A high-elevation Holocene pollen record from Iztaccíhuatl volcano, central Mexico

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Abstract: Pollen data from 3860 m in the Agua El Marrano valley on the northwest side of Iztaccíhuatl volcano (southeastern part of the Basin of Mexico, 19°N), combined with data on the glacial chronology and tephrochronology, document Holocene climatic and vegetation changes near the present timberline. Glacial advances occurred between ~12 000 and ~10 500 cal. yr BP (Milpulco-1) and between 8300 and 7300 cal. yr BP (Milpulco-2). A 450-cm core was drilled in sediments accumulated in a Milpulco-1 moraine depression. The sequence covers the last 11 000 cal. yr BP, according to three ¹⁴C dates and the presence of a distinctive pumice deposit dated elsewhere at 5700 cal. yr BP. The pollen record of Agua El Marrano shows barren conditions after glacier retreat, followed by a gradual colonization by elements of the alpine grasslands around 10 900 cal. yr BP. This plant community remained until c. 7200 cal. yr BP. Between c. 7200 cal. yr BP and 6500 cal. yr BP coniferous forest grew close to or at the site, but alpine grasslands were re-established between 6500 cal. yr BP and c. 5000 cal. yr BP, apparently in connection with mid-Holocene dry conditions recorded in central Mexico. The upper timberline attained its modern altitude (~4000 m) in the last 3000 years. During this period no significant changes are observed in the pollen spectra. Comparison with other palaeoecological records from central Mexico suggests that the timberline fluctuated in response to both temperature and precipitation changes during the Holocene.

Key words: Pollen, glaciation, vegetation history, central Mexico, tropical mountains, Holocene.

Introduction

The tectonic and volcanic evolution of the Mexican Volcanic Belt (MVB) during the late Tertiary and Quaternary led to the formation of high stratovolcanos and depressions with endorheic sedimentary basins. This geological province crosses Mexico with a NNW–SSE orientation between 21° and 19°N (Ferrari et al., 1994; Ferrari, 2000). Extensive lakes formed in some of the tectonic depressions, preserving the palaeoenvironmental signal through continuous and semi-continuous sedimentation. Research on late Pleistocene vegetation history and palaeoecology carried out in the last decade in several sedimentary sequences of the MVB lakes provides information of climatic change and human impact in a region considered the northern limit of the American tropics (Metcalfe et al., 1991; Lozano-Garcia et al., 1993; Xelhuantzí-López, 1994; Lozano-Garcia and Ortega-Guerrero, 1994; 1997; Caballero, 1995; Caballero and Ortega-Guerrero, 1998; Bradbury, 2000; Caballero et al., 2002; Velázquez, 2003).

The pattern of climatic change for the last 20 000 years in the central highlands of Mexico is rather complex (Metcalfe et al., 2000). In the Basin of Mexico, one of the most studied areas, several sequences covering the last glacial maximum have been analysed and the pollen data indicate cool and dry conditions. Most of the palaeorecords from central Mexico show climatic oscillations during the transition from the Last Glacial to the Holocene but a clear picture has not yet emerged. Palaeoclimatological evidence for the early Holocene is contradictory as dry conditions are inferred from palaeolimnological data while pollen stratigraphy suggests an increase in montane mesic taxa. Indications of drier conditions for a short period during the mid-Holocene emerge from several palaeorecords in central Mexico (Grimm et al., 2001). The late Holocene climatic change signal in many of the MVB basins is disrupted by the long history of human occupation. Indications of higher lake levels for the last c. 3000 years in the Basin of Mexico point towards moister climates (Caballero and Ortega, 1998; Caballero et al., 2001, 2002), although most of the late Holocene sediments are lost because of human impact on the environment, making it difficult to define the climatic variability for this interval. In the neighbouring Lerma basin, periods of drought have been documented for the last 1000 years, with low lake levels during the Classic archaeological period (c. AD 800) (Caballero et al., 2002). Most of the existing palaeoecological records come from lake basins between elevations of 1800 and 2600 m, i.e., relatively low areas within...
Few published records exist for the mid slopes (around 3000 m) of the volcanic mountains (Ohngemach, 1977; Ohngemach and Straka, 1983; Almeida-Leñero, 1997; Caballero et al., 2001) and none for sites above 3100 m.

