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23,000 yr of vegetation history of the Upper Lerma, a tropical high-altitude basin in Central Mexico

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Abstract

Pollen analysis on a 9.54-m sediment core from lake Chignahuapan in the upper Lerma basin, the highest intermontane basin in Central Mexico (2570 m asl), documents vegetation and limnological changes over the past ~23,000 ^{14}C yr. The core was drilled near the archaeological site of Santa Cruz Atizapán, a site with a long history of human occupation, abandoned at the end of the Epiclassic period (ca. 900 AD). Six radiocarbon AMS dates and two well-dated volcanic events, the Upper Toluca Pumice with an age of 11,600 ^{14}C yr B.P. and the Tres Cruces Tephra of 8500 ^{14}C yr B.P., provide the chronological framework for the lacustrine sequence. From ca. 23,000 ^{14}C yr B.P. to ca. 11,600 ^{14}C yr B.P. the plant communities were woodlands and grasslands based on the pollen data. The glacial advances MII-1 and MII-2 correlate with abundant non-arboreal pollen, mainly grasses, from ca. 21,000 to 16,000 ^{14}C yr B.P., and at ca. 12,600 ^{14}C yr B.P. During the late Pleistocene, lake Chignahuapan was a shallow freshwater lake with a phase of lower level between 19,000 and 16,000 ^{14}C yr B.P. After 10,000 ^{14}C yr B.P., tree cover in the area increased, and a more variable lake level is documented. Late Holocene (ca. 3100 ^{14}C yr B.P.) deforestation was concurrent with human population expansion at the beginning of the Formative period (1500 B.C.). Agriculture and manipulation of the lacustrine environment by human lakeshore populations appear at 1200 ^{14}C yr B.P. (550 A.D.) with the appearance of *Zea mays* pollen and abundant charcoal particles.

Keywords: Pollen; Late Pleistocene; Holocene; Vegetation history; Paleolimnology; Glaciations; Tropical mountains; Archaeology; Mexico

Introduction

The Trans-Mexican Volcanic Belt region crosses Mexico from east to west at latitudes of 19 to 21°N (Fig. 1A). In this mountainous region a variety of landscapes is present with ice-capped volcanoes and high-altitude basins, some with lakes. Sediment records from several of these lakes provides evidence of changes in the plant communities as well as in lake levels over the last 25,000 ^{14}C yr B.P. (Bradbury, 2000; Caballero, 1995; Caballero and Ortega-Guerrero, 1998; Caballero et al., 2001, 2002; Lozano-García and Ortega-Guerrero, 1994, 1998; Lozano-García et al., 1993; Metcalfe et al., 1991; Xelhuantzi-López, 1994; Velázquez, 2003). New data from the central Mexican volcanoes provide evidence of shifts in the altitude of the equilibrium line of glaciers, suggesting synchrony with mid-latitude North American alpine glaciations (Vázquez-Selem, 2000; Vázquez-Selem and Heine, 2004). However, a clear picture of the extent and intensity of late Pleistocene climate change and its impact on plant communities in this region has not yet emerged. There are indications of cool climates during the late glacial maximum (LGM) although more complex climatic variability has recently been suggested (Metcalfe et al., 2000).

A paleoclimatic model based on lake-level data assumes that during the LGM drier conditions prevailed in the eastern and central sector of the Trans-Mexican Volcanic Belt (TMVB) due to the displacement of the easterly winds

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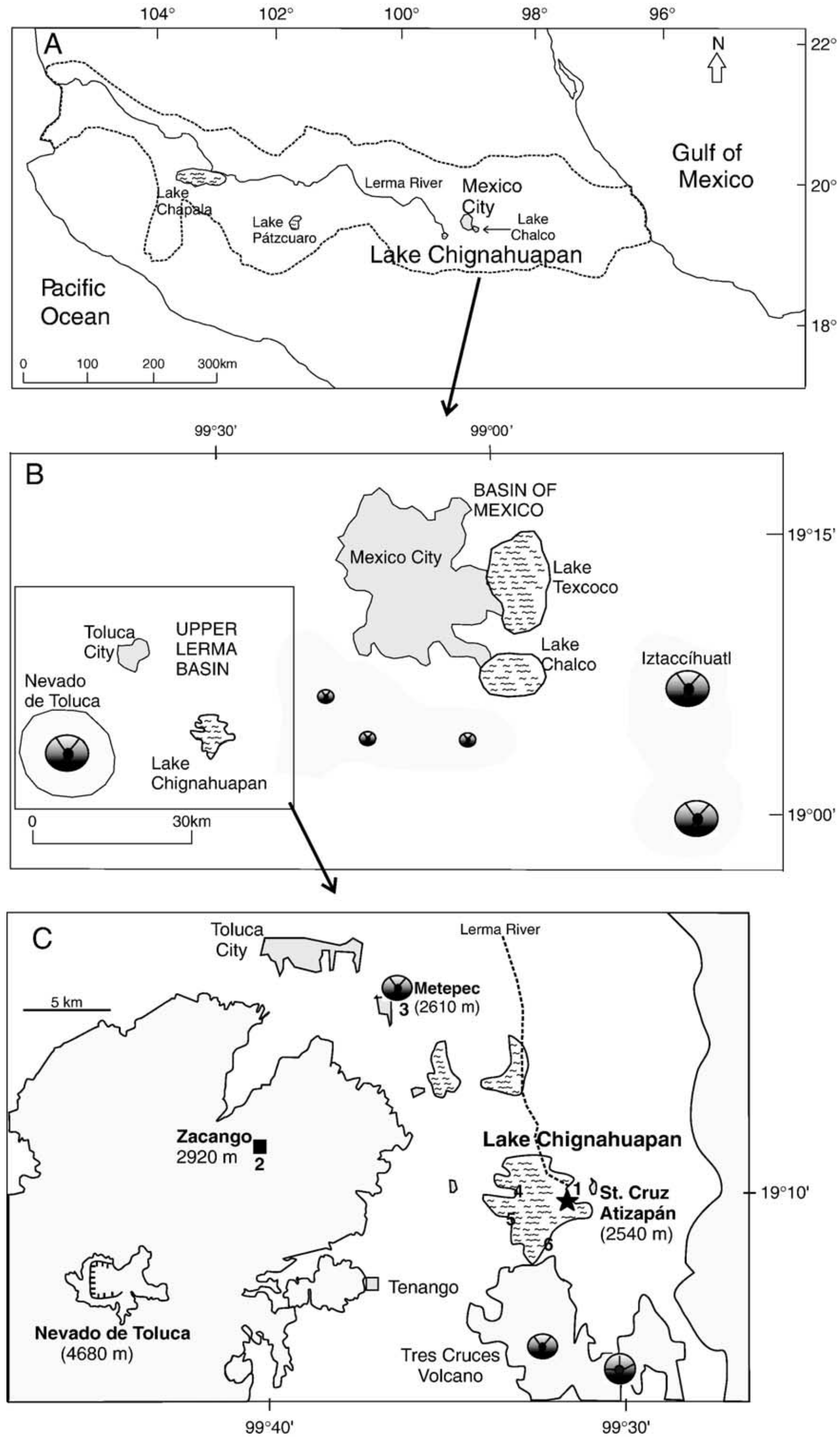


