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 ^{14}C 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 palaeolimnology 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-García *et al.*, 1993; Xelhuantzi-López, 1994; Lozano-García 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 Lateglacial to the Holocene but a clear picture has not yet emerged. Palaeoecological 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

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the MVB. 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 Popocatépetl (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 stratrovolcano 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, Popocatépetl 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 Popocatépetl 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.

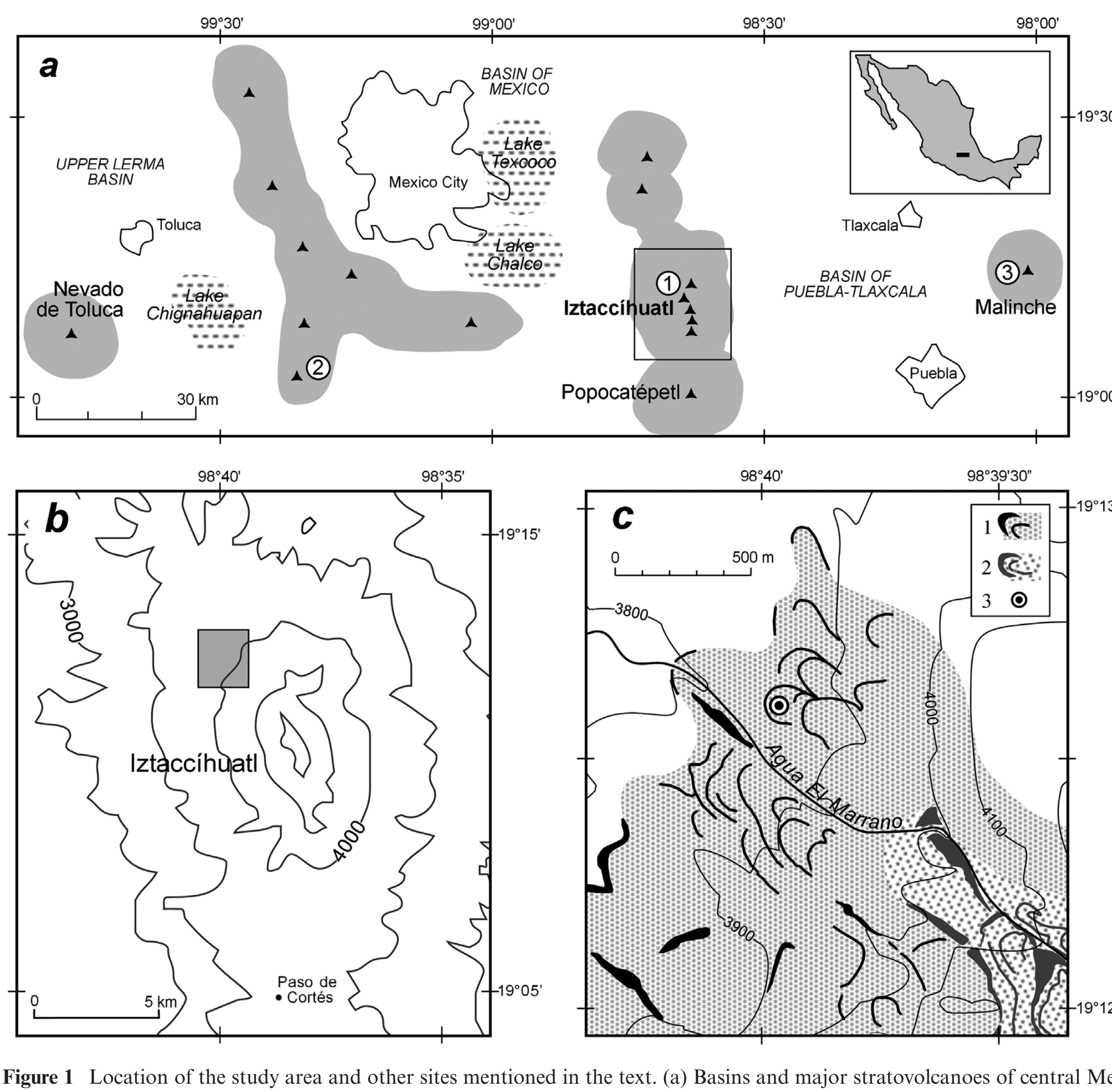

Figure 1 Location of the study area and other sites mentioned in the text. (a) Basins and major stratovolcanoes of central Mexico. 1, Agua El Marrano site; 2, Lake Quila site; 3, Tláloc crater site. (b) Iztaccíhuatl volcano. (c) Northwest Iztaccíhuatl, showing extent of glacial advances around Agua El 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 tephrochronology (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; rapid glacier retreat between 14 000 and 13 000 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 1000 cal. yr BP, presumably related to the Little Ice Age.

The present altitudinal distribution of vegetation belts in the Sierra Nevada (Iztaccíhuatl and Popocatépetl volcanos) 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) (Table 1). 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

Community		
Alpine grasslands	Coniferous forests	
3900–4500 m	3460–4000 m	2850–3540 m
Festuca livida	*Pinus hartwegii*	*Abies religiosa*
Arenaria bryoides	*Festuca tolucensis*	*Cupressus lusitanica*
Calamagrostis tolucensis	*Calamagrostis tolucensis*	*Senecio callosus*
Penstemon gentianoides	*Cirsium jorullensis*	*Quercus laurina*
Lupinus montanus	*Geranium potentillaefolium*	
Draba jorullensis		

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-Nájera, 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