The aim of this paper is to use the pollen record to document changes in the Holocene plant communities of a high-elevation site (3860 m) located near the present timberline of Iztaccíhuatl volcano. In addition, new evidence on Holocene glacial advances of Iztaccíhuatl allows an evaluation of the impact of glaciation and related climatic changes on vegetation at local and regional scales.

The site and its environmental context

The study site is located in a moraine depression of the glacial valley Agua Agua El Marrano (3860 m) on the northwest side of Iztaccíhuatl volcano at 19°12′35.67″N and 98°39′57.00″W. Iztaccíhuatl (5286 m) and Popocatepetl (5452 m) volcanos are part of the Sierra Nevada range, which separates the basins of México and Puebla-Tlaxcala (Figure 1a). The eruptive history of Iztaccíhuatl stratovolcano consists of two main phases of construction, the old volcanic series with an age of > 600 Ma and the younger volcanic series of < 600 Ma (Nixon, 1989). Several glacial advances have been documented on Iztaccíhuatl during the late Pleistocene and Holocene (White, 1962; Heine, 1988; Vázquez-Selem, 2000), postdating volcanic activity. At present small glaciers cover the summit area of Iztaccíhuatl above 4900 m (Lorenzo, 1964; White, 2002). In contrast, Popocatepetl volcano has been active throughout the late Pleistocene and Holocene (Siebe et al., 1996) and is still active at present (Martin-Del Pozzo et al., 2002). As a consequence of repeated explosive eruptions, a number of tephra layers from Popocatepetl can be found in the lacustrian beds in the Basin of Mexico (Mooser, 1967; Lambert 1986; Ortega and Newton, 1998; Ortega-Guerrero et al., 2000) and on the slopes of neighbouring mountains, such as Iztaccíhuatl (Heine, 1975; Siebe et al., 1996; Vázquez-Selem, 2000).

The depression from which the core was collected is perched on a structural bench of the valley side-slope (Figure 1a,b). A moraine ridge isolates it from the main valley stream. The depression has internal drainage, but there are no signs of flooding either on the surface or in the sediment column, as volcanic rocks and sediments of the area are highly permeable.

Figure 1 Location of the study area and other sites mentioned in the text. (a) Basins and major stratovolcanoes of central Mexico. 1, Agua El Marrano site; 2, Lake Quila site; 3, Tláloc crater site. (b) Iztaccíhuatl volcano. (c) Northwest Iztaccíhuatl, showing extent of glacial advances around Agua El Marrano valley and coring site. 1, Milpulco-1 glacier area and moraines; 2, Milpulco-2 glacier area and moraines; 3, Coring site.
No streams enter the depression. Sediments trapped by the moraine consist of colluvium derived from the inner slopes of the moraine and tephras produced by the main eruptions of Popocatépetl volcano, located 21 km to the south-southeast. The entire catchment has an area of c. 2 ha, including c. 0.5 ha of the flat accumulation surface covered by bunchgrasses, and c. 1.5 ha of moraine slopes covered by open forest and bunchgrasses.

A revised glacial chronology of Iztaccíhuatl is based on surface exposure cosmogenic nuclide dating ($^{36}$Cl) and tephol-chronology (Vázquez-Selem, 2000; Vázquez-Selem and Heine, 2004). Inasmuch as the production rates of cosmogenic $^{36}$Cl in rocks are estimated mainly from calibrated $^{14}$C ages (Phillips et al., 1996), $^{36}$Cl ages are assumed to be equivalent to calibrated dates. The chronology includes two glacial advances (Hueyatlaco 1 and 2) between 20,000 and 14,000 cal. yr BP; a glacier advance (Milpulco-1) and retreat between ∼12,000 and ∼10,500 cal. yr BP; a short advance (Milpulco-2) peaking by 8300 cal. yr BP, with recession lasting through 7300 cal. yr BP; and a re-advance (Ayoloco) younger than 10,000 cal. yr BP, presumably related to the Little Ice Age.