Figure 1. Locations Maps. (A) Transmexican Volcanic Belt with the location of Lake Chignahuapan, Mexico City, and Lakes Chalco and Pátzcuaro. (B) Upper Lerma Basin and Basin of Mexico with the Iztaccíhuatl volcano. (C) Upper Lerma Basin with the location of the study site: (1) Santa Cruz Atizapán core (★) and other palynological records: (2) Zacango and (3) Metepec. Location of previous published paleolimnological studied sites: (4) La Isla core II (Caballero et al., 2001); (5) Pit 2 (Metcalfe et al., 1991); (6) Pit 1(Metcalfe et al., 1991); (7) Almoloya del Río core (Caballero et al., 2002; Newton and Metcalfe, 1999). Shaded areas indicate elevations over 2800 m asl.

towards the south, but that winter precipitation was enhanced in the western part of the region by the displacement of the westerlies (Bradbury, 1997, 2000). In the few pollen records that cover from the full glacial through to the late Holocene in Central Mexico, a clear pattern of regional climatic change is difficult to identify because the sites are sparsely located. One of the most studied basins in the Mesoamerican highlands is the Basin of Mexico (BM) (Fig. 1B) where paleoecological investigations began in the 1950s (Bradbury, 1971, 1989; Caballero, 1997; Caballero and Ortega-Guerrero, 1998; González-Quintero, 1986; González-Quintero and Fuentes-Mata, 1980; Lozano-García and Ortega-Guerrero, 1994, 1998; Lozano-García and Vázquez-Selem, in press; Lozano-García et al., 1993; Sears, 1952; Sears and Clisby, 1955). Most of the sites in the Basin of Mexico have good microfossil preservation for the full glacial/interglacial cycle but only a few have adequate preservation in the Holocene, particularly where human disturbance has modified the paleoenvironmental record of the last 5000 yr. The Upper Lerma Basin (ULB) (Figs. 1B and C) located 30 km west of the Basin of Mexico is less disturbed and offers an ideal site for paleolimnological and paleoclimatic research.

The sediment sequence from the Upper Lerma Basin discussed in this paper has particularly good resolution for the Holocene. We present the history of plant communities during the last 23,000 ^{14}C yr B.P. and evidence of the limnological evolution of Lake Chignahuapan. The pollen stratigraphy is compared with the revised glacial history of the adjacent Nevado de Toluca volcano and the late Holocene pollen record is related to the archaeological record. A comparison between the pollen records of the Upper Lerma Basin and the nearby Basin of Mexico is presented.

Environmental setting

The Tertiary volcanic–tectonic activity of the TMVB led to the formation of several lacustrine basins such as the ULB, the highest intermontane basin (2575 m asl) in Central Mexico (Figs. 1A and B). Late Quaternary volcanic sierras in the east, west, and south limit the ULB (Fig. 1C), whose main elevation is the Nevado de Toluca (4680 m asl), an andesitic–dacitic stratovolcano of late Pliocene to Holocene age. Geological studies have demonstrated significant late Pleistocene–Holocene activity of the volcano (Bloomfield and Valastro, 1974; Cantagrell et al., 1981; García-Palomo et al., 2002).

Springs, wetlands, and shallow lakes characterize the basin's floor. From south to north there are three water bodies connected by the Lerma River, the longest river in Mexico (Fig. 1C). Today, water demand from nearby Mexico City has let to decline of the lakes. The climate is temperate with a mean annual temperature of 12.2°C and mean annual precipitation of 933 mm that peaks during the summer.

In recent years a great part of the natural vegetation has been modified by agricultural and forestry activities. Some patches of the natural coniferous forests and the oak forests are preserved in the southern highlands of the basin. The main plant communities according to their altitudinal ranges are as follows: Alpine grasslands (4300–4000 m), *Pinus hartwegii* forest (4000–3500 m), *Pinus* and *Quercus* mixed forests (3500–2600 m), *Abies* forest (3600–2560 m), and *Quercus* forest (3100–2350 m) (Martínez and Matuda, 1979; Ramos, 2000). An inventory of the aquatic vegetation of the lakes was carried out by Ramos (2000).

Volcanic history

In common with many of the highest mountains in Central Mexico, the Nevado de Toluca volcano (4680 m) was active during the late Pleistocene, with a complex eruptive history involving the construction and destruction of the volcanic edifice (García-Palomo et al., 2000; Macías et al., 1997). Evidence of two important dome collapse episodes before 50,000 ^{14}C yr B.P. is found in the deposits of the southern flanks of the volcano (Capra and Macías, 2000; Macías et al., 1997). Explosive activity continued between 42,000 and 28,000 ^{14}C yr B.P. with several pumice deposits and block and ash flows (García-Palomo et al., 2002; Macías et al., 1997). Two important plinian eruptions are documented, the first at ca. 24,500 ^{14}C yr B.P. named the Lower Toluca Pumice (LTP) and the second at ca. 11,600 ^{14}C yr B.P. named the Upper Toluca Pumice (UTP) (Bloomfield and Valastro, 1974, 1977). Other plinian pumices (14,000, 12,100, and 3300 ^{14}C yr B.P.) have been recognized recently by Macías et al. (1997) and García-Palomo et al. (2002). Pyroclastic products (ashes and pumices) were spread over vast areas around the volcano reaching the lacustrian plain, where they are preserved. These volcanic layers provide stratigraphic markers inside the basin and in some cases between basins (Arce et al., 2003; Newton and Metcalfe, 1999). It is also possible to find products of numerous monogenetic volcanoes such as the Tres Cruces tephra (TCT), dated at 8500 ^{14}C yr B.P.

Glacial history

In spite of the significant volcanic history of Nevado de Toluca evidences of glaciations and periglacial activity are preserved. Based on tephrachronology and ^{14}C dates Heine (1976a,b, 1988, 1994) described the moraine systems and rock glaciers, establishing a glacial chronology that is correlative with other glacial sequences from Central Mexico. New data and a revised glacial chronology are proposed by Vázquez-Selem and Heine (2004), identifying four dated moraines in the Nevado de Toluca: MI older than 40,000 ^{14}C yr B.P.; MII-1 between 24,000 and 17,000 ^{14}C yr B.P.; MII-2 younger than 17,000 ^{14}C yr B.P. and older than 11,000^{14}C yr B.P.; and MIII younger than 11,600 ^{14}C yr B.P.; MIII has been related to the Younger Dryas event (Arce et al., 2003).

Paleoenvironments

Previous paleolimnological studies were done by Metcalfe et al. (1991) in two Holocene pits from Lake Chignahuapan (Fig. 1C), recording fluctuations in water level and chemistry. Diatom content of a ca. 14,000 ^{14}C yr B.P. sediment core (La Isla) from the western part of the lake (Fig. 1C) was analyzed by Caballero et al. (2001) but the record is interrupted by significant deposits of volcanic material. Late Pleistocene–Holocene lake level fluctuations based on diatom analyses and magnetic properties are documented from the Santa Cruz Atizapán (Fig. 1C) core and Almoloya del Río core (Fig. 1C) (Caballero et al., 2002), in the eastern and central sectors of the lake. Caballero et al. (2002) summarize and integrate all the paleolimnological evidence from lake Chignahuapan in a lake level fluctuation curve for the last ca. 22,000 ^{14}C yr B.P. The pollen sequence presented in this paper is from the Santa Cruz Atizapán core (Fig. 1C).

