüina tephra (CP7; $\sim 28 \text{ km}^3$ tephra, $\sim 19 \text{ km}^3$ DRE, $4.1 \times 10^{13} \text{ kg}$) (Table 1, Fig. 11, 12).

Regarding tephra distributions of eruptions that are characterized by few (<10) data points we compared the tephra volumes based on sparse data using the Fierstein and Nathenson method with the minimum estimates determined by the method of Legros (2000; Table 1, S5), assuming different opening angles of the ash distribution fan (30° to 60°). We found a complete overlap for the first-order approximations of the distal erupted tephra volumes (table 1) of AC3 (7 - 13 km^3) and CMT (6 - 12 km^3). For eruptions that also emplaced their tephra load upwind in the Pacific (AOT and LCO), the minimum estimates using the Fierstein and Nathenson method show larger discrepancies (volumes reduced by a factor of 0.5 to 3; table 1, S5) when comparing them with the method of Lagros (2000), most probably from not considering the upwind tephra deposition when applying a tear-shape distribution starting at the source.

In summary, the erupted volumes and masses reported by Kutterolf et al. (2008b) increase by factors between 1.2 and 10.6 with the inclusion of our new data. Respective eruption magnitudes ($M = \log_{10}(\text{erupted mass, kg}) - 7$), often similar to the volume and plume-height-dependent VEI index of Newhall and Self (1982) for most eruptions (Pyle 2000), increase by up to one magnitude point (i.e. order of magnitude estimated deposit mass; Table 1). This leads us also to suggest that Los Chocoyos, the largest known Pleistocene eruption in Central America, can be

classified, with a VEI of 8, as a “super eruption.” Therefore, the distal ash beds in Lake Petén Itzá sediments better constrain the size of CAVA eruptions (Table 1) and demonstrate, in general, how important distal outcrops are for characterization of large explosive eruptions.

Conclusions

We used the glass compositions of reference data from widespread, Pleistocene plinian tephra deposits along the Central American Volcanic Arc, to correlate 24 ash beds in drill cores from Lake Petén Itzá to ten dated eruptions. Using these correlations, we were able to 1) establish new estimates and revise old estimates of eruptive volumes, masses and eruption magnitudes, for the respective Central American eruptions and 2) provide dated horizons that enable assignment of dates to depths in the lake stratigraphy. Previously unknown eruptions were identified and allocated to potential eruptive centers, in seven multi-site/hole tephra layers, as well as seven single-site tephra beds, using compositional variations along the Central American and Mexican arc. The combination of new age estimates and widespread correlations with proximal Central American tephra deposits, as well as site-to-site correlations, yielded a tephro-chronostratigraphic framework for the Petén Itzá sediment successions extending back to ~400 ka. The revised age models for each drill site will enable interpretation of unprecedented continental records of climate and environmental change in the lowland Neotropics.

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Figure 1: A) Geographical overview map of Central America based on the colored SRTM elevation model of Central America (NASA/JPL/NGA, 2000; Farr et al. 2007) including high-resolution bathymetry along the MAT from Ranero et al. (2005) modified from Kutterolf et al. (2008b). The front of Central American arc volcanoes that generated Pleistocene eruptions extends for almost 800 km at a distance of 200 km parallel to the Middle American Trench (MAT). The numbers correspond to the listed individual explosive volcanic centers. The black arrow indicates the direction of the Cocos Plate motion and relative velocity to the Caribbean Plate after DeMets (2001). Black dots show core positions of ash bearing gravity cores in the Pacific after Kutterolf et al. (2008a). Yellow stars indicate drill site positions of deep sea drilling programs. Blue ellipsoid marks inset area B and Petén Itzá lake location. B) Lake Petén Itzá bathymetry and drill sites after Mueller et al. (2010)

Figure 2: A) to D) Pictures of large caldera systems in northern Central America. E) Simplified composite stratigraphic successions of known Late Pleistocene/Holocene tephras from highly explosive eruptions in northern Central America (modified from Kutterolf et al. 2008d) along the Northern part of the CAVA; tephra acronyms of respective eruptions are given in the table to the right. Yellow bars mark silicic tephras, and green bars mafic widespread tephras. Major unconformities in the successions are shown by black zigzag bands. Individual numbers next to

tephra layers give known eruption ages (Kutterolf et al., 2008b); Tephra without numbers are estimated on the basis of field observations (e.g. thickness of soils and sediments).

Figure 3: Photographs of selected felsic (A-D, F, H, J-L) and mafic (E, G, I) ash beds and smear-slide microphotographs showing glass-shard textures of silicic (M-O) and mafic (P-R) Petén Itzá ash beds. Thin white lines help to indicate the base of ash beds.

