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Tephrochronological evidence for the late Holocene eruption history of El Chichón Volcano, Mexico

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Resumen

Las sociedades prehispánicas de las zonas bajas Mayas fueron afectadas en repetidas ocasiones por la caída de ceniza de las erupciones del Volcán El Chichón, Chiapas, México. Los horizontes de tefra del Holoceno Tardío se preservaron en los sedimentos deltaicos del Río Usumacinta-Grijalva, aproximadamente 150 km al NNE del volcán. Un núcleo de sedimentos del delta que cubre los últimos 2100 años, fue examinado para tefra, polen, polimorfos y macrofósiles. Se utilizaron la tefracronología y palinología para reconstruir la temporalidad, magnitud, e impacto de las erupciones pasadas. Siete de los diez horizontes de tephra reconocidos se relacionaron a las erupciones pasadas del Volcán El Chichón y muestran el fuerte impacto de las erupciones. Una gran erupción ocurrida alrededor de A.D. 539 produjo un efecto dramático en el núcleo del área de la civilización Maya y posiblemente fue la causa del *Hiatus Maya* y del desplazamiento demográfico hacia el Delta del Usumacinta-Grijalva. Esta erupción también parece haber provocado cambios ambientales repentinos a nivel mundial.

Palabras clave: Volcán Chichón, tefracronología, palinología, erupciones del holoceno tardío, zonas bajas mayas, México

Abstract

Pre-Columbian societies in the Maya Lowlands were repeatedly exposed to tephra-fall from past eruptions of El Chichón volcano, Chiapas, Mexico. Late Holocene tephra layers are well preserved in sediments of the Usumacinta-Grijalva river delta, about 150 km NNE of the volcano. A sediment core from the delta spans the last 2100 years, and was examined for tephra, pollen, palynomorphs and macrofossils.

We used tephrochronology and palynology to reconstruct the timing, magnitude and impact of past eruptions. Seven of the ten recognised tephra layers are related to past eruptions of El Chichón volcano and show remarkable impacts of the eruptions. A large eruption around A. D. 539 had a dramatic effect on the core area of Maya civilisation and was probably responsible for the onset of the *Maya Hiatus* and a demographic shift towards the Usumacinta-Grijalva delta. The eruption also seems to have caused rapid environmental changes worldwide.

Key words: El Chichón volcano, tephrochronology, palynology, late holocene eruptions, maya lowlands, Mexico.

Introduction

In 1982 El Chichón volcano had a violent plinian eruption that devastated an area of approximately 153 km^2 surrounding the volcano (Sigurdsson *et al*., 1984). Besides the impact near the volcano, a large area was affected by tephra fall. Eastern Mexico was covered by fine white ash that produced total darkness in the adjacent state of Tabasco, close to our research site. The 5 mm isopach for the 1982 tephra fall, measured during and immediately after the eruption (Fig. 1), indicates an even larger affected area in comparison with earlier published data (Varekamp *et al*., 1984).

The plinian nature of the eruption and the extremely high sulphur content of the magma (Luhr *et al*., 1984) caused the emission of large quantities of sulphur into the stratosphere as detected by the Nimbus 7 satellite (Krueger, 1983). The stratospheric cloud circled the earth in three weeks (Robock and Matson, 1984) and subsequent deposition of aerosol particles caused sulphate peaks that were registered in snow pits and ice cores from Greenland (Zielinski *et al*., 1997), Antarctica (Traufetter *et al*., 2004) and the Himalayas (Hou Shugui *et al*., 2003).

Several authors demonstrated that El Chichón frequently erupted during the Holocene (Tilling *et al*.,

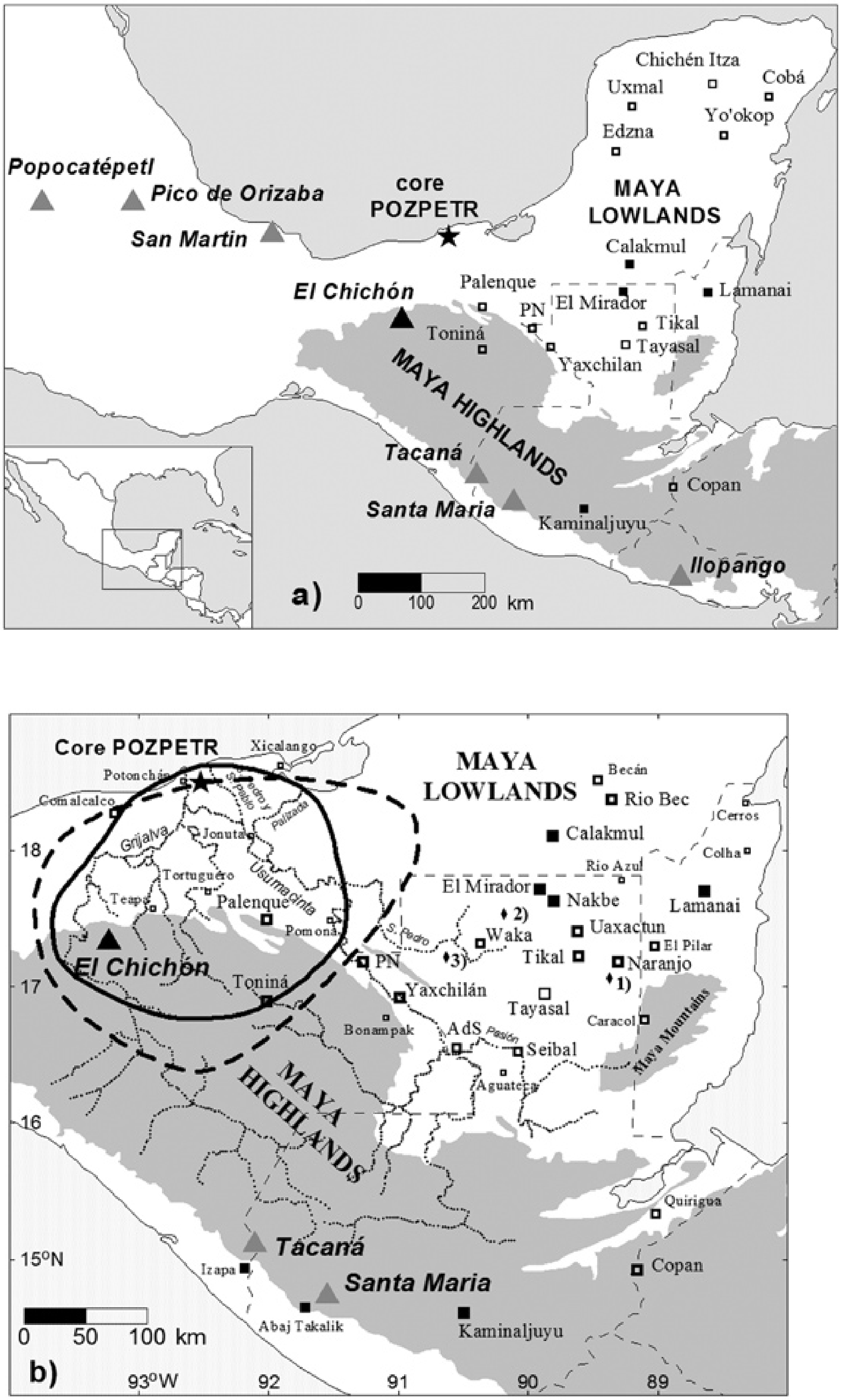

Fig. 1. (a) Location of the POZPETR coring site, El Chichón volcano (▲) and nearby volcanoes with known plinian eruptions during the last 2000 years (△). (b) The 5 mm tephra fall isopach (black line) is based on measurements during and after the eruption from March 29 to April 6, 1982. The 1 mm tephra fall isopach (dashed line) is after Varekamp et al. (1984). Indicated are major Maya cities during the Preclassic (■), Classic (□) and Postclassic period (□), PN=Piedras Negras, AdS=Altar de Sacrificios. Also indicated are lakes mentioned in the text (◆); 1)= lake Yaxhá-Sacnab, 2)=lake Puerto Arturo, 3)= Lake Tuspán.