Table 2 Radiocarbon dates of Agua El Marrano core and radiocarbon dates of the ~5000 year old marker pumice layer from Popocatépetl volcano

Sample	Laboratory code	Radiocarbon date (yr BP)	Calibrated date (yr BP)[a]	Material dated	Source
Core 85 depth	Beta158794	3460±50	3694	Pollen	This paper
Core 296 depth	Beta-113912	8870±80	10 023	Charcoal	This paper
Core 339 depth	Beta-113913	9290±150	10 454	Charcoal	This paper
Core 431 depth[b]	Beta-122934	8020±90	9030	Organic coating on root channel	This paper
N side of Popocatépetl (Paso de Cortéz)	Hv-4883	4805±60	5525	Charcoal inside pumice	Heine (1975)
NW side of Popocatépetl	Tx-1671 Tx-1671 Tx-1671 (weighted av.)	5081±45	5750	Paleosol immediately below yellow pumice lapilli	Lambert and Valastro (1976)
NE side of Popocatépetl	A-8321 A-8321	5080±85 4965±65	5725 5832	Charcoal from surge sequence	Siebe *et al*., 1996

[a] Radiocarbon calibration (1 sigma) using CALIB (Stuiver and Reimer, 1993; version 4.1) and calibration data set by Stuiver *et al*. (1998).
[b] Rejected date.

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 ^{36}Cl (Zreda and Phillips, 2000). The boulder yielded 10 000±500 ^{36}Cl kyr BP, which falls within the recessional phase of Milpulco-1 advance of Iztaccíhuatl (Vázquez-Selem, 2000) and is roughly equivalent to 9000 ^{14}C 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 (Zreda *et al*., 1994; Putkonen and Swanson, 2003).

Palynology

A total of 66 pollen taxa were identified in the Agua El Marrano core at different taxonomic levels. Pollen data are presented in a relative percentage summary pollen diagram (Figure 3). Taxa are grouped according to their ecological habits to show changes in plant communities. Alpine grassland taxa cluster in group 1; taxa growing in the *Pinus hartwegii* forest, but which can also reach higher elevations towards the lower alpine grasslands, constitute group 2; taxa of the coniferous forests are included in group 3; mesophytic forest taxa make up group 4; elements indicative of disturbance and fern spores are arranged in group 5; and taxa indicative of swampy conditions group 6 (Figure 3).