Figure 4: Matrix-glass compositional ranges of Lake Petén Itzá ashes (normalized to anhydrous compositions). A) Total alkali versus silica plot to indicate compositional variability in Petén Itzá tephra and to discriminate between volcanic rock classes after Le Maitre et al. (2002). B) The analyzed glass shards distribute into major compositional groups after Kutterolf et al. (2007b). D= potassium-rich dacites to trachytes; C1= low silica, low potassium rhyolites; C2= low silica, high potassium rhyolites; B= medium silica, high potassium rhyolites; A= high silica, high potassium rhyolites.

Figure 5 A to F: Major element glass shard compositions of Lake Petén Itzá ash beds compared with proximal glass-composition fields of North-CAVA tephra after Kutterolf et al. (2008) and our own data; see Fig. 1 for tephra acronyms. For clarity, data are averages of all analyses made for each tephra. Compositional variations per analyzed tephra are shown with grey bars. Letters in the legend and in diagrams identify CP-layers. Additional diagrams are given in Figure S1.

Figure 6 A to D: Continued trace element glass shard compositions. Trace element correlation fields are limited to remaining possible correlations based on major elements only. Compositional variations per analyzed tephra are shown with grey bars.

Figure 7: Comparison of average glass compositions of seven tephra layers (CP1-3, CP6, CP-14, CP16-17) and seven uncorrelated ash beds with Ba/Zr, U/Th, Rb/Hf, and La/Yb variations along the CAVA as discussed in the text. Along-arc variations of CAVA are based on corresponding felsic and mafic ratios as well as glass and bulk rock compositions (Kutterolf et al. 2015; Carr et al. 2007). Mexican compositional fields are only based on bulk rock data, given in Luhr et al. (2006), but are assumed to provide the same provenance information. Positive distances along the arc represent CAVA provenances; Negative distances along the arc indicate Mexican origin. The compositional groups contain two or more ash beds and show the compositional range of the respective group with the colored bars along the arc; encompassing darker rectangle represents the resulting best fit for the source area considering all available trace element ratios, including those of Figure S2.

Figure 8: Cumulative sediment thickness versus age for drilled Lake Petén Itzá sites. Filled symbols show tephra layers correlated to proximal and marine tephra (cf. Figs. 5,6) of known age; acronyms like in Figure 2. Unfilled circles represent felsic and mafic ash beds of unknown ages, which can here be constrained by linear interpolation assuming constant sedimentation rates. Unfilled triangles represent ^{14}C ages taken from Mueller et al. (2010). The slopes of line segments between tephra yield average accumulation rates (numbers in cm/ka). Right part of each age model shows depth (mblf) versus sedimentation rate (cm/ka.).

Figure 9: Sedimentation rates versus age of Petén Itzá sites PI-1 through 7. The inset focuses on the last 100 ka. MIS borders after Peterson et al. (2000) modified by Mueller et al. (2010) for Petén Itzá sediments marked with dashed lines.

Figure 10: Compositionally correlated tephra layers CP1 through CP19 provide stratigraphic links between the six sites from the Lake Petén Itzá drilling. Correlations with well-known proximal (bold red labels) and marine (blue labels) tephra as well as the resulting age

constraints for the Petén Itzá sediments are indicated to the right. *Italic red labels indicate age estimates for tephra layers from sedimentation rates.*

Figure 11: Isopach maps for the E-Fall Tephra (EFT), Arce Tephra (ACT), Los Chocoyos (LCY), Congo Tephra (CGT), L-Fall and Flow Tephra (LFT), W-Fall and Flow Tephra (WFT), Old Pacayal Tephra (OPT), Lower Ataco Tephra (AC3), Lower Cosigüina Tephra (LCT), Old Atitlán Tephra (AOT), and Chilamatal Tephra (CMT), with proximal isopachs taken from the references mentioned in the text that sum to 50 to 243 data points (excluding OPT, AC3, LCT, AOT, and CMT, for which 5-10 data points were used). For clarity, we do not distinguish between well and poorly constrained isopach sections, but note that the pattern of distal isopachs is constrained by few available data. Bold numbers represent isopach thicknesses, italic numbers stand for thicknesses at the distal outcrops, and black stars indicate positions of the capitals shown in Figure 1. Black diamonds represent cores from Rabek et al. (1985)

Figure 12: Natural logarithm of isopach thickness versus square-root of isopach area for all tephra given in Figure 9. Most tephra data can be fitted by two line segments. Note: data for OPT, AC3, LCT, AOT, and CMT (strolled lines) are only rough minimum estimates because of the sparse data base.

Table 1: Summary of tephra correlations within the Lake Petén Itzá sediments and to the proximal tephra of Central American volcanic arc, including new and revised tephra volumes and masses.