Some evidence of Pleistocene vegetation in the area, based on pollen records, has been reported. Pollen analysis in the fluvial–lacustrian sediments of the Metepec sequence (Fig. 1C), in the northern part of the Upper Toluca basin, indicates the presence of abundant *Isöetes* aff. *mexicana* spores from ca. 35,000 to 11,500 ^{14}C yr B.P., along with Pleistocene megafauna remains, *Mammuths columbi*, *Bison*, *Equus* and *Camelops*, between 27,180 and 24,000 ^{14}C yr B.P. (Caballero et al., 2001) (Fig. 1C). Another record of ca. 30,000 ^{14}C yr B.P. in paleosols and lacustrian sediments from a quarry in Zacango (2920 m asl) (Fig 1A) is dominated by grass pollen related to alpine grasslands (Caballero et al., 2001). Other sources of paleoenvironmental information are the paleosols-tephra sequences studied from two quarries (Zacango and Arroyo la Ciervita) on the northeastern flanks of Nevado de Toluca (Sedov et al., 2003). The data indicate drier stages during the formation of two late Pleistocene paleosols with ages between 28,100 ^{14}C yr B.P. and 27,900 ^{14}C yr B.P.

Archaeology

The riverine–lacustrine environments of the ULB, rich in natural resources, have played an important role through thousands of years of human history. Archaeological investigations (Sugiura, 1992, 2000; Sugiura et al., 1994) reveal that the lakeshore region was colonized, at the latest, during the middle Formative period at around 800 BC, with a series of permanent settlements based on fishing, hunting, and collecting of water resources and some rudimentary agriculture. It was, however, after several hundred years, at around 550–600 AD, that the marshland was successfully exploited by human groups. Classic period populations constructed numerous islands in the shallow waters of Chignahuapan such as the Santa Cruz Atizapán site. Archaeological investigations reveal that they developed a complex society well adapted to these particular environmental conditions. During the subsequent Epiclassic period (ca. 650–900 AD), this lacustrine culture reached its apogee, when more than a hundred man-made islands of different sizes were built. All of these sites, however, were abandoned by the end of the Epiclassic period, ca. 900 AD.

Methods

A pit of 200 cm was excavated near the Santa Cruz Atizapán archaeological site in the western sector of Lake Chignahuapan (Fig. 1C). At the base of the pit, a core of 754 cm was drilled using an Eijkelkamp percussion soil sampler. Samples of 2 cm^3 were taken every 10 cm along the pit and the core for pollen analysis. All samples were treated with a dispersant agent (Sigmaclin) and *Lycopodium clavatum* tablets were added to each sample to calculate pollen concentration values. 10% HCl and 5% KOH were used to eliminate carbonates and remove the organic matter, respectively. The silicates were removed with 50% HF over 24 h and the residue was mounted in glycerin jelly. Microscope analyses were performed with an Olympus BX50. Minimum counts of 500 pollen grains and spores excluding the algae were done; during the pollen counting, charcoal particles of >50 μm were also counted.

For pollen identification, the reference collection of the Instituto de Geología, UNAM, was used. A total of 126 fossil pollen and spore types were found in the Santa Cruz Atizapán (STCRZ) sequence. TILIA and TILIAGRAPH softwares were used for calculation and presentation of the pollen data (Grimm, 1987, 1992). The pollen counts are presented in percentage pollen diagrams where the taxa are arranged into six categories: (1) trees, (2) shrubs and herbs, (3) Pteridopytes, (4) swamp, (5) aquatics, algae, and (6) fungi spores. Taxa belonging to categories 1, 2, and 3 were included in the pollen sum, whereas categories 4, 5, and 6 are presented as percentages of the pollen sum.

The magnetic properties, diatoms and LOI analyses and ^{14}C dates of the same sequence are reported separately by Caballero et al. (2002).

Results

Chronology and lithology

The chronology of the core is based on six AMS ^{14}C dates (Caballero et al., 2002) and two dated tephra layers, the Upper Toluca Pumice (UTP) dated at ~11,600 ± 110 ^{14}C yr B.P. (Bloomfield and Valastro, 1974, 1977) and the Tres Cruces tephra (TCT) with an age of 8500 ^{14}C yr B.P. (Bloomfield, 1975). The age model is presented in Figure 2. The STCRZ core is a sequence of silt, sands, and volcanic products (pumices and ashes). The lithology is shown is Figures 3 and 4 and a detailed description is given by Caballero et al. (2002).

The pollen record

The Santa Cruz Atizapán (STCRZ) pollen record is continuous from 950 cm to 90 cm; from 90 cm to the surface, which corresponds to the time of human occupation, no pollen was found; only charcoal particles were recovered. The charcoal abundance in the top 90 cm was extremely high.

The pollen stratigraphy is presented in percentage pollen diagrams with the most important taxa showing the

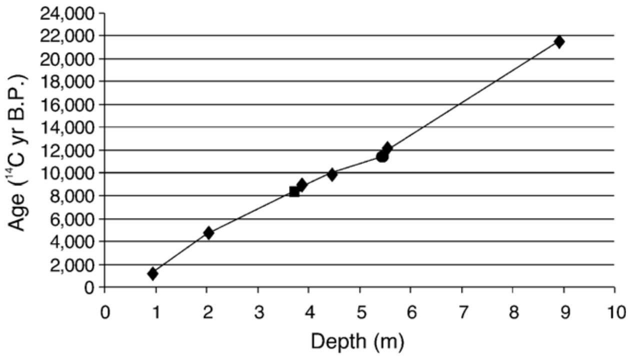


Figure 2. Age model. Depth vs. AMS ^{14}C dates. Solid diamond (◆) corresponds to ^{14}C dates of Santa Cruz Atizapán core. The solid circle (●) to the UTP tephra and the solid star (★) to the Tres Cruces tephra. See Caballero et al. (2002) for more details on chronology.

downcore changes (Figs. 3 and 4). Pollen zones were established using CONISS, a stratigraphically constrained cluster analysis (Grimm, 1987). The pollen diagrams are divided into two by the UTP (ca. 11,600 ^{14}C yr B.P.), separating the Pleistocene (zones I and II) and Holocene (zones III, IV, and V) periods.

The diversity of trees, shrubs, and herbs in the STCRZ pollen record is of 126 taxa but only 65 are presented in Figures 3 and 4. The main pollen taxa representing the coniferous forests and the mixed forest are *Pinus*, *Quercus*, *Alnus*, *Abies religiosa*, and Cupresaceae-type (Fig. 3). Other taxa present in low percentages are *Picea*, *Salix*, and *Bursera* and the mesophytic assemblage (*Fraxinus*, *Fagus*, *Taxus*, *Carya*, *Juglans*, *Liquidambar*, Ericaceae, and *Heliocarpus*). *Acacia* is the only shrub taxon identified. Among the herb taxa, Poaceae is dominant, but 20 herbaceous taxa with low percentages are also present. In the upper part of the diagram *Zea mays* pollen is present indicating human presence in the area. *Sellaginella*, *Pteris*, *Lycopodium*, Schizeaceae, *Telypteris*, *Polypodium*, monolete, and trilete types are grouped as a fern spore assemblage. In the local diagram (Fig. 4) the swamp assemblage includes the following: (a) *Arenaria* which grow in humid soils; (b) Cyperaceae, *Typha*, *I.* aff. *mexicana*, and *Polygonum* which live on the shoreline; and (c) the floating mat rooting *Potamogeton* and *Myriophyllum*. In the aquatic assemblage, included are the free floating *Nymphaceae*, *Hydrocotile*, *Nuphar*, *Azolla*, *Lemna*, and the algae *Spirogyra*, *Mougeotia*, *Zygnemataceae*, *Botryococcus*, *Pediastrum*, *Coelastrum*, and *Staurastum*.