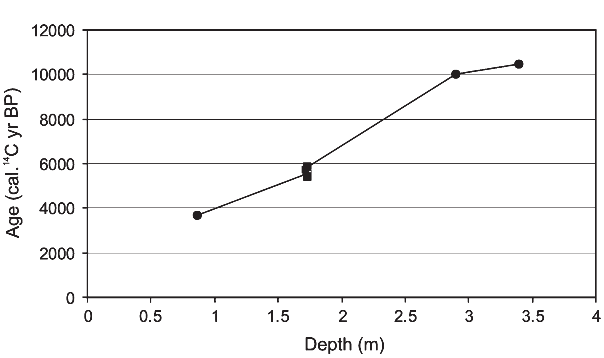

Figure 2 Age model. Average depth versus calibrated AMS ^{14}C dates. Solid circles correspond to samples of Agua el Marrano core and solid squares to the ~5700 calibrated radiocarbon pumice

Results of the modern pollen rain at the site correspond to the 0-cm sample in the summary diagram (Figure 3). The composition is simple, with pine pollen dominant (75%). Other taxa that are not present at the site but contribute with low percentages to the pollen rain are: *Quercus* (10%) and *Alnus* (4.8%). Among the taxa present in the modern vegetation, which are part of the pollen rain, are: *Ceratium, Conyza* and *Eryngium* within the herbs, and the pine epiphytic *Arceuthobium* aff. *globosum*.

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 ^{14}C yr pollen concentration varied between 46 821 and 1681 grains per cm^3. An average pollen accumulation rate of 682 grains per cm^2 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). Arboreal taxa belonging to group 3, *Pinus, Quercus* and *Alnus* vary between 7.6% and 1% and are probably related to upslope pollen transport. Pollen concentration fluctuates between 5500 grains per cm^3 at the base of the sequence (382 cm) and 26 000 grains per cm^3 before the deposition of the grey tephra at 290 cm. A reduction in the