1984; Macías, 1994; Espíndola *et al*., 2000). Espíndola *et al* (2000) identified 12 explosive eruptions of the volcano that occurred at approximately 550, 900, 1250, 1500, 1600, 1900, 2000, 2500, 3100, 3700 and 7700 years before present (BP). The ~550, ~1250 and ~3700 yr BP eruptions were larger or similar in magnitude than the 1982 eruption which had a VEI (Volcanic Explosive Index) between 4 and 5 (Macías *et al*., 2008). Only the ~550 and ~1250 yr BP eruptions have so far been linked to plinian activity that dispersed large amounts of tephra, as the 1982 eruption did (Espíndola *et al*., 2000; Macías *et al*., 2003). The impact of ancient eruptions on Maya societies is largely unknown and only a few attempts have been made to link past eruptions with the archaeological record (Gill and Keating, 2002).

In this paper we reconstruct the tephrochronological archive from the Usumacinta-Grijalva delta. Tephrostratigraphy, ^{14}C-dating and palynology were used to estimate the timing and magnitude of past volcanic eruptions. Microprobe analyses were used to identify the source volcano for one of the most distinct tephra layers. The impact of past eruptions was estimated and correlated with demographic changes within the Maya Lowlands.

We are not aware of any palaeoecological or palaeolimnological work in the Maya Lowlands that included the study of tephra. Although tephra may not always show up as distinct layers, a petrographic study by Steen-McIntyre (Sheets, 1983) demonstrated the presence of tephra within the sediments of lake Yaxhá-Sacnab, northern Guatemala (Fig. 1b). The widespread use of air-fall tephra as ceramic temper throughout Maya history (Simmons and Brem, 1979; Ford and Rose, 1995) also indicates that tephra deposition was common in the Maya Lowlands.

The combination of tephrostratigraphy and AMS ^{14}C-dating allows for the construction of a tephrochronological framework. Tephrochronology may help establish an accurate time chronology for the Maya Lowlands. This would be a boon for Maya archaeologists because conventional radiocarbon dating is less accurate, and for the Maya Lowlands even more problematic because of the "old carbon effect".

Materials and methods

In 2000, twelve cores were taken in the Usumacinta-Grijalva delta, about 150 km NNE of El Chichón volcano. The cores were taken primarily to assess spatial and temporal variation in sediment accumulation rates. Many cores, however, contained distinct volcanic ash layers and it became clear that the delta sediments possess an important tephrostratigraphic archive. One site was of particular interest because of its distinct tephrostratigraphy. The site, Pozo Petrolero (18º29'72"N, 92º31'43"W) is located in a distal marshy flood basin between the Usumacinta and the San Pedro y San Pablo rivers (Fig. 1). Two 120-cm-long parallel cores were taken with a 5-cm-diameter corer in 66 cm of standing water. After transport to the Netherlands, the cores were stored in a dark room at 4ºC. Loss on Ignition (LOI), an estimate of organic matter content, was determined by heating weighed samples at 550ºC for four hours and re-weighing (Heiri *et al*., 2001).

Pollen samples were taken every 1 to 5 cm and prepared using standard palynological extraction procedures, but without a HF treatment (Faegri and Iversen, 1989). For each sampled depth a complete slide was counted for pollen and palynomorphs at 400x magnification. The diatoms that were present in the pollen slides were counted along with the pollen and other palynomorphs. Macrofossils were isolated from 2-cm thick samples using a 5% KOH treatment and a 150-μm sieve. Abundance classes for volcanic glass shards, charcoal and palynomorphs were estimated from the macrofossil samples and the pollen slides.

Glass shards from two tephra layers at 32 and 60 cm depth were isolated from untreated tephra samples by hand picking. Microprobe analyses of the glass shards were carried out at Laboratorio Universitario de Petrología, UNAM. Forty-five microprobe glass analyses from twelve shards were made on the Jeol JXA 8900R with beams of 10 and 15 microns. The composition of the glass shards was compared with data from deposits of nearby volcanoes to identify the source volcano.

Six samples of terrestrial macrofossils and one bulk material sample were selected for AMS radiocarbon dating. The AMS ^{14}C-dates were calibrated to calendar years with Oxcal 3.10 (Bronk Ramsey, 1995; 2000) using the IntCal04 calibration curve (Reimer *et al*., 2004).

Results and discussion

Both cores show the same lithology with fine beach ridge sands at their base (Fig. 2). As a result of relative sea-level rise, these ridges were gradually submerged and organic accumulation started about 2100 years ago. The results of the AMS-radiocarbon dates (Table 1) and the age-depth model (Fig. 2) indicate that, except for the unconsolidated upper 20 cm, organic accumulation rates gradually decreased from 0.5 to 0.3 mm/year.

Three tephra layers, at 1, 32 and 60 cm depth, were very obvious and visible with the naked eye.