Zone STCRZ-I (940–690 cm): ca. 23,000 to 16,600 ^{14}C yr B.P.

This zone is characterized by high values of herbs with two maxima (53%) at 881 cm (55.3%) and between 740 cm and 700 cm mainly represented by Poaceae (16–49%), and Asteraceae (19–2%). The coniferous and mixed forest trees, such as *Pinus* (22–47%), *Quercus* (5–15%), *Alnus* (4–10%), Cupresaceae (3–11%), and *A. religiosa* (1–2%) exhibit low values. Among the swamp taxa, Cyperaceae, *Potamogeton*, *I.* aff. *mexicana*, and *Lemna* are well represented. *Pediastrum*, *Spirogyra*, and Zygnemataceae are regularly present and *Botryococcus* increases at the top of the zone. The fungi spores have reduced values in the upper part of the zone.

Zone STCRZ-II (690–445 cm): ca. 16,000 to 11,850 ^{14}C yr B.P.

A general reduction in the Poaceae values (7–14%) defines this zone; although a notable peak (60%) is recorded at 569 cm. At the top of the zone there is an increase in Cheno-Am (6%), Asteraceae (16–25%), Verbenacae (7%), and the highest percentage of *Artemisa* (14%) is present. An increase in the percentages of the forests taxa (26–83%) with *Pinus* (18–52%), *Quercus* (13%), and *Alnus* (7–13%) is documented. The last record of *Acacia* between 675 and 601 cm is present in this zone. At the top of the zone, the swamp assemblage Cyperaceae, *Potamogeton*, *Lemna*, and *Typha* show an increase in their values. A high number of fungal spores are also present in this zone but this decreases at the top.

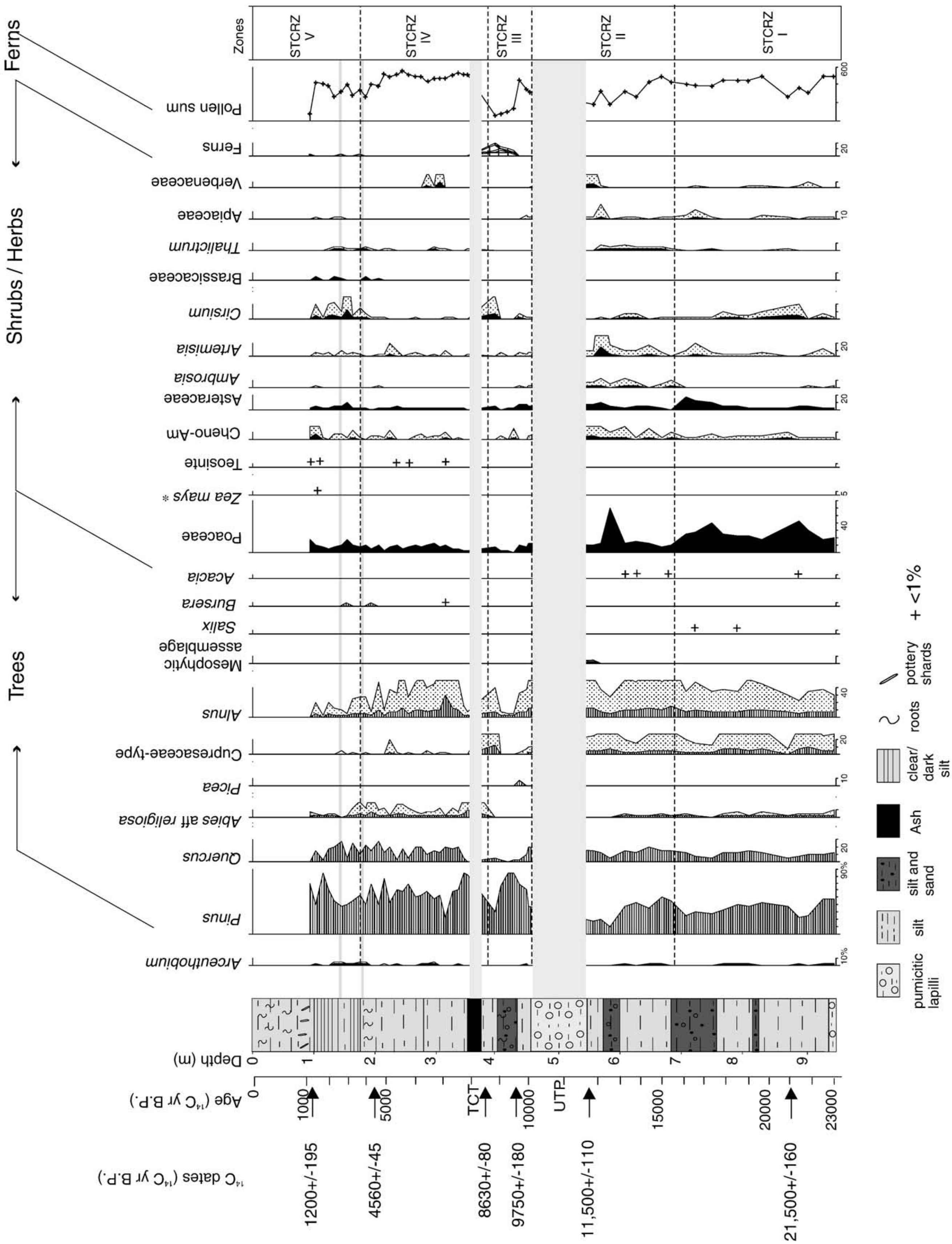
Zone STCRZ-III (445–390 cm): ca. 11,850 to 8500 ^{14}C yr B.P.

Fluctuations in the values of the forest taxa characterize the zone, with high values of *Pinus* (30–85%) and a trend towards lower percentages of *Quercus* (20–1%) and *Alnus* (12–1%) at the middle part of the zone. Other taxa such as *A. religiosa* and the mesophytic assemblage are absent. The only record of *Picea* (1%) is found at the end of this zone (340 cm). The herbs show lower values (3–26%) than in the previous zones. Fern spores increase markedly in this zone achieving a maximum of 20%, with *Polypodium* (1–10%) as the main taxa. The swamp taxa, Cyperaceae, *Typha*, and *Lemna* decrease their presence. This is the only zone where *Azolla* is present. Microspores of *I.* aff. *mexicana* show their maximum values. The Zygnemataceae (1–20) and Spirogyra (7–33) are present in the zone. Fungi spores decrease significantly (4–89) in comparison with the previous zone values.