The present altitudinal distribution of vegetation belts in the Sierra Nevada (Iztaccíhuatl and Popocatépetl volcanoes) and their diagnostic species have been documented in several studies (Cruz-Cisneros, 1969; Lauer, 1978; Islebe and Velázquez, 1994; Almeida et al., 1994; Velázquez et al., 2000; Rzedowski and Rzedowski, 2001). Vegetation at the coring site is an open community of Pinus hartwegii with bunchgrasses (Calamagrostis tolucensis and Festuca tolucensis). Pinus hartwegii is the only tree species growing above 3600 m and therefore forming the timberline of the high volcanos in central Mexico. In the Sierra Nevada ranges it is distributed in a belt at altitudes between 3100–3200 m and 3800–4000 m, where a wide ecotone with the alpine bunchgrassland is established, displaying variations depending on local factors (soils, winds, exposure, etc.) (Beaman, 1962; Lauer and Klaus, 1975; Almeida et al., 1994). The mean elevation of the timberline on Iztaccíhuatl is 4020 m, with a standard deviation of 50 m (Beaman, 1962). The association of P. hartwegii and bunchgrasses represents a natural fire climax association (Lauer, 1978). However, man-induced fires apparently have lowered the timberline from its potential elevation of 4250 m (upper elevation of trees) to its present position of around 4000 m (Lauer, 1978). It has been hypothesized that the elevation of the timberline on Iztaccíhuatl is controlled by low temperatures (Beaman, 1962) or by low soil temperature in combination with soil moisture deficiency (Lauer, 1978).

Mean annual temperature at the timberline in central Mexico (c. 4000 m) is 5°C (Lauer and Klaus, 1975).

### Table 1 High-altitude plant communities in central Mexican mountains and their characteristic species

<table>
<thead>
<tr>
<th>Community</th>
<th>Coniferous forests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpine grasslands</td>
<td>Pinus hartwegi, Abies religiosa, Cupressus lusitanica, Senecio callosus, Quercus laurina</td>
</tr>
<tr>
<td>3900–4500 m</td>
<td>Festuca livida, Calamagrostis toluensis, Calamagrostis toluensis, Cirisium jorullensis, Geranium</td>
</tr>
<tr>
<td>3460–4000 m</td>
<td>Pinus hartwegi, Festuca toluensis, Calamagrostis toluensis, Cirisium jorullensis, Geranium</td>
</tr>
<tr>
<td>2850–3540 m</td>
<td>Senecio callosus, Quercus laurina, Cupressus lusitanica, Senecio callosus, Quercus laurina</td>
</tr>
</tbody>
</table>

### Previous palaeoecological studies

Palaeoenvironmental research in the Basin of Mexico has been carried out mainly in the southern section, in the sub-basin of Lake Chalco (Figure 1a). The catchment of this lake includes the western slopes of Iztaccíhuatl (Figure 1a). Diatoms, pollen and the geochemistry and magnetic properties of several dated lacustrine sequences in Lake Chalco have been studied recently (Lozano-García et al., 1993; Lozano-García and Ortega-Guerrero, 1994; 1997; Caballero and Ortega, 1998; Ortega-Guerrero and Newton, 1998). Pollen data in the cores indicate changes in the early and mid-Holocene forest communities (Lozano-García et al., 1993; Lozano-García and Ortega-Guerrero, 1994; 1997; Lozano-García, 1996; Sosa-Najera, 2001). The late Holocene vegetation record is disrupted by human activity in the sub-basin, but other proxy indicators such as diatoms suggests an increase in water-level.