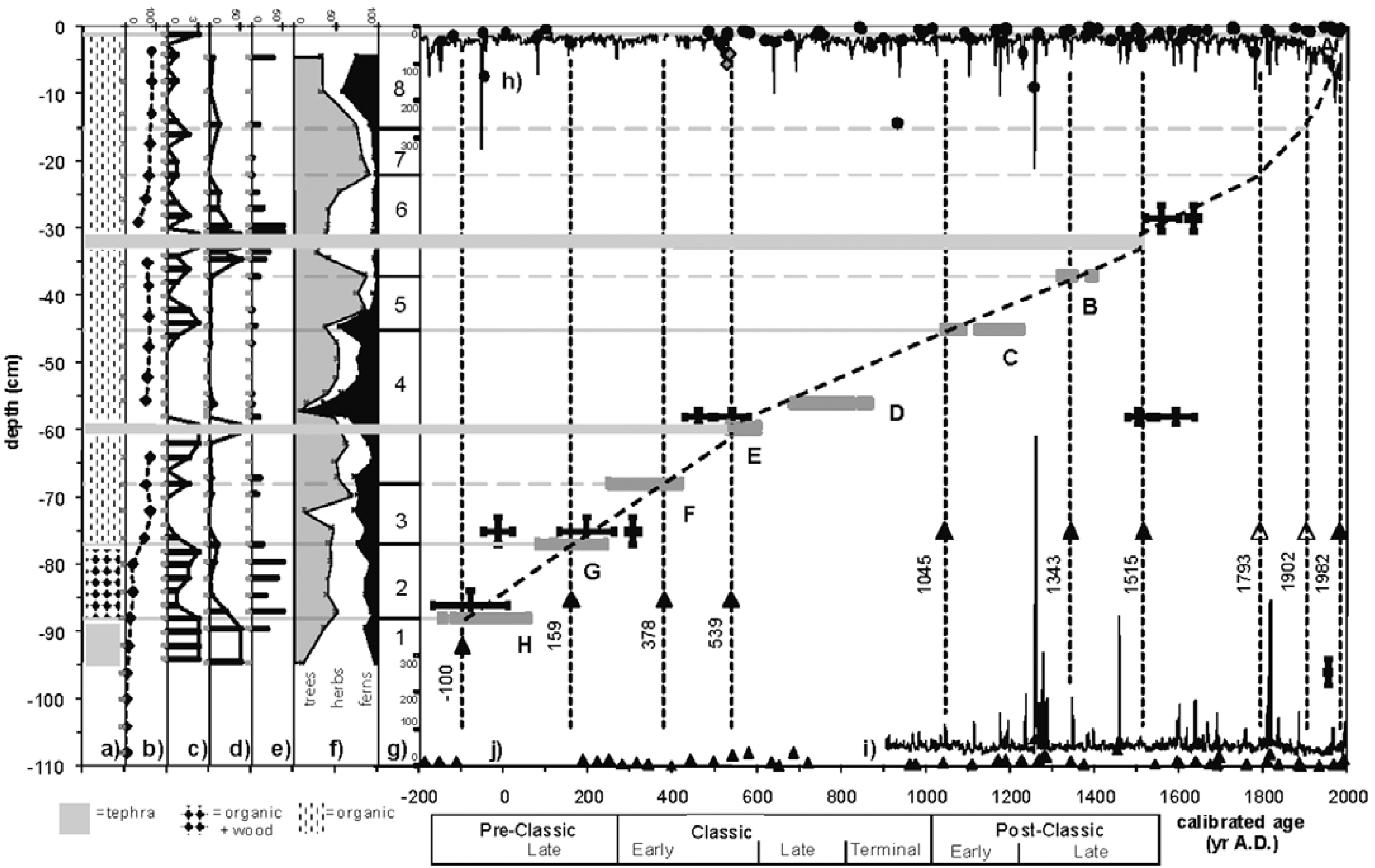

Fig. 2. Age-depth model for the Pozo Petrolero core. Calibrated ages of the AMS-dated samples in black and calibrated ages of units A-H (after Espindóla *et al.*, 2000) in grey (both at 68.2% probability). a) lithology; b) loss of ignition (%); c) volcanic glass shards > 150 μm (in abundance classes; 0=absent, 1=few, 2=moderately present, 3=abundant); d) number of volcanic glass shards in each pollen slide; e) number of diatoms in each pollen slide, f) summary of the pollen percentage diagram (%), g) zonation h) sulphate conc. GISP2 ice-core Greenland (μg/kg), after Zielinski (2000) and volcanic sulphate deposition (kg/km^2) in Greenland after Clausen *et al*. (1997)(•) and Larsen *et al*. (2008) (•), only the Larsen *et al*. (2008) data is conform the new GICC05 timescale (Vinther *et al*., 2006), i) sulphate conc. SP2000 ice-core Antarctica, after Cole-Dai, 2004, j) volcanic derived sulphate deposition Antarctica (▲)(kg/km^3) (Traufetter *et al*., 2004) and DEP-signal ice-core Antarctica (☐) (Hofstede *et al*., 2004).

Table 1

AMS radiocarbon dates for the Pozo Petrolero core

depth (m)	dated material	sample nr.	^{14}C-age (yr B.P.)	δ^{13}C (‰)	calibrated age (yr A.D./B.C.) (with 1-σ probability %)
0.23 – 0.27	seed, bud	UtC-11087	298 ± 38	-26.0	A.D. 1560 ± 40 (49.0); A.D. 1630 ± 20 (19.2)
0.51 – 0.53	wood [1]	UtC-11088	346 ± 34	-28.0	A.D. 1595 ± 45 (43.9); A.D. 1505 ± 25 (24.3)
0.57 – 0.59	charcoal	UtC-14169	1535 ± 44	-25.5	A.D. 460 ± 30 (31.9); A.D. 540 ± 40 (36.3)
0.66 – 0.70	17 seeds, charcoal	UtC-11089	1791 ± 34	-26.7	A.D. 195 ± 65 (57.0); A.D. 305 ± 15 (11.2)
0.66 – 0.70	bulk	UtC-11092	2017 ± 29	-27.3	15 ± 35 B.C. (68.2)
0.78 – 0.82	charcoal, wood	UtC-11090	2055 ± 59	-28.2	80 ± 90 B.C. (68.2)
0.89 – 0.93	wood [1], 1 seed	UtC-11091	-86 ± 33	-28.0	Modern

1) probably a root

Other tephra layers were identified on the basis of peaks in the abundance of volcanic glass shards within the macrofossil samples and the pollen slides. We describe the tephra layers and the environmental changes associated with them as inferred from the analysis of pollen (Fig. 3), palynomorphs and macrofossils (Fig. 4).

The tephra layers are related to past eruptions of El Chichón (Table 2) or other volcanoes by comparing the timing of tephra deposition with the estimated eruption data from nearby volcanoes. One tephra layer could be related to a particular volcano according to the results of the microprobe analyses (Table 3 and Fig. 5). Possible

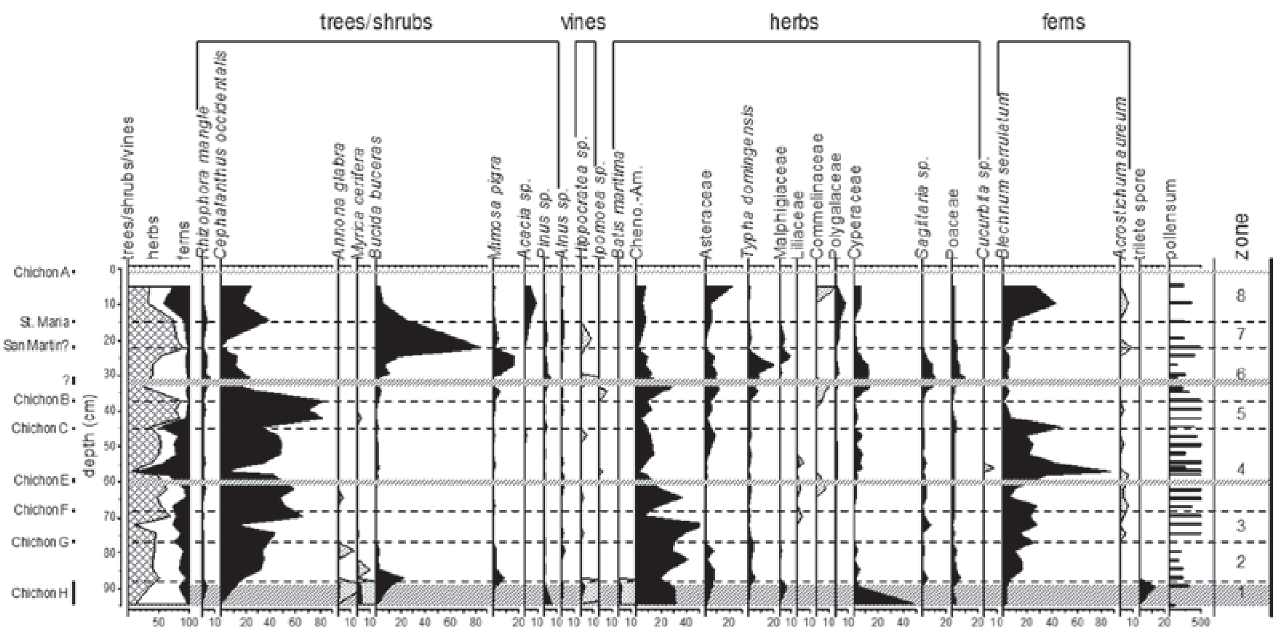

Fig. 3. Pollen percentage diagram for core Pozo Petrolero. Fern spores are included in the pollen sum.