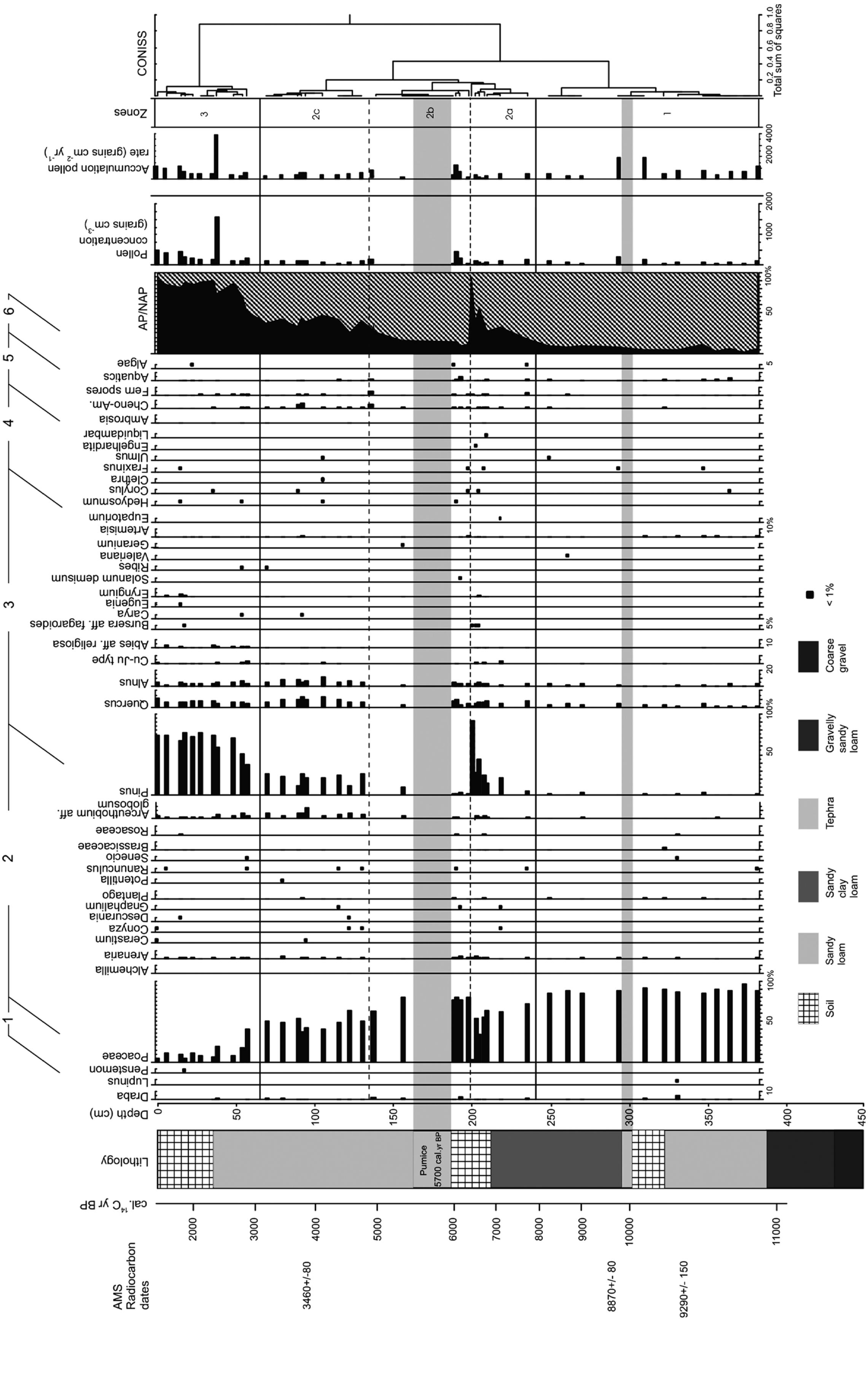

Figure 3 Pollen percentage diagram of selected taxa from Agua El Marrano core. Pollen groups as in the text. AP, arboreal pollen; NAP, non-arboreal pollen. Solid square indicates pollen less than 1%. Timescale and lithology are shown in the left side of the figure. Shaded areas correspond to the tephra 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 *Eryingium* (2.5%) and *Arcethobium* aff. *globosum* (3%). This pollen assemblage is similar to the *Pinus hartwegii* forest modern pollen rain (Palacios, 1977; Ohngemach and Straka, 1983; Tovar, 1987). *Arceuthobiumn 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. *Hedyosmum* and *Engelhardtia*, 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 cm^3) 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 (44 870–6947 grains per cm^3). 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 *Arcethobium* 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 15 000 grains per cm^3, with an average pollen accumulation rate of 500 grains per cm^2 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 (156 800 grains per cm^3) 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 11 500 cal. yr BP, however we believe this occurred some time later, probably around 11 000 cal. yr BP, when Milpulco-1 glaciers were receding on Iztaccíhuatl (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 (~ 12 000 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 Tláloc cráter 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 ^{14}C 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 ^{14}C 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 Iztaccíhuatl 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,