Two Holocene pollen sequences from the middle slopes of mountains have been studied in neighbouring basins: Tláloc crater (3100 m) on the eastern flank of Malinche volcano (Ohngemach and Straka, 1983) and Lake Quila (3010 m) in the Zempoala volcanic range (Almeida-Leñero, 1997) (Figure 1a).

### Methods

We obtained a 450-cm sediment core using an Eijkelkamp soil sampler. In the laboratory samples for pollen analysis were taken at 5-cm intervals. *Lycopodium clavatum* spores were added in 2-cm$^3$ sediment samples at the beginning of the technique. Pollen was extracted from the samples using standard palynological techniques (Batten, 1999). In most samples a pollen sum of 500 grains was reached, although some levels were barren of pollen. Samples below a depth of 382 cm contained no pollen. The pollen sum was calculated based on the arboreal (AP) and non-arboreal pollen (NAP) excluding aquatic and subaquatic taxa. Calculation of pollen percentages and concentrations was carried out with Tilia and Tilia-Graph programs (Grimm, 1992). Pollen zones were established by CONISS Zonation (Grimm, 1987).

Fragments of charcoal and pollen extract, processed according to Brown et al. (1992), were submitted to Beta Analytic for AMS radiocarbon dating (Table 2).

### Results

#### Chronology and lithology

The sequence is dominated by dark grey sandy loams, presumably colluvially reworked volcanic ashes (see Figure 3). Near the bottom the sediments are gravelly sandy loams. We interpret the coarse gravel of the bottom of the sequence as ground moraine deposits.

The sediment sequence covers the last 11,000 cal. yr BP. The chronology is based on three AMS radiocarbon dates from the core itself plus the reported age (c. 5700 cal. yr BP) of a plinian pumice deposit from Popocatépetl volcano that was unequivocally identified in our core at a depth of 173 cm (Table 2). This pumice has been radiocarbon dated in the area between Popocatépetl and Iztaccíhuatl (Heine, 1975; Lambert and Valastro, 1976; Siebe et al., 1996), with calibrated ages ranging from 5525 to 5810 cal. yr BP (Table 2). The calibrated radiocarbon ages increase with depth and display a general linear relationship (Figure 2), with the exception of a sample near the bottom of the core (431 cm). We believe this age is
anomalously young, presumably resulting from contamination from higher levels, and therefore it is not included in the age model.

According to the age model (Figure 2), sediment accumulation in the moraine depression could have begun around 11 500 cal. yr BP, following the retreat of the glacier from its end moraine. However, we believe that sedimentation started some time later (probably around 11 000 cal. yr BP) based on the observation that erosion rates of moraine slopes (and therefore accumulation rates of colluvium at the base of moraines) are usually highest immediately after glacier recession, under periglacial conditions (Ballantyne, 2002).

In addition, the exposure age of a boulder from the enclosing moraine ridge, located 15 m from the coring site, was determined by means of the cosmogenic nuclide 36Cl (Zreda and Phillips, 2000). The boulder yielded 10 000 ± 500 36Cl kyr BP; which falls within the recessional phase of Milipulco-1 advance of Iztaccí´huatl (Va´zquez-Selem, 2000) and is roughly equivalent to 9000 14C yr BP. The exposure age appears to be younger than the true age of moraine formation, which is a common situation in surface exposure dating of moraines (Ballantyne, 2002).

No pollen was found at the bottom of the sequence from 440 to 390 cm, where the lithology is gravelly loamy sand. Pollen deposition starts at 382 cm depth (c. 10 900 cal. yr BP according to the age model), after the retreat of the glacier. During the last 9800 14C yr pollen concentration varied between 46 821 and 1681 grains per cm². An average pollen accumulation rate of 682 grains per cm² per year was calculated (Figure 3).