Table 2

Calibrated ages of El Chichón pyroclastic deposits B through H (after Espíndola *et al*., 2000).

Unit	dated material	sample. nr.	^{14}C-age (yr B.P.)	rounded average age (yr. B.P.)	calibrated age (yr A.D./B.C.) (with 1-σ probability %)2)
B	charcoal	EC-220	550 ± 60	550	A.D. 1335 ± 20 (49.2);
	charcoal	EC-184	550 ± 60		A.D. 1395 ± 10 (19.0)
	charcoal	CH19407	550 ± 60		
	charcoal	EC-201	570 ± 60		
	charcoal	EC-218	600 ± 70		
	charcoal	CHAR-1	650 ± 100		
	charcoal	EC-222	700 ± 70		
C	charcoal	CH19304	845 ± 75	900	A.D. 1065 ± 25 (18.1);
	charcoal	CH19240	900 ± 90		A.D. 1175 ± 55 (50.1)
D	charcoal	CH19205	1225 ± 105	1250	A.D. 755 ± 75 (60.5);
	charcoal	DT-10	1250 ± 70		A.D. 855 ± 15 (7.7)
E	charcoal	CH19318	1465 ± 95	1500	A.D. 567 ± 37 (68.2)
	charcoal	CH19515	1490 ± 45		
	charcoal	CH19602	1520 ± 75		
	charcoal 1)	EC-189	1580 ± 70		
F	charcoal	CH19373	1695 ± 65	1600	A.D. 335 ± 85 (68.2)
G	charcoal	CH19403	1780 ± 95	1900	A.D. 95 ± 15 (4.6);
	charcoal	EC-198	1870 ± 70		A.D. 180 ± 60 (63.6)
H	charcoal	CH19727	2025 +85/-80	2000	30 ± 90 B.C. (66.0);
	charcoal	CH19797	2040 +125/-120		145 ± 5 B.C. (2.2)

1) Espíndola *et al*. (2000) correlate this sample from Tilling *et al*. (1984) to deposit F.
2) Because all ^{14}C-ages were used in the calibration with Oxcal 3.10 (Bronk Ramsey, 1995;2000) ages differ somewhat from the calibrated ages given by Espíndola *et al*. (2000).

Table 3

Micro-probe analyses of glass shards from the tephra layer at 60 cm depth.

Sample	60-S1	60-S3	60-S6	60-S7	60-S9	60-S11
SiO_2	76.552	76.974	76.879	77.440	76.776	76.736
TiO_2	0.093	0.091	0.110	0.108	0.119	0.079
Al_2O_3	13.020	12.479	12.599	12.678	12.552	12.630
FeO	0.513	0.464	0.619	0.475	0.487	0.529
MnO	0.080	0.082	0.072	0.092	0.090	0.082
MgO	0.077	0.067	0.078	0.068	0.050	0.040
CaO	0.556	0.595	0.574	0.607	0.577	0.584
Na_2O	4.028	3.727	4.149	3.921	3.946	3.893
K_2O	4.071	3.917	4.067	3.995	4.001	3.976
P_2O_5	0.000	0.039	0.062	0.011	0.047	0.002
BaO	0.114	0.114	0.133	0.120	0.138	0.059
Total	99.104	98.549	99.342	99.515	98.783	98.610

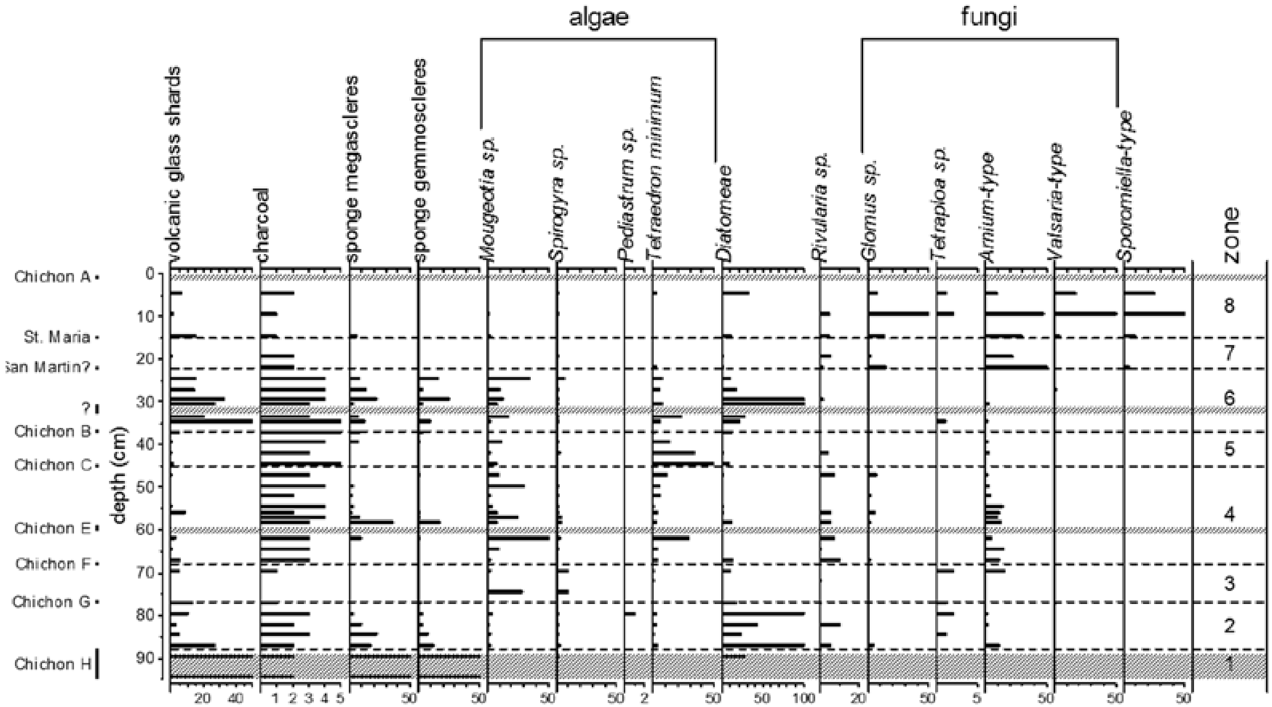

Fig. 4a. Pozo Petrolero core with palynomorphs found in the pollen slides expressed as total numbers/slide. Charcoal presence ranges from absent (0) to highly abundant (5).