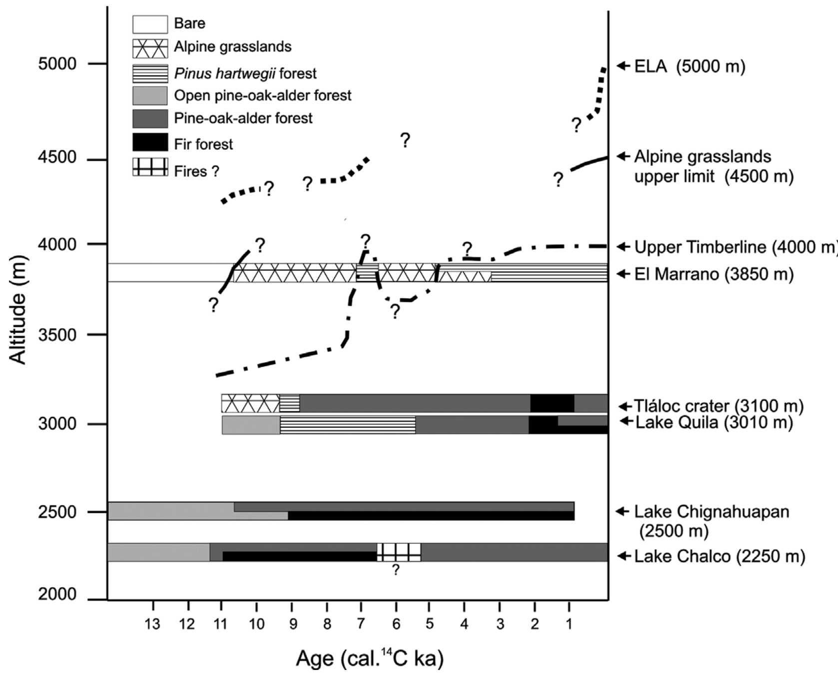

Figure 4 Vegetation records based on pollen diagrams from eastern-central Mexico. Location is shown on Figure 1. References of the sites are as follows: Agua El Marrano (this paper); Tlaloc crater (Ohngemach, 1977; Straka and Ohngemach, 1989); Lake Quila (Almeida-Leñero, 1997); Lake Chignahuapan (Lozano-García *et al*., 2003); Lake Chalco (Lozano-García *et al*., 1993; Lozano-García and Ortega-Guerrero, 1994, 1997; Sosa-Nájera, 2001). Equilibrium line altitude (ELA) of glaciers of Iztaccíhuatl (Vázquez-Selem, 2000). The ELA, the upper limit of alpine grasslands and the upper timberline are indicated with different types of lines

1984; Islebe and Hooghiemstra, 1997; Flenley, 1998; Wille *et al*., 2001).

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 lacustrian 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 lacustrian 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–oak–alder 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 (~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 (~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 ~7800 and ~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 ~6800 and ~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 (Xelhuantzi-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 (Rodíguez-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 Xelhuantzi-Lóplez, 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-García *et al.*, 1993; Lozano-García and Ortega-Guerrero, 1994; 1997; Lozano-García, 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-Leñero, 1997), and between ~2800 and ~1300 cal. yr BP (2670–1365 ^{14}C yr BP) in Tlaloc crater (Ohngemach 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 (9800 ^{14}C 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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References

Almeida, L., Cleff, A., Herrera, A., Velázquez, A. and **Luna, I.** 1994: El zacatonal alpino del volcán Popocatépetl, México y su posición en las montañas tropicales de América. *Phytocoenologia* 23, 391–436.

Almeida-Leñero, L. 1997: Vegetación, fitogeografía y paleoecología del zacatonal alpino y bosques montanos de la región central de México. Unpublished Ph.D. Thesis, Universiteit van Amsterdam.

Ballantyne, C.K. 2002: Paraglacial geomorphology. *Quaternary Science Reviews* 21, 1935–2017.

Batten, D.J. 1999: Small palynomorphs. In Jones, T.P. and Rowe, N.P., editors, *Fossil plants and spores: modern techniques.* London: The Geological Society, 15–19.

Beaman, J.H. 1962: The timberlines of Iztaccíhuatl and Popocatépetl, Mexico. *Ecology* 43, 337–85.

Bradbury, J.P. 2000: Limnologic history of Lago de Patzcuaro, Michoacan, Mexico for the past 48,000 years: impacts of climate and man. *Palaeogeography, Palaeoclimatology, Palaeoecology* 163, 65–95.

Brown, T.A., Farwell, G.W., Grootes, P.M. and **Schmidt, F.H.** 1992: Radiocarbon AMS dating pollen extracted peat samples. *Radiocarbon* 34, 550–56.

Caballero, M.M. 1995: Late Quaternary Paleolimnology of Lake Chalco, The Basin of Mexico: new evidence for paleoenvironmental and paleoclimatic change in central Mexico during the last 45 000 years. Unpublished Ph.D. dissertation, University of Hull, UK.

Caballero, M. and Ortega-Guerrero, B. 1998: Lake levels since 40 000 ago at Chalco Lake, near Mexico City. *Quaternary Research* 50, 90–106.

Caballero M., Macías, J.L., Lozano-García, S., Urrutia-Fucugauchi, J. and **Castañeda, B.R.** 2001: Late Pleistocene–Holocene volcanic stratigraphy and paleoenvironments of the upper Lerma basin, Mexico. *Special Publications of the International Association of Sedimentologists* 30, 247–61.