Pollen zonation was established by CONISS, a stratigraphically constrained cluster analysis (Grimm, 1987).

Zone 1 lasts from c. 10 900 cal. yr BP to c. 8000 cal. yr BP (382–235 cm depth). Pollen deposition began at 382 cm. This zone is characterized by the highest percentages of non-arboreal pollen (> 80%), mainly Poaceae with lower values of Draba, Arenaria and Plantago, which are elements from groups 1 and 2. The alpine bunchgrassland was therefore present near the coring site during the Pleistocene–Holocene transition. It was clearly established by 10 900 cal. yr BP and remained through c. 8000 cal. yr BP. Alpine grassland fossil pollen rain at other high-altitude sites of the MVB shows similar percentages (Straka and Ohngemach, 1989; Caballero et al., 2001). Arboresal taxa belonging to group 3, Pinus, Quercus and Ahtus vary between 7.6% and 1% and are probably related to upslope pollen transport. Pollen concentration fluctuates between 5500 grains per cm² at the base of the sequence (382 cm) and 26 000 grains per cm² before the deposition of the grey tephra at 290 cm. A reduction in the

![Figure 2](image-url)
Figure 3  Pollen percentage diagram of selected taxa from Agua El Marrano core. Pollen groups as in the text. AP, arboreal pollen; NAP, non-arboreal pollen. Solid square indicates pollen less than 1%. Timescale and lithology are shown in the left side of the figure. Shaded areas correspond to the tephra layers.
average pollen accumulation rate is observed after this volcanic event.

Zone 2 spans c. 8000 cal. yr BP to c. 3000 cal. yr BP (235–70 cm depth). Changes in the pollen stratigraphy allow the subdivision of this zone into three subzones. In the basal subzone 2a from c. 8000 to c. 6500 cal. yr BP (235–202 cm depth) the pollen data show an increase in coniferous forest elements. A trend towards higher values of arboreal pollen with Pinus (4.6–21.5%), Quercus (4.6–7.6%), Alnus (4.6–2.6%) and Abies aff. religiosa (<1%) begins in the first two samples from c. 8000 to c. 7200 cal. yr BP. Indicators of flooding conditions at the site, included in group 6, increase in this period, which corresponds to the Milpulco-2 glacial advance. Between c. 7200 and c. 6500 cal. yr BP Pinus show a trend towards higher values, reaching 92%. There are also slight increases in Quercus, (8%) Alnus (3.8%) and Cu.-Ju. type (3%), along with Eryngium (2.5%) and Arcetebium globosum (3%). This pollen assemblage is similar to the Pinus hartwegii forest modern pollen rain (Palacios, 1977; Ohngemach and Straka, 1983; Tovar, 1987). Arcetebium globosum, a characteristic element in the pollen rain of the Pinus hartwegii community, is considered to be an indicator of this coniferous forest (Ohngemach and Straka, 1983; Almeida-Leñero, 1997). Higher representation of these taxa is indicative of climate amelioration, with pine forest growing near or at the site for a short period. The mesophytic forest assemblage (group 4) is present in low percentages during this period. Hedysomum and Engelhardia, taxa of group 4, indicate mountainous humid environments and are no longer part of the modern mesophytic forests of the central Mexican highlands (Rzedowski and Rzedowski, 2001), but are found growing today in the tropical southern regions of Mexico. During this peak of arboreal taxa, elements of group 6, which indicate swampy conditions, display reduced values, suggesting a period similar to modern conditions. Pollen concentration decreases compared with the previous zone, reaching its minimum value of the sequence (1700 grains per cm³) in the uppermost sample (202 cm, c. 6500 cal. yr BP). This supports the interpretation of reduced water accumulation in the depression.