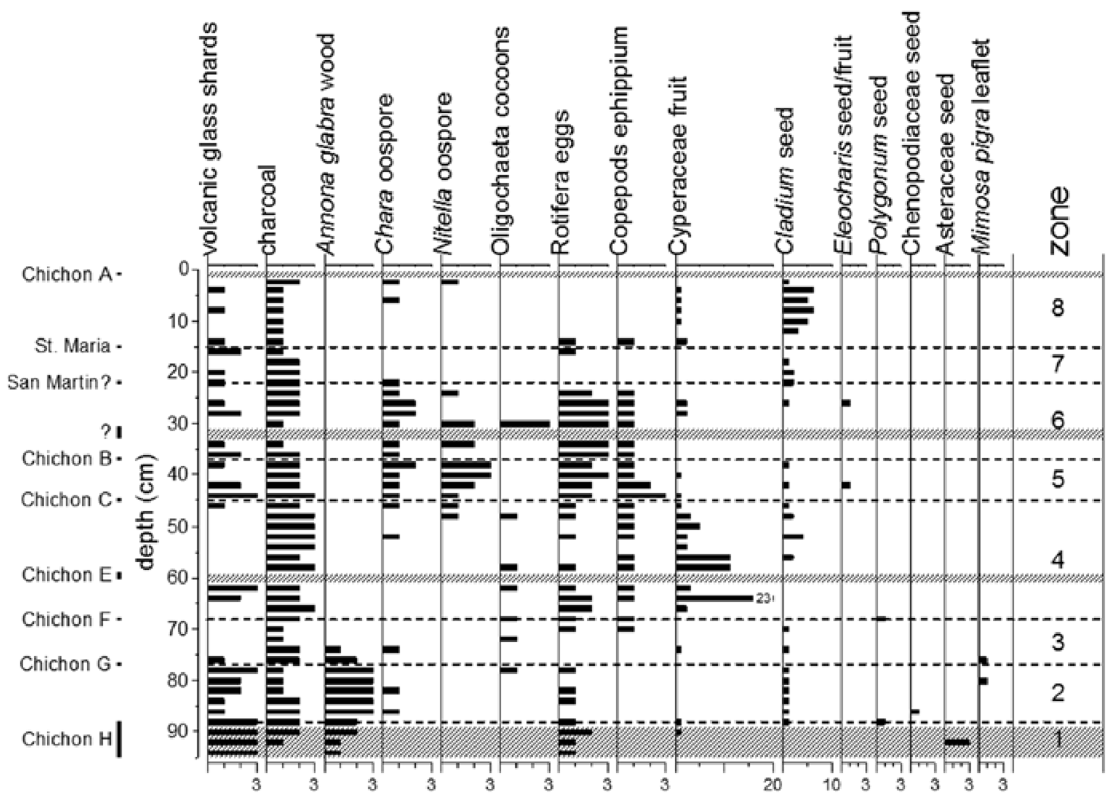

Fig. 4b. Pozo Petrolero core with macrofossil samples; indicated as total numbers or as abundance classes; 0=absent, 1=few, 2=moderately present, 3=abundant.

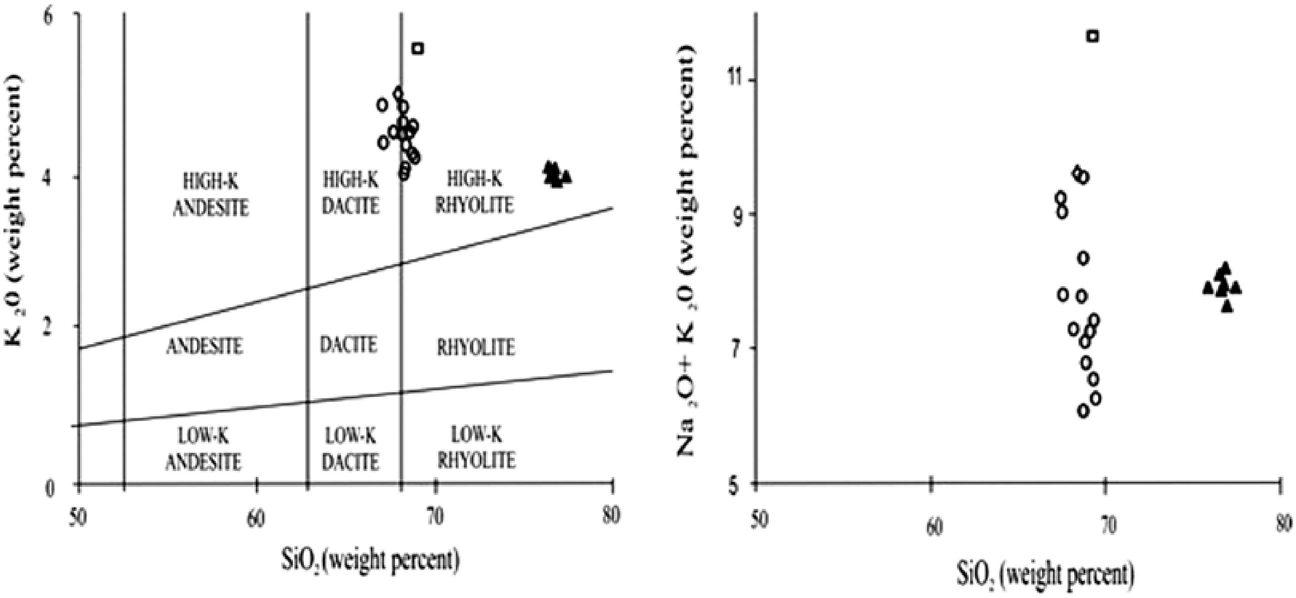

Fig. 5. Composition of glass shards from 60 cm depth (triangles) compared with analysed glass shards from El Chichón unit A, after Cocheme *et al*., 1982 (square) and Luhr *et al*., 1984 (diamond) and El Chichón unit B, after Macias *et al*., 2003 (circles).

relations with the archaeological data are given (Fig. 6). Finally, a tentative estimation of the eruption date is given by correlating the age-depth model with sulphate peaks in ice cores from Greenland (Zielinski *et al*., 1994; Clausen *et al*., 1997; Zielinski, 2000; Larsen *et al*., 2008) and Antarctica (Budner and Cole-Dai, 2003; Cole-Dai, 2004; Traufetter *et al*., 2004, Hofstede *et al*., 2004). Regarding the high sulphur content of older deposits (Rose *et al*., 1984), it is likely that large pre-1982 eruptions also left a sulphate signal in ice cores.

El Chichón Tephra, unit H

Volcanic glass shards are abundant within the upper part of the sandy deposits (88->96 cm depth). Pollen is preserved poorly in sandy samples, but the taxa encountered indicate a turbulent sedimentation environment with early successional trees like *Myrica cerifera* and *Mimosa pigra* (zone 1). The sandy deposits contain abundant freshwater sponge megascleres and gemmoscleres from *Racekiela sheilae* indicating the presence of a shallow coastal wetland (Volker-Ribeiro *et al*., 1988).

A wooded freshwater swamp (zone 2) followed the turbulent environment with tephra deposition (zone 1). The LOI gradually increases to ~25% and deposits are rich in wood fragments of *Annona glabra*. Pollen from *Annona glabra* is scarce, but present. The number of remains of the freshwater sponge *Racekiela sheilae* decreases and diatoms, characteristic of shallow freshwater habitats like *Eunotia* spp., *Gomphonema* spp. and *Nitzschia* spp., are abundant. The transition from zone 1 to 2 could be related partly to the eruption of El Chichón, but the transition is probably mainly caused by an increase in water level.

We relate the tephra to an eruption of El Chichón volcano (unit H). Although wet pyroclastic surges and ash-flow deposits of unit H were found near the volcano, no fallout layers associated for this eruption have been identified previously (Espíndola *et al*., 2000; Macías *et al*., 2008). The hydromagmatic eruption had an estimated VEI of 2-3 (Macías *et al*., 2008). The calibrated age of deposit Unit H is 30 ± 90 B.C. (Table 2) (Espíndola *et al*., 2000). A wood/charcoal sample from above the tephra layer yielded a calibrated age of 80 ± 90 B.C. (Table 1).

Although archaeological data for this period are relatively scarce, there are indications of a Pre-Classic stagnation and probably even a slight decrease in the formation of Maya polities between 100 and 0 B.C. (Fig. 6) (Cioffi-Revillia and Landman, 1999). Galop *et al*. (2003) found palaeoecological evidence for a decrease in agricultural activity around lake Tuspán (Fig. 1b) after approximately 100 B.C.