Zone STCRZ-IV (390–170 cm): ca. 8500 to 3700 ^{14}C yr B.P.

The group of trees shows the highest percentages of the record (59–98%). *Pinus* (41–81%), *Quercus* (5–20%), and *A. religiosa* (1–10%) increase their percentages while Cupressaceae-type values are minimal (1–4%) and are absent at some levels. The herbs reduce their values (1–25%) and are represented by Poaceae (1–11%), Asteraceae (1–3%), and Verbenaceae (1–8%). The first record (1%) of Teosite is at 250 cm, reaching 4% at the top of the zone. Fern spores decrease (1–2%) in relation to the previous zone. Swamp elements have low values but at the

Figure 3. Percentage summary pollen diagram of Santa Cruz Atizapán core from lake Chignahuapan. ^{14}C AMS dates, age (^{14}C yr B.P.), tephrachronology, depth, and lithology are shown in the left side of the diagram. Trees, shrubs, and herb pollen with dotted area shows a fivefold exaggeration for less frequent taxa. $^{+}$ pollen 1%, (*) indicate cultigens.



Trees
Shrubs / Herbs
Ferns
Zones
STCRZ V
STCRZ IV
STCRZ III
STCRZ II
STCRZ I
Pollen sum
Ferns
Verbenaceae
Apiaceae
Thalictrum
Brassicaceae
Cirsium
Artemisia
Ambrosia
Asteraceae
Cheno-Am
Teosinte
Zea mays *
Poaceae
Acacia
Bursera
Salix
Mesophytic assemblage
Alnus
Cupresaceae-type
Picea
Abies aff religiosa
Quercus
Pinus
Arceuthobium
Depth (m)
Age (^{14}C yr B.P.)
^{14}C dates (^{14}C yr B.P.)
TCT
UTP
1200+/-195
4560+/-45
8630+/-80
9750+/-180
11,500+/-110
21,500+/-160
pumicitic lapilli
silt
silt and sand
Ash
clear/ dark silt
roots
pottery shards
+ <1%

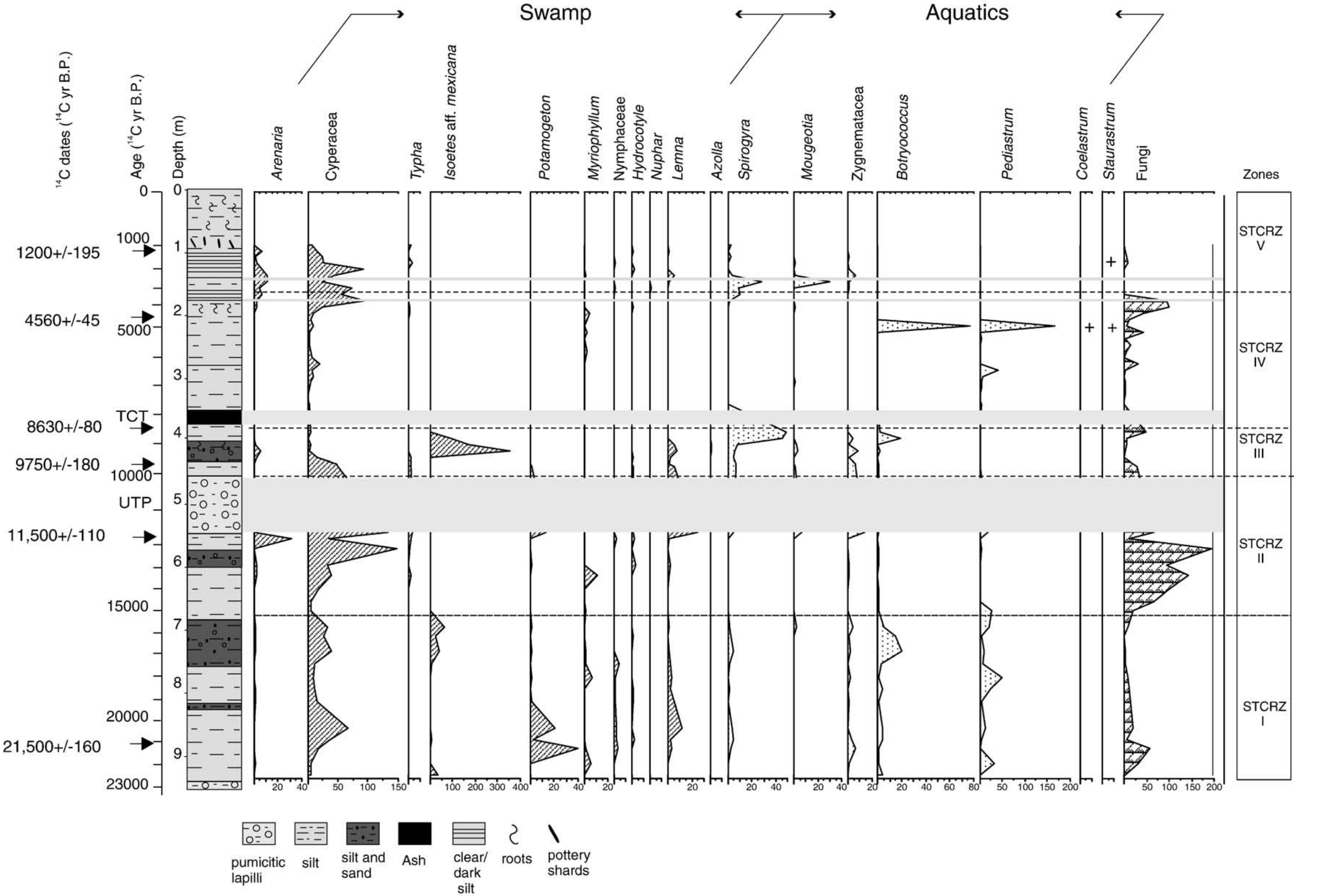


Figure 4. Local pollen diagram of Santa Cruz Atizapán core from lake Chignahuapan. ^{14}C AMS dates, age (^{14}C yr B.P.), tephrachronology, depth, and lithology are shown in the left side of the diagram. Swamp and aquatics taxa are presented as percentage of the pollen sum.

top of the zone the Cyperaceae increases. Large peaks of algae occur at 230 cm, with *Botryococcus* and *Pediastrum* with *Staurastrum* and *Coelastrum* occurring for the first time in the record High numbers (426) of fungal spores occur at the top of the zone (190 cm).

Zone STCRZ-V (170–90 cm): ca. 3700 to 1200 ^{14}C yr B.P.

All taxa registered in the previous zone continue to be present but some increase in representation namely Poaceae (5–16%), Asteraceae (1–7%), *Cirsium* (13%), and others such as *A. religiosa* (1%), Cupressaceae-type (1%), and the mesophytic assemblage showed lower percentages (1%). Taxa indicative of human activity characterized this zone with *Z. mays* (1.4%) at 100 cm. Fern spores show values between 1% and 4%. Swamp taxa (*Arenaria* and Cyperaceae) values increase. The aquatics have low values and only the algae *Spirogyra*, *Mougeotia*, and Zygnemataceae present high values at 150 cm. Fungal spores decrease suddenly in comparison with the previous zone. Charcoal particles reach the highest values of the record with maximum of 1000 at 90 cm (Fig. 4).