Subzone 2b has an interpolated age of c. 6500 to c. 5000 cal. yr BP (202–139 cm depth). The boundary between 2a and 2b is given by the sudden reduction of pine pollen, the re-establishment of previous percentages of grass pollen (80%) and a decrease in the percentages of group 3. Pollen stratigraphy indicates the return of alpine grasslands at the site. Pollen concentration values are higher (44870–6947 grains per cm³). The pollen assemblage was interrupted by the deposition of the 5700 cal. yr BP tephra and after this event a reduction in the pollen taxa diversity is evident.

Subzone 2c spans c. 5000 to c. 3000 cal. yr BP (139–70 cm depth). In this subzone, lower values of groups 1 and 2 and an increase in group 3 elements are observed, along with an increase of forest elements. Montane forest pollen becomes more abundant: Pinus (12–37%), Quercus (5–12%) and Alnus (4–11%). The record of the epiphytic Arcetebium aff. globosum is present continuously at significant values (3–13%). Among the herbs, the percentage of the grasses gradually decreases from 60% to 45%. A combination of taxa from the alpine grasslands and the coniferous forest elements established around the site, suggesting an upslope movement of the vegetation belts. Pollen concentration fluctuates between 8000 and 15000 grains per cm³, with an average pollen accumulation rate of 500 grains per cm² per year.

Zone 3 covers the last c. 3000 cal. yr BP (70–0 cm depth). It documents the dominance of coniferous forest components (group 3) in the pollen spectra, and culminates with the highest values of arboreal pollen (51–88%). The main montane elements Pinus (58–76%), Quercus (4.9–7.8%), Alnus (3.5–8.5%), Abies (1.1–2.2%) and Cu.-Ju. type (1–2.8%) are continuously present in this part of the sequence. Pollen of grasses and herbaceous taxa show the lowest values of the record (5–17%). The late Holocene pollen assemblages are similar to the modern pollen rain at the site, indicating that the Pinus hartwegii forest was present during this period. High pollen concentration values are documented with a significant increase (156800 grains per cm³) at 38 cm.

Discussion

Pollen analysis of Agua El Marrano sediments provides information about the Holocene vegetation changes in the highlands of the Basin of Mexico, in particular on the establishment and altitudinal fluctuation of the alpine grassland and the upper forest. According to the age model, sediment accumulation behind the Milpulco-1 moraine in Agua El Marrano valley began around 11500 cal. yr BP, however we believe this occurred some time later, probably around 11000 cal. yr BP, when Milpulco-1 glaciers were receding on Iztacchuatl (Vázquez-Selem, 2000).

The absence of pollen in the lower part of the core (450–382 cm depth) supports the existence of marked periglacial conditions immediately after the retreat of the glacier and for the next few hundred years. Temperatures c. 4°C colder than present have been estimated for the Milpulco-1 advance (~12000 to ~10 500 cal. yr BP) based on the altitudes of the equilibrium line of glaciers (Vázquez-Selem, 2000). Assuming that the altitude of the timberline was controlled by temperature, and applying a lapse rate of 6°C/km, temperatures ~4°C colder than present may have produced a timberline ~700 m lower than today, i.e., at ~3300 m (Figure 4). This is compatible with two vegetation-based estimates of cooling from the region. Using pollen spectra (by Ohngemach and Straka, 1983) from Tlaloc crater at 3100 m on Malinche volcano, D’Antoni (1993) estimated temperatures 3.5–2°C lower than present between ~11 500 and ~9500 cal. yr BP (~10 000 to ~8500 14C yr BP). In the Petén lowlands of northern Guatemala, Leyden et al. (1993) calculated temperatures 3.0–4.7°C lower than present between ~12 500 and 10 200 cal. yr BP (10 500–9000 14C yr BP). Temperatures during the earliest Holocene apparently were too low for forest development at 3860 m. However, by c. 10 900 cal. yr BP, alpine grasslands had developed at the site and existed there for the next 3000 years. No major change in vegetation composition is observed during the timespan of the Milpulco-2 glacier advance (c. 8300–7300 cal. yr BP), which formed moraines at elevations between 4000 and 4300 m in the same valley (Figure 1C). Temperatures reconstructed from the equilibrium line altitudes of glaciers are 3.3±0.7°C and 2.6±0.6°C lower than present for the early (maximum) and recessional stages of the Milpulco-2 advance, respectively (Vázquez-Selem, 2000). A cooling of ~3°C probably depressed the timberline ~500 m below its modern elevation, which is consistent with the absence of forest around the coring site. However, the cooling was not sufficient to eliminate the alpine grassland from the area.