Within the time range of deposit H, the GISP 2 Greenland ice core shows three sulphate peaks. One of the largest sulphate peaks over the last 5000 yr. was recorded at 53 B.C. (Zielinski, 2000). The source volcano has not been identified yet, although a high-latitude Northern Hemisphere eruption is most likely given the absence of a sulphate peak in ice cores from Antarctica around this date (Hofstede *et al*., 2004). Two smaller sulphate peaks occurred in the GISP 2 core around 100 and 44 B.C. The

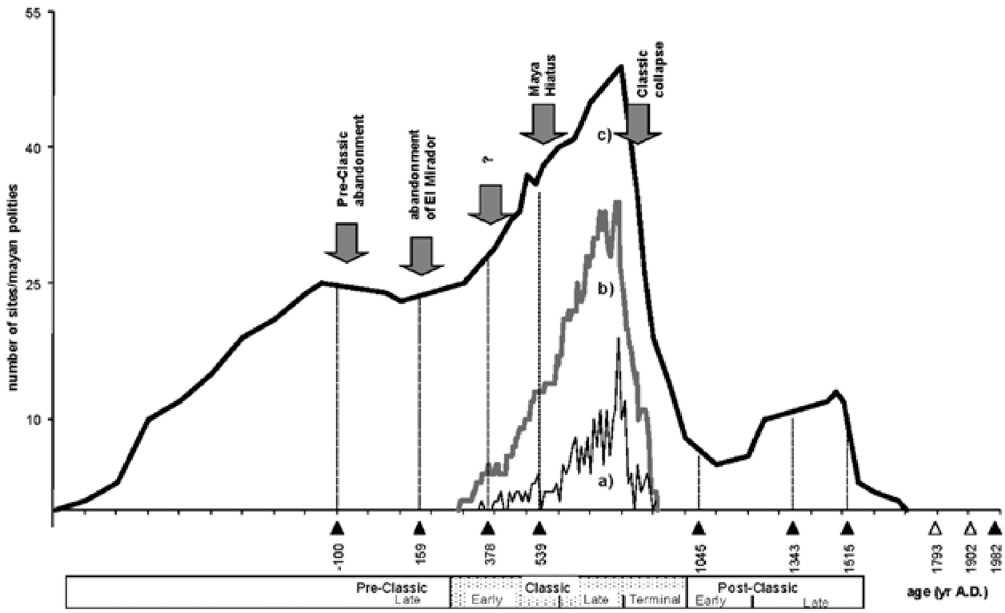

Fig. 6. The eruptions of El Chichón (▲) and other volcanoes (△) within the archaeological time frame. Indicated are: a) the number of monuments with (quarter) katun markers (after the early record by Morley, 1938), b) the number of sites engaged in the production of monuments (after Lowe, 1985) and c) the number of Maya polities in the Mesoamerican system (modified from Cioffi-Revillia and Landman, 1999).

44 B.C. peak is related to an eruption of Etna volcano in Italy, which caused a dry fog in Italy and northern China (Stothers and Rampino, 1983; Stothers, 2002). We relate the 100 B.C. peak to an eruption of El Chichón. Around the same date, 114 B.C., Hofstede *et al*. (2004) found a small dielectric profiling (DEP)-peak (indicative of sulphate) in an ice core from Antarctica.

El Chichón Tephra, unit G

A small peak in the abundance of volcanic glass shards within the macrofossil and pollen samples occurred at ~77 cm depth. The tephra layer marks a change from a temporarily flooded wetland environment to permanently flooded conditions (zone 3). Many shallow open water indicators like zoospores from charophytes, resting eggs of rotifers and copepods, diatoms and sponge megascleres and gemmoscleres disappear. Only spores of the filamentous green algae *Mougeotia* and *Spirogyra* remain. *Cephalanthus occidentalis* trees gradually replace *Annona glabra* trees, the former having a higher flood tolerance. Pollen from *Cephalanthus occidentalis* increases to ~60% at the end of zone 3.

The tephra layer at 77 cm depth is probably related to an eruption of El Chichón volcano and to wet pyroclastic surges and ash-flow deposits of unit G found near the volcano (Espíndola *et al*., 2000). The hydromagmatic eruption had an estimated VEI of 2-3 and fallout layers have not been identified yet (Macías *et al*., 2008). The calibrated age of Unit G is A.D. 180 ± 60 (Table 2). We obtained a calibrated age of A.D. 195 ± 65 for a seeds/charcoal sample from above the tephra layer.

The Preclassic Abandonment of important Maya cities like El Mirador (Guatemala),which was rapidly depopulated around A.D. 150 (Hansen *et al*., 2002), could be related to the eruption of El Chichón. Palynological evidence for this abandonment comes from a study of Lake Puerto Arturo, located nearby El Mirador. A minimum in disturbance indicators (Poaceae and Asteraceae) occurred at approximately A.D. 140 (Wahl *et al*., 2006). Other smaller centres like Cerros and Colha were also abandoned and Tikal and Lamanai experienced a period of stasis in construction (Freidel and Schele, 1988 and references therein).

Within the time range of deposit G there is not a clear sulphate signal in ice cores from Greenland and Antarctica that could be related to the El Chichón eruption. We tentatively assign the small signal around A.D. 159-161 in the GISP2 and GRIP ice cores (Clausen *et al*., 1997; Zielinski, 2000) to the eruption of El Chichón. No signal was found in Antarctic ice cores around this date (Hofstede *et al*., 2004.

El Chichón Tephra, unit F

During the first analysis of the macrofossil samples no tephra was recognised at 68 cm depth. However, a small peak in the number of tephra shards in the pollen slides, a slight decrease in LOI, and the appearance of diatoms around 68 cm depth (Fig. 2) do point to a deposition of tephra at this depth. A macrofossil sample from the parallel core did confirm the presence of volcanic glass shards.

Although no major changes occurred in the pollen assemblage at this depth (Fig. 3) we identified a zone change (zone 3 to 4) on the basis of changes within the palynomorphs and macrofossil samples. Charcoal particles become abundant and the cyanobacterium *Rivularia* sp. and *Arnium*-type fungi ascospores show a marked increase, probably related to intensification of human activity in the area.

The tephra can be related to an eruption of El Chichón volcano and ash flow deposits of unit F (Espíndola *et al*., 2000). The eruption was probably hydromagmatic with a VEI of approximately 2-3 (Macías *et al*., 2008). Like the previous two eruptions no fallout layers associated with the eruption have been found yet. The calibrated age of deposit Unit F is A.D. 335 ± 85 (Espíndola *et al*., 2000).

Although the delta was already inhabited for many centuries, the eruption could have caused a significant migration towards the Usumacinta river and the delta. A stagnation in the erection of monuments occurred within the Maya Lowlands (Fig. 6) (Lowe, 1985) and archaeologists describe a period of political instability related to the arrival of the stranger 'Fire Is Born' in A.D. 378.

Unfortunately, the GISP2 data contain a 'hiatus' between ~A.D. 363 and ~A.D. 381 (Zielinski, 2000) and no sulphate peak was found in the GRIP ice core around this date (Clausen *et al*., 1997). Ice cores from Antarctica show increased sulphate deposition at A.D. 315 ± 19, A.D. 341 ± 18 and A.D. 395 ± 18, all from an unknown source volcano (Traufetter *et al*., 2004).

El Chichón Tephra, unit E

A 1.3-cm-thick yellowish tephra layer is present at 60 cm depth. The tephra contains rhyolithic sharp-edged or vesiculated glass shards and angular crystals up to 400 μm in size.