Interpretation and discussion of the pollen record

The Late Pleistocene record

The lake Chignahuapan pollen record in the Upper Lerma basin provides historical information on Pleistocene and Holocene paleoflora and gives insights into the paleoenvironments of the highest basin in Central Mexico. The STCRZ Pleistocene pollen assemblages (zones STCRZ-I and STCRZ-II) from ca. 23,000 to 11,850 ^{14}C yr B.P. are clearly distinct from those of the Holocene (Figs. 3 and 4). The regional Pleistocene vegetation record, before deposition of the UTP tephra (11,600 ^{14}C yr B.P.), is characterized by low percentages of forest pollen types, high values of herbaceous taxa, mainly Poaceae, Asteraceae, and high numbers of swamp taxa (Fig. 5). Grass pollen in modern forest pollen rain spectra reaches values of <10% (Palacios-Chávez, 1977; Tovar, 1987). Higher percentages of Poaceae (>10%) can be found in the pollen rain of alpine grasslands, at higher elevations open forest (3500–4000 m asl) and grasslands (Palacios-Chávez, 1977; Tovar, 1987). Therefore, this high percentage of Poaceae is interpreted as indicative of the presence of open forest around Chignahuapan.

Three maxima (>50%) of non-arboreal pollen are documented at ca. 21,300 ^{14}C yr B.P., between ca. 17,500 and 16,000 ^{14}C yr B.P. and at ca. 12,600 ^{14}C yr B.P. according to the age model (Fig. 2). These high values of herbaceous taxa correlate in the local diagram (Fig. 4) with increases in swamp vegetation, Cyperaceae and *I.* aff. *mexicana*, a submerged fern indicative of cool shallow waters (Bonilla-Barbosa and Novelo-Retana, 1995). In addition, the pollen concentration values are low throughout most of core, ranging between 460 and 10,500 grains/cm^3, except for a peak of 66,000 grains/cm^3 just below UTP (Fig. 5). Altitudinal fluctuation of the plant communities during the local glacial advances could explain the high percentages of grass pollen. In the revised glacial stratigraphy of the Nevado de Toluca volcano proposed by

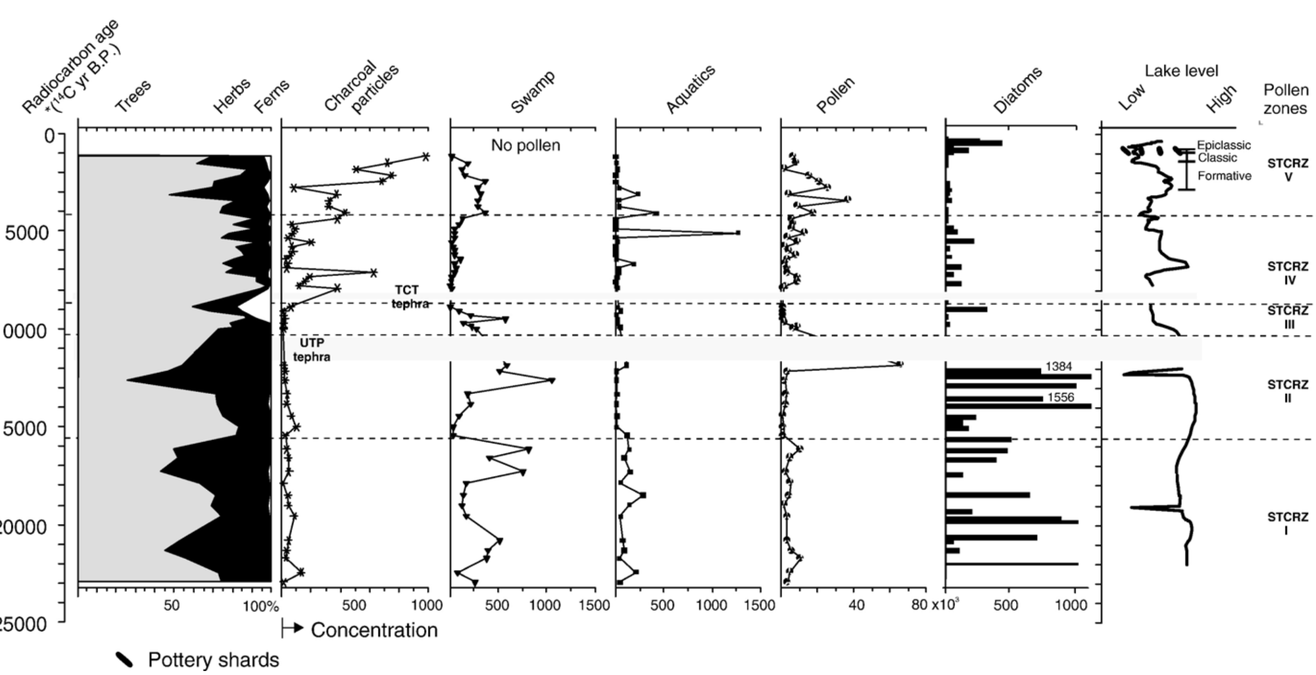


Figure 5. Summary diagram of Santa Cruz Atizapán core showing variations in percentages of arboreal pollen vs. non-arboreal pollen and concentration of microscopic charcoal particles, swamp, aquatic, and total pollen taxa. Lake-level curve and diatoms concentration is based on Caballero et al. (2002). Radiocarbon age is shown on the left side of the diagram.

Vázquez-Selem and Heine (2004), the ages given to the Pleistocene moraines are as follows: M-II-1 24,000 to 17,000 ^{14}C yr B.P.; and M-II-2 17,000 to 11,600 ^{14}C yr B.P. We consider that the three non-arboreal maxima correspond to these glacial advances, as there is good age correlation. The new glacial chronology available for the Central Mexico volcanoes points to a lowering in the altitude of the equilibrium line of 930 m to 730 m during late Pleistocene local advances, with a lowering in temperature of 5° to 9°C (Vázquez-Selem, 2000; Vázquez-Selem and Heine, 2004). The timberline position was also depressed, probably between about 900 and 700 m below its present position, thus modifying the local distribution and the composition of the plant communities. Today the ecotone between the alpine grasslands with bunch grasses and the *P. hartwegii* forest is located at 4000 to 4300 m on the Nevado de Toluca volcano, as in other high elevations in Central Mexico (Beaman, 1962; Lauer, 1978; Lauer and Klaus, 1975). Assuming a 900-m depression in the timberline during the late Pleistocene, the limit between the *P. hartwegii* forest and the alpine bunch grasses would be established at ca. 3100 m asl. Some of the volcanic products of the Nevado de Toluca have been dated with charcoal fragments found within pumices and ashes, but for the UTP (11,600 ^{14}C yr B.P.) the absence of tree trunks and charcoal suggests that arboreal vegetation was not present above 3000 m, providing further support for a depression in tree line (Arce et al., 2003). Further fossil pollen spectra (ca. 30,000^{14}C yr B.P.) from Zacango (2920 m asl), located at 25 km NW of the STCRZ record (Fig. 1C), show consistently higher percentages (>40%) of grass pollen suggesting the dominance of alpine grasslands at this site (Caballero et al., 2001). Late Pleistocene pollen data from Tlaloc II of La Malinche volcano (3100 m asl), 95 km E of the ULB indicate the presence of alpine grasslands with high values of grass pollen between 40% and 60% (Straka and Ohngemach, 1989).