In summary, the early Holocene timberline position at Iztacchuatl volcano is estimated at between c. 700 and c. 500 m below its modern elevation (Figure 4). Similar calculations based on pollen records have been reported for other tropical highlands (van der Hammen and González, 1960; van Geel and van der Hammen, 1973; Hooghiemstra,
Comparing our high-altitude (3860 m) pollen data with records from the mid slopes of other mountains in the region and with those from the lacustrine beds of the Basin of Mexico (Lake Chalco, 2200 m), the following conclusions may be drawn. During the period of the Milpulco-1 glacial advance (c. 10 250 to c. 9000 $^{14}$C yr BP) on Iztaccíhuatl, a trend towards higher percentages of arboreal taxa (mainly pine and oak) is reported in the lacustrine pollen sequences (Figure 4). For the early Holocene from 10 900 to 8000 cal. yr BP, while colonization of the alpine grasslands took place in Agua El Marrano, the improvement in temperature as a response to the Northern Hemisphere maximum insolation (Kutzbach, 1983), made the expansion of the pine/alder forest and fir forests possible in the lowlands (Figure 4). At Lake Quila (3010 m), a mid-altitude site located 30 km southwest of the basin of Mexico and 60 km west-southwest of Iztaccíhuatl (Figure 1A), simultaneous reduction in the pine–oak–alder forest and an increase in the pine forest is documented by c. 10 400 cal. yr BP ($\sim$ 9250 $^{14}$C yr BP) (Almeida et al., 1994). Pollen sequences Tlaloc I and II of La Malinche volcano (3100), 60 km east of Iztaccíhuatl volcano (Figure 1A), are characterized by the presence of alpine grassland before c. 9500 cal yr BP ($\sim$ 8500 $^{14}$C yr BP), and afterwards by the expansion of the Pinus hartwegii (Ohngemach, 1977; Straka and Ohngemach, 1989). The data from Malinche volcano (but not those from Quila) suggest that the upper timberline in the earliest Holocene was situated near 3000 m. During the early Holocene increasing temperature and precipitation compared with the late glacial environments (Metcalfe et al., 2000) promoted forest expansion in the mid-altitude areas of the TMVB, but the forest did not reach sites as high as Agua El Marrano until c. 7200 cal. yr BP.

A change in pollen composition is detected by 7200 cal. yr BP coinciding with the end of the Milpulco-2 advance (Figure 3). Elements of the coniferous forests (Table 1) became more abundant, indicating that these communities were near or at the site during early–mid Holocene, 7200–6500 cal yr BP (6500–6000 $^{14}$C yr BP). We interpret this event as a combination of higher temperatures – consistent with glacier recession – and increased moisture, recorded by different proxies from central Mexico between $\sim$ 7800 and $\sim$ 6800 cal. yr BP (7000–6000 $^{14}$C yr BP) (Metcalfe et al., 2000; Caballero et al., 2002). Between c. 6500 and 5000 cal. yr BP a return of the alpine grasslands to the coring area is documented (Figure 3). Based on other records from central Mexico, we interpret this mid-Holocene lowering of the timberline to be a result of drier conditions recorded by different proxies in the region (Metcalfe et al., 2000; Caballero et al., 2002).