Caballero, M.M., Ortega, B., Valadéz, F., Metcalfe, S., Macías, J.L. and **Sugiura, Y.** 2002: Sta. Cruz Atizapán: a 22-ka lake level record and climatic implications for the late Holocene human occupation in the upper Lerma basin, central Mexico. *Palaeogeography, Palaeoclimatology, Palaeoecology* 186, 217–35.

Cruz-Cisneros, R. 1969: Contribución al conocimiento de la ecología de los pastizales en el Valle de México. Unpublished MS Thesis, Instituto Politécnico Nacional, México.

D'Antoni, H.L. 1993: Paleotemperatures of La Malinche: a palynological hypothesis. *Grana* 32, 354–58.

Ferrari, L. 2000: Avances en el conocimiento de la Faja Volcánica Transmexicana durante la última década. *Boletín de la Sociedad Geológica Mexicana* 53, 84–92.

Ferrari, L., Garduño, V.H., Pasquare, G. and **Tibaldi, A.** 1994: Volcanic and tectonic evolution of Central Mexico – Oligocene to present. *Geofísica Internacional* 33, 91–115.

Flenley, J.R. 1998: Tropical forest under the climates of the last 30 000 years. *Climate Change* 39, 177–98.

González-Quintero, L. and **Fuentes-Mata, M.** 1980: El Holoceno en la porción central de la cuenca del valle de México. Memorias del III Coloquio sobre Paleobotánica y Palinología. *Colección Científica 86: Instituto Nacional de Antropología e Historia*, 195–200.

Grimm, E.C. 1987: CONISS: a FORTRAN program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computer and Geosciences* 13, 13–35.

—— 1992: *TILIA 2 software*. Springfield IL: Illinois State Museum.

Grimm, E., Lozano-García, S., Behling, H. and **Markgraf, V.** 2001: Holocene vegetation and climate variability in the Americas. In Markgraf, V., editor, *Interhemispheric climate linkages.* San Diego CA: Academic Press, 325–63.

Heine, K. 1975: *Studien zur jünquartären Glazialmorphologie mexikanischer Vulkane. Mit einem Ausblick auf die Klimaentwicklung*. Wiesbaden: Franz Steiner.