The tephra layer was deposited within zone 4. The pollen diagram shows an enormous change in the pollen assemblage. High abundance of charcoal and the occurrence of a few pollen grains from *Cucurbita* sp. and Ipomoea sp. do indicate an increase of human presence in the area. Severe human-induced burning caused the disappearance of trees like *Cephalanthus occidentalis* and temporary dominance of marshy vegetation by the fern *Blechnum serrulatum*. The pollen diagram shows an increase in fern spores of more than 80%. A time lag between the deposition of the tephra and the major vegetation changes indicates that the effect of the El Chichón eruption was indirect. There was probably a large demographic shift from inland locations toward the Usumacinta-Grijalva delta. Archaeological data support this hypothesis. Gunn and Folan (2000) describe a large population shift during the Late Classic period (A. D. 600 – 800) when the Maya populations moved from inland locations toward the plains of the lower and middle Usumacinta River (including the San Pedro y San Pablo and Palizado rivers) and the coast. During the Terminal Classic period (A.D. 800 – 1100) these populations had their maximum influence along these rivers and the coast.

The glass shard chemical composition (Table 3) indicates that the glass shards are slightly more silicic and contain less Aluminium than the glass shards reported for El Chichón unit A (Cocheme *et al*., 1982; Luhr *et al*., 1984) and unit B (Macías *et al*., 2003). However they also show high potassium concentrations typical of El Chichón glass shards (Fig. 5), making El Chichón the most likely source volcano. The tephra layer is probably related to unit E, although no fallout layers have been associated with the massive block and ash flow deposits of unit E (Espíndola *et al*., 2000; Macías *et al*., 2008). The eruption has been assigned a VEI of 3 and probably included a dome destruction event (Macías *et al*., 2008). The average of four radiocarbon-dated samples (Table 2) yielded a calibrated age of A.D. 567 ± 37 (at 68.2 % probability). Probably the best sample was from carbonised tree branches from a pyroclastic flow deposit with white pumice which gave an AMS radiocarbon age of 1520 ± 75 14C yr. B.P. (A.D. 520 ± 90 at 68.2 % probability) (Espíndola *et al*., 2000). We eliminated the AMS radiocarbon age of 346 ± 34 14C yr. B.P. on a wood sample, probably a root, from directly above the ash-layer. A charcoal sample from the same depth gave an AMS radiocarbon age of 1535 ± 44 14C yr. B.P. (A.D. 460 ± 30 and A.D. 540 ± 40 at 68.2 % probability). This age is in line with the calibrated age for volcanic deposit unit E.

There was a worldwide reduction in tree growth between about A.D. 539 and A.D. 545 that was detected using tree-ring analysis (Eronen *et al*., 2002; D'Arrigo, 2001; Baillie, 1994; Scuderi, 1990, 1993) and crop failure, famine and disease were widespread in Eurasia and Africa (Gunn, 2000).

This might have been the result of the sulphate aerosol cloud that was formed after the eruption. The stratospheric cloud probably spread globally and caused a strong reduction in direct solar irradiation worldwide.

It is remarkable that around the same time, a dense and persistent dry fog occurred in Europe and the Middle East. Historical records describe meteorological phenomena like those observed in A.D. 536-537: "The sun was dark and its darkness lasted for eighteen months; each day it shone for about four hours; and still this light was only a feeble shadow…the fruits did not ripen and the wine tasted like sour grapes." (Stothers, 1984). However, it is not very likely that the stratospheric cloud of the El Chichón eruption caused this dry fog. Large plinian eruptions can cause climatic forcing, but most dry fogs are caused by minor events that inject toxic volatile gases and aerosols only into the troposphere (Grattan and Pyatt, 1999).

According to Maya archaeologists, the period after approximately A.D. 539 is known as the "Maya Hiatus." The "Maya Hiatus" was first noted by Morley (1938) as a period of diminished dedication of historical carved monuments (stelae) at ancient Maya sites (Fig. 6). During the "Hiatus," important cities like Tikal and cities along the Río de la Pasión and the Usumacinta River were devastated (Gill and Keating, 2002). For the Rio Azul area, the "Hiatus" was comparable to the Classic Maya Collapse of the 9th century AD, the only difference being that there was a recovery from the "Hiatus" (Adams, 2003). Adams (1990) showed that both elite centres and rural areas were devastated during the "Hiatus". Other evidence comes from a palynological study of a core from Lake Tuspán, a lake 300 km east of El Chichón volcano. Results of the pollen analyses show a drastic interruption of agricultural activity at approximately A.D. 540 (Galop *et al*., 2005), just after a high magnetic susceptibility peak.

A large volcanic sulphate peak was found in ice cores from Greenland around A.D. 529-530 (Zielinski, 2000; Larsen *et al*., 2008). The peak was caused by a mid to high northern latitude eruption (Larsen *et al*., 2008) and was likely related to the dry fog of A.D. 536-537. Larsen *et al*. (2008) also found a large volcanic sulphate peak in the Dye-3, GRIP and NGRIP ice cores from Greenland at A.D. 533-534 ± 2, using the new GICC05 timescale (Vinther *et al*., 2006). The peak was not found in the GISP2 ice core and previously underestimated in the GRIP core (Clausen *et al*., 1997). Probably the same volcanic eruption caused a large signal around A.D. 547 ± 17 in Antarctic ice cores (Traufetter *et al*., 2004). Given the amount and distribution of sulphate deposition, the eruption must have been a tropical volcanic eruption of somewhat larger magnitude than the A.D. 1815 Tambora eruption (Larsen *et al*., 2008). El Chichón was the probable source volcano and we tentatively assign A.D. 539 as the most likely year of eruption (Nooren *et al*., in prep.).

El Chichón Tephra, unit D

Although the number of volcanic glass shards in the pollen slides show a small peak at 56 cm depth, we did not find clear evidence of tephra deposition related to this large plinian eruption of ~1250 yr BP. The eruption left thick ash flow and surge deposits (unit D) near the volcano (Espíndola *et al*., 2000) and contained abundant pottery shards (Tilling *et al*., 1984), and had an estimated VEI of 4 (Macías *et al*., 2008). The calibrated age of deposit Unit D is A.D. 755 ± 75 and A.D. 855 ± 15 at 68.2% probability (Table 2) (Espíndola *et al*., 2000).

El Chichón Tephra, unit C

At a depth of about 45 cm, volcanic glass shards are abundant in the macrofossil samples. Changes in the pollen assemblage are comparable with the situation after the ~A.D. 539 eruption, although changes are less pronounced. Fern spores increase at the expense of *Cephalanthus* pollen. After the temporary decrease in *Cephalanthus* pollen, they rapidly regain their dominance and reach their highest percentages in the pollen diagram. The tephra marks the transition from zone 4 to zone 5. Relatively high abundance of Tetraedron minimum and an increase of Characeae oospores (*Chara* sp. and *Nitella* sp.) indicate a change to wetter conditions.

We relate the tephra to the El Chichón eruption (VEI ~3) that resulted in massive pumice flow deposits (Unit C) near the volcano (Macías *et al*., 2008). At 68.2% probability, the calibrated age of deposit Unit C shows two intervals A.D. 1065 ± 25 and A.D. 1175 ± 55 (Espíndola *et al*., 2000).