From c. 7200 to 6500 cal. yr BP pine forest near Agua El Marrano correlates with low lake levels in Lake Chalco and a slight reduction in the forest cover around this lake. At the mid-altitude site of Lake Quila dry conditions are not evident at this time. Between $\sim$ 6800 and $\sim$ 5700 cal yr BP (6000–5000 $^{14}$C yr BP) indicators of drier conditions can be found in several lacustrian pollen sequences of central Mexico (Xelhuanztzi-López, 1994; Metcalfe et al., 2000; Sosa-Nájera, 2001).

After 5700 cal. yr BP (5000 $^{14}$C yr BP) there was a gradual increase of taxa from the coniferous forest, coeval with an increase in moisture in the region. This trend culminates with the establishment of the Pinus hartwegii forest at the site since around 3000 cal. yr BP. Pinus hartwegii has been reported as a pioneer and also a climax tree at high altitude in the mountains of central Mexico (Rodríguez-Trejo and Fulé, 2003). Agua El Marrano pollen spectra indicate no major change in this community during the last 3000 years, in contrast to the pollen data of the lakes in the basin of Mexico where evidence of human impact is well documented (González-Quintero and Fuentes-Mata, 1980; Niederberger, 1987; Lozano-García et al., 1993; Lozano-García and Ortega-Guerrero, 1994; Lozano-García and Xelhuanztzi-López, 1997; Sosa-Nájera, 2001).
The establishment of the Pinus hartwegii forest in Agua El Marrano at 3000 cal. yr BP corresponds to a period of higher lake levels in Lake Chalco. Human impact around the lake produced lower values of pine and oak pollen and higher numbers of disturbance taxa (Cheno.-Am. and Asteraceae) in the lake Chalco pollen spectra, suggesting deforestation in the lowlands (Lozano-Garcia et al., 1993; Lozano-Garcia and Ortega-Guerrero, 1994; 1997; Lozano-Garcia, 1996; Sosa-Nájera, 2001). The development of Pinus forests at higher elevation also corresponds with a trend towards moister and cooler climate that culminates with the establishment of Abies forest around 2000 cal. yr BP in lakes Quila and Zempoala (Almeida-Lebrero, 1997), and between ~2800 and ~1300 cal. yr BP (2670–1365 14C yr BP) in Tlaloc crater (Ongemach and Straka, 1983; Heine, 1985; D’Antoni, 1993).

In summary, while a strong human impact is well documented by the pollen data from the lakes in the lower parts of the Basin of Mexico (2200 m) since c. 3000 cal. yr BP, there is no evidence of human disturbance in the high-elevation pollen record of Agua El Marrano (3860 m). At present human impact remains low at the site because of difficulty of access and a relatively severe climate. Logging and grazing have taken place in the upper forest of Iztaccíhuatl in the last few decades, but agriculture has not been practiced above 3300 m.

Conclusions

The pollen analysis of the high-altitude Agua El Marrano sequence reflects a continuous history of vegetation spanning the last ~11 000 cal. yr BP. The pollen diagram shows the establishment of the alpine grasslands by 10 900 cal. yr BP, when Milpulco-1 glaciers were receding. The permanence of these grasslands until c. 7200 cal. yr BP likely reflects cooler conditions than at present, which is consistent with the glacial record of Iztaccíhuatl during the first half of the Holocene. The development of coniferous forest from 7200 to 6500 cal. yr BP at or near the site suggests a sudden temperature improvement immediately after the Milpulco-2 glacial advance, in combination with a wet climate across central Mexico. Conditions for forest growth deteriorated rapidly after 7200 cal. yr BP, and the alpine grasslands returned to the area for the next 1000–1500 years, apparently in connection with drier climates recorded across central Mexico around the mid-Holocene (c. 6000 cal. yr BP). There is evidence of the continuous presence of the Pinus forest at the coring site for the last 3000 years. When compared with other proxies from the region, the pollen record of Agua El Marrano suggests that the upper timberline in central Mexico has fluctuated significantly during the Holocene in response to the complex interplay of temperature and precipitation, and reached its modern elevation only in the last third of the Holocene.

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