Lake level reconstruction based on diatom content indicates that during the late Pleistocene, Lake Chignahuapan was a shallow freshwater lake (Caballero et al., 2002). Particularly between 19,000 and 16,000 ^{14}C yr B.P. the magnetic properties of sediments of the STCRZ core (Caballero et al., 2002) show an increase in sediment input and slightly lower lake level, probably related to high erosion rates and/or poor soil development. This correlates with high percentages of grasses and high number of swamp taxa and fungal spores (Figs. 3 and 4). From ca. 16000 ^{14}C yr B.P. to ca. 13,000 ^{14}C yr B.P., the diatom data indicate a slight increase in water level while a peak in *Pediastrum* along with a reduction in the Cyperaceae and *Isoetes* is noted (Fig. 4). During the latest Pleistocene (ca. 12,600 ^{14}C yr B.P.), before the fallout of the UTP, a short period of dry conditions is recorded with the highest values of grasses (69%), and significant Cyperaceae values (Fig. 4). The magnetic signal change, with the rise of hematite content indicates oxidizing conditions associated with marshy environments in the eastern and western shores of lake Chignahuapan at ca. 12,400 ^{14}C yr B.P. (Caballero et al., 2002).

In the STCRZ record it is possible to correlate high non-arboreal taxa, low pollen concentration, the lowering of the timberline, high sediment input to the lake, and marshy conditions with the glacial chronology, in particular at ca. 21,000 ^{14}C yr B.P., between ca.17,500 to 16,000 and 12,600 ^{14}C yr B.P. This weak representation of forest pollen during the Late Pleistocene has been found in pollen records from the neighboring Basin of Mexico (Lozano-García, 1996; Lozano-García and Ortega-Guerrero, 1994, 1998; Lozano-García et al., 1993; Sosa-Nájera, 2001), suggesting the existence of extensive woodlands and parklands with abundant grasses related to cold, dry late Pleistocene climates.

The glacial and late-glacial pollen records of the ULB show similarities with the pollen assemblages of Lake Chalco, located 25 km to the east (Fig. 1B) in the basin of Mexico, such as low pollen concentration, important representation of herbaceous taxa (mainly grasses, 10–20%), and continuous presence with significant percentages of Cupressaceae-type pollen (10–20%) (Lozano-García, 1996; Lozano-García and Ortega-Guerrero, 1994; Lozano-García et al., 1993; Sosa-Nájera, 2001).

The occurrence of glacial advances and open woodlands in both basins is consistent with cold climates during the LGM. It is inferred that the modern summer rainfall regime was rather different (Emiliani et al., 1975; Guilderson et al., 1994) with a significant reduction in rainfall in these basins during the LGM. The palynological responses to the glacial drier climate are as follows: (i) the presence of Cupressaceae pollen (*Juniperus* or *Cupressus*) with percentages of ~20% in the records of Chalco in the basin of Mexico and Chignahuapan in the ULB, (ii) increases in *Mimosa* aff. *biuncifera* which in the basin of Mexico has been reported in the southern lake Chalco at 17,000 ^{14}C yr B.P. and 15,000 ^{14}C yr B.P. along with Cupresaceae pollen and high values of grass pollen (Lozano-García, 1996; Lozano-García and Ortega-Guerrero, 1994; Lozano-García et al., 1993; Sosa-Nájera, 2001). Today, *M. biuncifera* grows in the northern regions of the basin, where mean annual precipitation is 500 mm/yr (Rzedowski and Rzedowski, 2001). Based on its modern distribution, we infer that high values of *Mimosa* pollen are related to glacial conditions, drier than today. Significant presence of Juniper, in the Lake Pátzcuaro pollen record in the western part of Central Mexico, was typical of the Pleistocene environment (Watts and Bradbury, 1982). An earlier interpretation was that this taxon represented a xeric juniper. Recently, Bradbury (2000) re-considered this interpretation and related the *Juniperus*-pollen type to the swamp cypress (*Taxodium mucronatum*), based on the fact that a *Taxodium* log, found in the western shore of Lake Chalco, dated to 23,150 ^{14}C yr B.P. According to González-Quintero (1986), the swamp cypress indicates local climates with mean annual precipitation of 1500 mm/yr and mean annual temperatures of 20°C. Such climatic parameters only occur today in low altitudes of the tropical areas of the Mexican coasts, both Gulf of Mexico and in the Pacific, the last under the influence of the ITCZ (Mosiño and García, 1974). Such conditions are not likely to have been present in the Upper Lerma during the LGM, so we infer that this pollen type is related to Cupresaceae rather than the swamp cypress. Paleolimnological reconstruction from Lake Chalco (Caballero and Ortega-Guerrero, 1998) indicates a trend towards lowering lake level as glacial conditions were established (ca. 30,000 ^{14}C yr B.P.) until ca 22,000 ^{14}C yr B.P. when volcanic activity disrupted the record. However, low lake level conditions prevailed in Chalco between ca. 18,500 and 14,000 ^{14}C yr B.P.

The Holocene record

The Holocene pollen record (zones STCRZ-III, STCRZ-IV and SRCRZ-V) is characterized by an increase in forest taxa (60–95%), a reduction in herbaceous (Fig. 3), swamp and aquatics assemblages (Fig. 4), a higher pollen concentration, and an important number of charcoal particles (Fig. 5).

There is an interruption in pollen deposition due to the UTP fallout but the pollen record is re-established after this event. The two available AMS ^{14}C dates of the SCTRZ core bracket the pumice between 11,850 and 9950 ^{14}C yr B.P. and these dates are in agreement with the age of 11,600 ^{14}C yr B.P. proposed by some authors for the UTP event (Arce et al., 2003; Bloomfield and Valastro, 1974; Macías et al., 1997). After the volcanic episode, the sediments register expansion of the coniferous forest elements between ca. 10,000 and ca. 9000 ^{14}C yr B.P. In this period, pollen of *Picea* (Fig. 3) was found at 340 cm (ca. 9700 ^{14}C yr B.P.) suggesting that cold conditions prevailed in the area. Today, the three Mexican spruce species (*P. martinenzii*, *P. mexicana* and *P. chihuahuana*) are distributed in the northern part of Mexico in cool temperate montane forest with small fragmented populations restricted at altitudes between 2000 and 3700 m (Ledig et al., 1997, 2000). Late Pleistocene fossil pollen of *Picea* has been reported in sediment sequences of other locations of the TMVB (González-Quintero and Fuentes-Mata, 1980; Lozano-García et al., 1993; Ohngemach, 1977; Sosa-Nájera, 2001) suggesting a broad range of his boreal taxa during glacial times. During the early Holocene a glacial advance named M-III (younger than 11,600 ^{14}C yr B.P.) by Heine (1994) is documented for the Nevado de Toluca. This advance is correlated with the Milpulco-1 in the Iztaccíhuatl dated at 10,000 to 9000 ^{14}C yr B.P. (Vázquez-Selem and Heine, 2004). On the basis of diatom analyses (Caballero et al., 2002), lake level reconstruction indicates that during this period of cold environments, the lake was a shallow marsh. In the pollen record, the high amount of *I.* aff. *mexicana* spores support this interpretation (Fig. 4) but there is not evidence of an increase in the herbaceous assemblages as in the Late Pleistocene pollen data (Fig. 3).