Although no clear sulphate peaks occurred in the GISP2 ice core (Zielinski, 2000), ice cores from Antarctica show peaks at A.D. 1040 ± 8 (Traufetter *et al*., 2004) and around A.D. 1045 (Cole-Dai, 2004).An eruption around A.D. 1175 would also be in accordance with the calibrated age of deposit unit C. Both ice cores from Greenland and Antarctica show large sulphate peaks around A.D. 1175. However this date does not fit well in our age-depth model, making an eruption around A.D. 1045 most likely (Fig. 2).

El Chichón Tephra, unit B

A small peak in the abundance of volcanic glass shards within the macrofossil samples occurred at ~37 cm depth. This tephra marks the change from zone 5 to 6.

Cephalanthus pollen percentages decrease from more than 80% to less than 20% and they are replaced by a variety of pollen from *Bucida buceras*, *Rhizophora mangle*, *Mimosa pigra*, *Typha domingensis* and others. This might indicate a disturbance by increased salinity or drought. The absence of a fern peak makes this event different in comparison to the earlier human impact events. The exact environmental meaning of the decrease in *Cephalanthus* pollen at this level remains, however, unclear.

The tephra was probably deposited after the large plinian eruption of El Chichón around ~A.D. 1343 (unit B). The eruption (VEI ~4) mainly resulted in thick pumice fall deposits near the volcano (Macías *et al*., 2008). The calibrated age of deposit Unit B at 68.2% probability is A.D. 1335 ± 20 and A.D. 1395 ± 10 (Espíndola *et al*., 2000). The ~A.D. 1343 eruption column (~31 km) reached higher into the stratosphere than the three sustained plinian columns of the 1982 eruption (Macías *et al*., 2003). The distribution of the fall-out layers indicates a NE orientation of the plume for which Palenque (see Fig. 1) must have been covered by at least 2 cm of ash (Macías *et al*., 2003). At that time, Palenque had already been abandoned for centuries.

Ice cores from Greenland and Antarctica show large sulphate peaks at A.D. 1345 ± 2 (Zielinski, 2000), A.D. 1343 ± 5 (Traufetter *et al*., 2004) and around A.D. 1347 (Cole-Dai, 2004), which coincides with the age of this tephra layer based on the age-depth model (Figure 2) .

Unknown source volcano Tephra

A 2.4 cm thick, yellowish tephra layer is present from 30.5-32.9 cm depth within zone 6. The tephra layer contains sharp-edged vesiculated glass shards and angular crystals of comparable size to those from the tephra layer at 60 cm depth. The tephra contains relatively more basaltic hornblende and augite.

The same tephra layer was found at many of the 12 coring sites, pointing to widespread deposition of ash. From the available AMS radiocarbon dates (Tebbens, unpublished data) we calibrated an approximate age of A. D. 1515 for the deposition of the tephra layer.

Remarkably, the eruption did not cause a major change in the pollen assemblage. The only noted change is a short-term increase of freshwater sponges and diatoms, in response to the increased supply of silica after the tephra deposition. Likewise, Telford *et al*. (2004) found increased diatom and sponge concentrations after tephra deposition in central Mexican lake sediments.

Preliminary analyses of the glass shards indicate a different composition than those of the ~A.D. 539 eruption. The glass is more andesitic, has less silica and potassium, and more aluminium. Unfortunately we cannot identify the source volcano yet. Espíndola *et al*. (2000) did not find evidence of an eruption of El Chichón around this date.

A small sulphate peak was detected in the GISP2 and GRIP core at A.D. 1515 and A.D. 1512, respectively (Clausen *et al*., 1997; Zielinski, 2000). Traufetter *et al*. (2004) did not identify volcanic-derived sulphate in Antarctic ice cores around A.D. 1515. However, the SP2000 ice core shows a sulphate peak around A.D. 1508 (Cole-Dai, 2004).

Tephra San Martín (A. D. 1793)?

A small peak in the abundance of tephra within the macrofossil samples was found at the transition from zone 6 to 7 at 22 cm. *Bucida buceras* pollen increases rapidly and dominates the tree pollen assemblage. In the herb pollen assemblage, only Cyperaceae, Poaceae and Polygalaceae show a slight increase. The disappearance of algal remains, poor preservation of pollen, and increase in fungal spores indicate a change to drier conditions.

The abrupt change probably marks the onset of a severe drought period in Mesoamerica that occurred after the 1793 San Martín and 1815 Tambora eruptions (Gill and Keating, 2002). Caballero *et al*. (2006) found shallower lake levels at Lago Verde between circa A. D. 1785 and 1885, indicating drier conditions in the area near San Martín volcano.

We tentatively adopt an age for this tephra layer of A. D. 1793, mainly based on the age-depth model (Figure 2). Nonetheless, the 1793 eruption of San Martín was probably local and phreatomagmatic (Espíndola, personal communication), which might have produced only a minor impact at the study site.

Santa María Tephra (A.D. 1902)

The abundance of tephra shards within the macrofossils in the pollen slides shows a peak at 15 cm depth. The peak is probably related to an eruption of Santa María in Guatemala in A. D. 1902. Historical records do describe tephra deposition in Tabasco after the A. D. 1902 eruption of Santa María, and the Pozo Petrolero site is located within the 1 mm tephra fall isopach (Williams and Self, 1983).

The eruption marks the change from zone 7 to 8. The return of *Cephalanthus* does indicate a change towards wetter conditions. However samples above 15 cm contain few pollen and are dominated by fungal spores probably related to an increase of human activity in the area. During the mid 19th century canals were dug and dikes were built to make the area more accessible.

Tephra El Chichón, unit A (A.D. 1982)

At approximately 1 cm depth a ~1 mm thick tephra layer was encountered. The tephra layer contains sharp-edged vesiculate glass shards and angular crystals (including basaltic hornblende and augite) of comparable size as those from the tephra layer at 30 and 60 cm depth. Based on the shallow occurrence and the location of the coring site within the known distribution of the 1982 El Chichón 1mm isopach (Figure 1), it is highly likely that this tephra layer was deposited during the 1982 El Chichón eruption.

Conclusions

The Pozo Petrolero study site enabled us to build a tephrochronological framework which can be linked to the late Holocene eruption history of El Chichón volcano. Seven of the ten tephra layers could be related to past eruptions of El Chichón and correspond very well with units A, B, C, E, F, G and H as described by Espíndola *et al*. (2000). Although for many of these eruptions no fallout layers have been identified yet, our results indicate that most of the eruptions caused tephra fall at our study site, 150 km NNE of the volcano. Remarkably no clear evidence of tephra deposition was found at the study site after the large plinian eruption of ~1250 yr BP (unit D).

A tephra layer from an unknown volcano was deposited at approximately A.D. 1515.

Most eruptions could be related to sulphate peaks in ice cores from Greenland and Antarctica. However, further tephrochronological work in the area is needed to verify the tentative eruption data given.

Almost all tephra layers correlated with stratigraphic changes in the composition of the sediments. At this distant location, changes are not due to the direct impact of tephra fall, except for the short-term increase of freshwater sponges and diatoms in response to an increased supply of silica. Changes are mainly caused by human responses in severely affected areas. The eruption around A.D. 539 for example, registered in the core at 60 cm depth, had a devastating effect on the core area of Maya civilisation and was probably the onset of the *Maya Hiatus* that was characterised by a demographic shift towards the Usumacinta-Grijalva delta. The eruption also caused rapid environmental changes worldwide.

Limnological and palynological work at higher resolution, in combination with tephrochronology, will contribute to a more detailed understanding of the impact of past eruptions. We hope that this research will stimulate archaeologists to look for evidence of past eruptions of El Chichón. Eruptions that frequent and devastating must have been recorded by the ancient Maya.

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