—— 1985: Neue absolute Daten zur holozänen Gletscher-, Vegetations- und Klimageschichte zentralmexikanischer Vulkane. *Regensburger Geographische Schriften* 19/20, 79–92.
—— 1988: Late Quaternary glacial chronology of the Mexican volcanoes. *Die Geowissenschaften* 7, 197–205.
Hooghiemstra, H. 1984: *Vegetational and climatic history of the High Plain of Bogotá, Colombia: a continuous record of the last 3.5 million years*. Dissertactiones Botanicae, Vol. 79. Vaduz: J. Cramer, 368 pp.
Islebe, G.A. and **Hooghiemstra, H.** 1997: Vegetation and climate history of montane Costa Rica since the last glacial. *Quaternary Science Reviews* 16, 589–604.
Islebe, G.A. and **Velázquez, A.** 1994: Affinity among mountain ranges in Megamexico: a phytogeographical scenario. *Vegetatio* 115, 1–9.
Kutzbach, J.E. 1983: Modeling the Holocene climates. In Porter, S.C., editor, *Late Quaternary environments of the United States, Vol. II: The Holocene*. New York: Longman, 271–77.
Lambert, P.W. and **Valastro, S.** 1976: Stratigraphy and age of Upper Quaternary tephras on the northwest side of Popocatépetl Volcano, Mexico. In *American Quaternary Association, Fourth Biennial Meeting*. Tempe, AZ: American Quarters Association (AMQUA) 143 pp.
Lambert, W. 1986: Descripción preliminar de los estratos de tefra en Tlapacoya. In Lorenzo, J.L. and Mirambell, L., editors, *Tlapacoya: 35 000 años de historia del lago de Chalco*, México. Colección Científica 115: Mexico DF: Instituto Nacional de Antropología e Historia, 77–100.
Lauer, W. 1978: Timberline studies in Central Mexico. *Artic and Alpine Research* 102, 383–96.
Lauer, W. and **Klaus, D.** 1975: Geoecological investigations on the timberline of Pico de Orizaba. *Artic and Alpine Research* 74, 315–30.
Leyden, B.W., Brenner, M., Hodell, D.A. and **Curtis, H.C.** 1993: Late Pleistocene climate in the Central American lowlands. In Swart, P.K., Lohmann, K.C., McKenzie, J. and Savin, S., editors, *Climate change in continental isotopic records*. Geophysical Monograph 78. Washington DC: American Geophysical Union, 165–78.
Lorenzo, J.L. 1964: *Los glaciares de México*. México: Instituto de Geofísica, Universidad Nacional Autónoma de México.
Lozano-García, M.S. 1996: La vegetación del Cuaternario tardío en el centro de México: registros palinológicos e implicaciones paleoclimáticas. *Boletín de la Sociedad Botánica de México* 58, 113–28.
Lozano-García, M.S. and **Ortega Guerrero, B.** 1997: Late Quaternary environmental changes of the central part of the Basin of Mexico. Correlation between Texcoco and Chalco basins. *Review of Palaeobotany and Palynology* 99, 77–93.
Lozano-García, M.S. and **Xelhuanzti, L.M.S.** 1997: Some problems in the late Quaternary pollen records of central Mexico: Basin of Mexico and Zacapu. *Quaternary International* 43/44, 117–23.
Lozano-Garcia, M.S., Ortega-Guerrero, B., Caballero, M. and **Urrutia Fucugauchi, J.** 1993: Late Pleistocene and Holocene paleoenvironments of Chalco lake. *Quaternary Research* 40, 332–42.
Lozano-Garcia, M.S., Caballero, M.M., Ortega, G.B., Valadez, F. and **Suigura, Y.** 2003: Late Quaternary paleoecology of the Upper Lerma basin, central Mexico. In *Third International Limnogeology Congress*. 29 March–2 April 2003, Tucson AZ, 274 pp.
Lozano-García, S. and **Ortega Guerrero, B.** 1994: Palynological and magnetic susceptibility records of Chalco Lake, central Mexico. *Palaeogeography, Palaeoclimatology, Palaeoecology* 109, 177–91.
Martin-Del Pozzo, A.L., Cifuentes-Nava, G., Cabral-Cano, E., Sánchez-Rubio, G., Reyes, M., Martínez-Bringas, A., Garcia, E. and **Arango-Galvan, C.** 2002: Volcanomagnetic signals during the recent Popocatépetl (México) eruptions and their relation to eruptive activity. *Journal of Volcanology and Geothermal Research* 113, 415–28.
Metcalfe, S.E., Street-Perrott, F.A., Perrot, R.A. and **Harkness, D.D.** 1991: Palaeolimnology of the Upper Lerma Basin, Central Mexico: a record of climatic change and anthropogenic disturbance since 11,600 yr BP. *Journal of Paleolimnology* 5, 197–218.
Metcalfe, S.E., O'Hara, S.L., Caballero, M. and **Davis, S.J.** 2000: Records of Late Pleistocene–Holocene in Mexico – a review. *Quaternary Science Reviews* 1, 699–721.