As part of the volcanic activity reported for the east and south of the Toluca basin, the Tres Cruces volcano, located 5 km south of lake Chignahuapan (Fig. 1C), produced a tephra which was dispersed to the NNW (Bloomfield, 1975). In the SCRTZ core the TCT tephra is 23 cm thick. After the fallout of TCT, abundant charcoal particles are found in the sediments (Fig. 5), probably as the result of the fires caused by the volcanic activity. During the period ca. 8500 to 3700 ^{14}C yr B.P. (Zone IV) climatic amelioration is inferred, the forest communities with *Pinus*, *Quercus*, and *Alnus* are well represented and also, *A.* aff. *religiosa* with a continuous presence and higher percentages (1–10%) than during Late Pleistocene times (Fig. 3). A significant peak of *Alnus* (20%) occurs at ca. 7300 ^{14}C yr B.P. along with the lowest *Pinus* values during the Holocene and also high charcoal particles concentration (Figs. 3 and 5) although in the STCRZ sediment sequence no evidence of tephra deposition was found. In areas of Central Mexico the *Alnus* forest replaces the coniferous forest after disturbance (Velázquez et al., 2000) and the high concentration of microscopic charcoal suggest fires in the area. Other arboreal taxa such as Cupresaceae-type responded, reducing their contribution significantly for this time and the herb assemblage maintain low values (Poaceae, Asteraceae). In the basin of Mexico records, similar pollen responses are documented, in particular the marked presence of *Abies* during the Holocene (Lozano-García, 1996; Lozano-García et al., 1993; Sosa-Nájera, 2001).

Poor representation of the swamp taxa (Fig. 5) from ca. 8500 to 7000 ^{14}C yr B.P. suggests low lake levels which is in agreement with areophilous diatom taxa that gives indications of subaerial conditions after the TCT deposition (Caballero et al., 2002; Metcalfe et al., 1991). A minor phase of high lake level at ca. 6800 ^{14}C yr B.P., based on the diatom analysis, is recorded in the local pollen diagram (Fig. 4) only by a moderate increase of *Pediastrum*; after this episode, low water level conditions return. A short high water event, in comparison to the previous period, occurred during the mid-Holocene at ca. 5100 ^{14}C yr B.P. (230-cm) with the algae *Pediastrum* and *Botryococcus* present in the record at high numbers. After this event, a period of drier conditions can be inferred with the slight increase in the swamp taxa (Cyperaceae, *Typha*, and *Myriophyllum*) and low representation of the aquatics along with the increase of fungi between ca. 5000 and ca. 4000 ^{14} C yr B.P. (Fig. 4). This episode correlates with the marsh environment suggested in the lake level reconstruction (Fig. 5) based on the diatom data of Caballero et al. (2002). Paleolimnological data from sediment sequences in the western and southern sectors of the lake also show marsh conditions at this time, in spite of the incompleteness of the records (Metcalfe et al., 1991).

The late Holocene pollen record covers from ca. 3500 to ca. 1200 ^{14}C yr B.P. (1500 BC to 600 AD). During this period, the highest values of non-arboreal pollen (>50%) for the Holocene occur at ca. 3100 ^{14}C yr B.P. and can be related to deforestation (Fig. 5). According to the archaeological evidence, this time correlates with human population expansion in the area at the beginning of the Formative period (1500 BC) (Sugiura, 2000; Sugiura et al., 1994). The presence of Chenopodiaceae and *Z. mays* pollen at 1200 ^{14}C yr B.P. (AD 600) in the SCTRZ sequence (90 cm) is unequivocal evidence of human activity in the area I.

After 1200 ^{14}C yr B.P. the record is interrupted by the transformation of the lacustrine environment because of the construction of man-made mounds. Archaeological evidence (Sugiura, 1992, 2000; Sugiura et al., 1994) indicates that when the lacustrine society flourished in Chignahuapan, the islands were built directly over the lacustrian sediments as the water table descended enough by ca. 1400^{14}C yr B.P. (550 AD) (Caballero et al., 2002). The archaeological evidence of these man-made islands indicates that the original inhabitants did not rely on agriculture but that subsistence activities were based on the appropriation of aquatic resources. Therefore, pollen of *Z. mays* present in the SCTRZ record at 90 cm suggests that the original occupants of these mounds were active in exchanging lacustrine products with basic grains from the human groups settled on the nearby alluvial plain.

Ethnographic evidence points to the intervention and manipulation of the lacustrine environment by human lakeshore communities (Sugiura et al., 1994). Today, in order to keep the waterways and fishing, hunting and collecting areas in reasonable condition, people burn dried aquatic vegetation during the peak of the dry season (May). It is highly probable that the original inhabitants of these man-made islands also influenced their environment through similar practices for similar purposes. An unusual amount of charcoal fragments was uncovered during the excavations and in the microscopic charcoal record of the SCTRZ (Fig. 5), the highest concentrations of charcoal particles are attained in the upper part of the sequence.

Conclusions

The SCTRZ lacustrine sequence records the continuous history of the late Quaternary plant communities of the Upper Lerma Basin, Central Mexico. Late Pleistocene plant communities comprised extensive grasslands and open mixed forests. Between ca. 19,000 and 16,000 ^{14}C yr B.P. the maximum in non-arboreal elements, mainly grasses, correlates with an increase in the input of sediments to the lake, suggesting that this type of open plant community developed where the tree line was about ~ 900 m lower than today; all evidence points to a local tree line at ca. 3100 m asl. This period correlates with the LGM and the local MII-1 glacial advance. The other Pleistocene peak of grass pollen at ca. 12,600 ^{14}C yr B.P. occurred during the MII-2 local glacial advance. Although no evidence of the high input of sediments was found, there is some evidence of a short, low water phase at ca. 12,400 ^{14}C yr B.P. Levels in the Chignahuapan lake during the Late Pleistocene seem to have been more stable than during the Holocene; however, a slightly shallower phase is inferred between ca. 19,000 and 16,000 ^{14}C yr B.P. The more stable Late Pleistocene water table conditions in this area are perhaps related to lower evaporation rates during the dry season due to colder climatic conditions.

Pollen spectra of the Holocene are different from those of the Late Pleistocene, indicating the presence of dense coniferous and mixed forests related to increased temperature. Holocene forest expansion documented in the ULB pollen stratigraphy, associated with increases of *Pinus*, *Quercus*, *Alnus*, and *Abies*, is also evident in the lake Chalco (Basin of Mexico) pollen records. The palynological responses of the plant communities in both basins, with open forests and grasslands in the cold Late Pleistocene climate, and forest expansion during the climatic amelioration of the Holocene, are evidence of a regional climatic signal, in spite of local environmental disturbances such as volcanic eruptions.

During the Holocene lake Chignahuapan was shallow with variable lake levels. The Upper Lerma Basin has a long archaeological history and for the latest Holocene the construction of the man-made islands in the lake testifies to the close relationship between the human populations and the lacustrine ecosystem.

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