Supplementary Data:

S1 A-H: Additional chemical discrimination diagrams using major and trace elements

S2 I-N: Additional along-arc discrimination plots to distinguish between provenances of Lake Petén Itzá tephra

Supplementary Tables 1-5

Supplement method text

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Table 1

correlation #	site-core-section, intervals [cm]	specific tephra/eruption	along CAVA provenance	age [ka] from literature ^P / sed. rate ^S	Distance to Source [km] / <i>max distance of isopach along axis (km)</i>	max measured distribution area [km ²]/ <i>repective isopach thickness [cm]; this paper</i>	max measured distribution area [km ²]/ <i>repective isopach thickness [cm]; Kutterolf et al. 2008b</i>	Proximal Tephra Fallout Volume [km ³] <i>this paper</i>	Kutterolf et al. 2008b	Distal Tephra Volume [km ³] after Fierstein and Nathenson 1995(<i>Laves 2000</i>)	Kutterolf et al. 2008b	Estimated Flow Volumes [km ³]	Total Tephra Volume [km ³] <i>this paper</i>	Kutterolf et al. 2008b	factor of volume change	Tephra Volume DRE [km ³] <i>this paper</i>	Approx. Total Magma Mass [kg] <i>this paper</i>	M <i>Kutterolf et al. 2008b</i>	M old	VEI			
CP1	2B-5H-2, 64.7-65.2; 4A-5H-2, 24.9-25.6; 6C-4H-1, 91-93		North El Salvador, 320 km	9.9 ^s	350																		
CP2	2A-7H-1, 130-132; 3C-6H-1, 72.5-75.5; 6C-5H-1, 140.5-143		Mexico 600 to 700 km North along arc	13.2 ^s	600																		
CP3	3A-9H-2, 16.8-17; 6A-10H-2, 108.8-109.1; 6B-11H-1, 29.7-30		North El Salvador, 320 km	~30 ^s	350																		
CP4	2A-19H-2, 9.8-10; 3B-16E-2, 69.2-69.8	E-Tephra	Amatitlán, Guatemala	~51 ^D	300	6.3E+05	2	6.3E+05	1	5.0	5.0	50.8	40.0		55.8	45.0	1.2	36.3	7.6E+13	6.0E+13	6.9	6.8	6
CP5	1B-15H-2, 76.9-78.2; 2C-9H-1, 112-114; 6C-17E-2, 20.5-21.8	Congo Tephra	Cotepeque, El Salvador	53±3 ^D	350	1.4E+06	0.5	1.3E+06	1	6.3	5.5	96.5	12.6	10	112.8	18.1	6.5	74.6	1.6E+14	2.0E+13	7.2	6.3	7
		Congo Pazific			350	4.5E+05	1			6.3	5.5	29.5	12.6	10	45.8			27.7	5.8E+13				
		Congo Gulf of Mexico			350	3.9E+05	1					67.0			67.0				46.9	9.8E+13			
CP6	1B-16H-1, 56.5-58; 6A-18E-3, 124.5-126.3	Old Pacayal Tephra	Pacayal, South El Salvador	59 ^s	410/1150	1.0E+06	2	3.3E+05	0.5	27.3		104.5	12.4		131.7	12.4	10.6	77.0	1.6E+14	1.8E+13	#####	6.3	7
CP7	1B-16H-1, 88.2-89.4	Lower Cosiquina Tephra	Cosiquina, Nicaragua	~62 ^s	500/650	1.1E+05	1	-	-	-	-	27.5 / 3.7-6.9	-		27.5	-		19.3	4.0E+13	-	6.6 (6.0)		6 (6)
CP8+9		ARCE total	Cotepeque, El Salvador	72±3 ^D	350	1.8E+05	1	9.0E+05	0.5	11.6	9.6	18.0	6.6	10	39.6	16.2	2.4	20.4	4.4E+13	1.3E+13	6.6	6.1	6
CP10	1B-20H-3, 51-60; 1C-21H-1, 131-139; 6a-24E-2, 48.2-49.2	Los Chocoyos	Atitlán, Guatemala	~84 ^p	300	6.2E+06	3	7.6E+06	1	266.2	238.2	642.1	354.9	200	1108.3	593.1	1.9	611.3	1.3E+15	5.9E+14	8.1	7.8	8
CP11	7A-30E-3, 81-89; 7B-40E-1, 0-12	WFT	Atitlán, Guatemala	158±3 ^D	300	1.0E+06	3	2.9E+05	5	41.5	13.6	105.1	9.7	5	151.5	23.3	6.5	82.5	1.7E+14	1.8E+13	7.2	6.3	7
CP12	7A-32A-1, 24-27.5; 7B-41E-5, 30-34		Central Nicaragua (730 km, Las Sierras)	173 ^s	700																		
CP13	1A-27H-2, 121-131; 1B-31H-1, 72-99; 1C-30H-1, 89-94.5 to 1C-30H-2, 36-54	L-Tephra	Amatitlán, Guatemala	191±11 ^D	300	4.2E+06	2	6.6E+05	1	19.6	18.5	289.3	44.7	12	328.3	63.2	5.2	217.3	4.6E+14	7.5E+13	7.7	6.9	7
CP14	1A-30H-2, 7.5-11; 1B-33H-3, 106-112		Mexico ca. 650 km North along arc	225 ^s																			
CP15	7A-40E-2, 14-19	Atitlán old Tephra	Atitlán, Guatemala	~306 ^D	300/640	1.9E+05	5	-	-	-	-	93 / 18-33	-		93.0	-		65.1	1.4E+14	-	7.1 (6.8)		7 (6)
CP16	7A-42E-3, 33-36; 7B-54E-1, 30.5-32		Mexico ~600 km N along arc	342 ^s	600																		
CP17	7A-43E-2, 121-132; 7B-56E-1, 29.5-34		Mexico ~600 km N along arc	356 ^s																			
CP18	7A-47E-1, 147.5-150 to 7A-47E-2, 0-3	Lower Ataco Tephra	Ataco, El Salvador	~400 ^D	340/400	3.3E+04	5	-	-	45.5	-	10.5 / 7-13	-	27	82.8	-		43.1	9.0E+13	-	7.0 (6.9)		6 (6)
CP19	7A-47E-2, 113-118	Chilamatal	Chilamatal, El Salvador	406 ^s	340/375	5.1E+04	5	-	-	11.2	-	8.3 / 6.1-11.5	-	10	29.4	-		15.0	3.2E+13	-	6.5 (6.5)		6 (6)
														</

Figure2

Figure4

Figure 5

Figure 6

■ CP13: 1A-27H-2, 121-131 cm	● CP13: 1B-31H-1, 73-100 cm	● CP5: 2C-9X-1, 112.5-114 cm	▲ CP10: 6A-24X-2, 48.2-49.2 cm	■ 7A-15H-1, 71.5-74 cm	■ CP11: 7B-40E-1, 4-12 cm
● CP14: 1A-30H-2, 7.5-11 cm	★ CP14: 1B-33H-3, 107-113 cm	■ CP3: 3A-9H-2, 16.8-17 cm	● CP3: 6B-11H-1, 29.7-30 cm	● CP11: 7A-30E-3, 81-89 cm	● CP12: 7B-41E-5, 30-34 cm
■ CP5: 1B-15H-2, 77.2-78.2 cm	■ CP10: 1C-21H-1, 134-138 cm	■ 3A-18H-1, 20-20.5 cm	● 6B-11H-1, 35.9-36.1 cm	▲ CP12: 7A-32E-1, 24-27.5 cm	▲ 7B-46E-3, 90-95 cm
● CP6: 1B-16H-1, 56.5-58 cm	■ CP13: 1C-30H-1, 90-94 cm	■ CP4: 3B-16X-2, 69.2-69.8 cm	▲ CP8: 6B-19E-2, 106.4-106.8 cm	■ CP15: 7A-40E-2, 14-19 cm	■ CP16: 7A-42E-3, 33-35 cm
▲ CP7: 1B-16H-1, 88.2-89.4 cm	■ CP13: 1C-31X-1, 41-53 cm	■ CP2: 3C-6H-1, 72.3-74.5 cm	▲ CP8: 6B-19E-2, 106.4-106.8 cm	■ CP17: 7A-43E-2, 122-132 cm	■ CP17: 7B-54E-1, 29-29.3 cm
■ CP8: 1B-16H-2, 72.2-72.3 cm	■ CP2: 2A-7H-1, 130.5-132 cm	■ CP1: 4A-5H-2, 24.9-25.6 cm	■ CP9: 6B-19E-2, 111.1-112.4 cm	■ CP18: 7A-47E-1/2, 147.5-3 cm	■ CP19: 7A-47E-2, 113-118 cm
■ CP9: 1B-16H-2, 75.5-78 cm	■ CP4: 2A-19H-2, 9.8-10 cm	■ CP3: 6A-10H-2, 108.8-109.1 cm	■ CP1: 6C-4H-1, 93-93.6 cm	■ CP19: 7A-47E-2, 113-118 cm	■ CP17: 7B-56E-1, 130-33 cm
■ CP10: 1B-20H-3, 51.5-59 cm	■ CP1: 2B-5H-2, 65-65.2 cm	■ CP6: 6A-18X-3, 124-125.8 cm	■ CP2: 6C-5H-1, 142.3-143.4 cm	■ CP19: 7A-47E-2, 113-118 cm	
■ 1B-27H-1, 57-57.5 cm	■ 2C-6H-1, 45-45.5 cm	■ CP10: 6A-24X-2, 48.2-49.2 cm	■ CP5: 6C-17E-2, 21.1-21.7 cm	★ 7A-47E-2, 120.5-124.5 cm	

Figure7

Figure9

Figure10