Mooser, F. 1967: Tefracronología de la cuenca de México para los últimos treinta mil años. *Boletín, Instituto Nacional de Antropología e Historia* 30, 12–15.
Niederberger, B.C. 1987: Paleopaysages et archeology pre-urbaine du Bassin de Mexico (Mexique). Centre d'Etudes Mexicaines et Centroamericaines. *Collection Etudes Mésoaméricaines* 1, 1–337.
Nixon, G.T. 1989: The geology of Iztaccíhuatl volcano and adjacent areas of the Sierra Nevada and valley of Mexico. *Geological Society of America Special Paper* 219, 1–58.
Ohngemach, D. 1977: Pollen sequence of the Tlaloqua crater (La Malinche volcano, Tlaxcala, Mexico). *Boletín de la Sociedad Botánica de México* 36, 33–40.
Ohngemach, D. and **Straka, H.** 1983: *Beiträge zur Vegetations- und Klimageschichte im Gebiet von Puebla-Tlaxcala. Pollenanaysen im Mexiko-Projekt*. Wiesbaden: Franz Steiner.
Ortega-Guerrero, B. and **Newton, A.** 1998: Geochemical characterization of late Pleistocene and Holocene tephra layers from the Basin of Mexico, central Mexico. *Quaternary Research* 50, 90–106.
Ortega-Guerrero, B., Thompson, R. and **Urrutia-Fucugauchi, J.** 2000: Magnetic properties of lake Chalco, central Mexico, and their paleoenvironmental implications. *Journal of Quaternary Science* 15, 127–40.
Palacios, Ch.R. 1977: Lluvia de polen moderno en diferentes habitats del Valle de México. *Boletín de la Sociedad Botánica de México* 36, 45–69.
Phillips, F.M., Zreda, M.G., Elmore, D. and **Sharma, P.** 1996: A reevaluation of cosmogenic ^{36}Cl production rates in terrestrial rocks. *Geophysical Research Letters* 23, 949–52.
Putkonen, J. and **Swanson, T.** 2003: Accuracy of cosmogenic ages for moraines. *Quaternary Research* 59, 255–61.
Rodríguez-Trejo, D.A. and **Fulé, P.Z.** 2003: Fire ecology of Mexican pines and a fire management proposal. *International Journal of Wildland Fire* 12, 23–37.
Rzedowski, G.C. and **Rzedowski, J.** 2001: *Flora Fanerogámica del Valle de México*. Instituto de Ecología A:C y Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, Pátzcuaro (Michoacán) México.
Siebe, C., Abrams, M., Macias, J.L. and **Obenholzner, J.** 1996: Repeated volcanic disasters in Prehispanic time at Popocatépetl, central Mexico: past key to the future? *Geology* 24, 399–402.
Sosa-Nájera, S. 2001: Registro palinológico del Pleistoceno tardío-Holoceno en el extremo meridional de la cuenca de México: Paleoambientes e inferencias paleoambientales. Unpublished M.Sc. thesis Universidad Nacional Autónoma de México, México.
Straka, H. and **Ohngemach, D.** 1989: Late Quaternary vegetation history of the Mexican highland. *Plant Systematic and Evolution* 162, 115–32.
Stuiver, M. and **Reimer, P.J.** 1993: Extended 14C data base and revised calib 3.0 14C age calibration program. *Radiocarbon* 35, 215–30.
Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., v.d. Plicht, J. and **Spurk, M.** 1998: INTCAL98 Radiocarbon age calibration 24 000–0 cal BP. *Radiocarbon* 40, 1041–83.
Tovar, G.C. 1987: Lluvia de polen en el volcán Popocatépetl: un estudio a lo largo de un transecto altitudinal. Unpublished thesis, Universidad Nacional Autónoma de México, México.
van der Hammen, T. and **González, E.** 1960: Holocene and late glacial climate and vegetation of Páramo de Palacio (E. Cordillera, Colombia, S. America). *Geologie en Mijnbouw* 39, 737–45.
van Geel, B. and **van der Hammen, T.** 1973: Upper Quaternary vegetational and climatic sequence of the Fuquene area (Eastern Cordillera, Colombia). *Palaeogeography, Palaeoclimatology, Palaeoecology* 14, 9–92.

Vázquez-Selem, L. 2000: Late Quaternary glacial chronology of Iztaccíhuatl volcano, central Mexico. A record of environmental change in the border of the tropics. Unpublished Ph.D. dissertation, Arizona State University.

Vázquez-Selem, L. and **Heine, K.** 2004: Late Quaternary glaciation in Mexico. In Ehlers, J and Gibbard, P.L., editors, *Quaternary glaciations – extent and chronology, part III. South America, Asia, Africa, Australia, Antartica*. Amsterdam: Elsevier, 233–42.

Velázquez, A., Toledo, V.M. and **Luna, I.** 2000: Mexican temperate vegetation. In Barbour, M.G. and Dwigth Billings, W., editors, *North American terrestrial vegetation*. Cambridge: Cambridge University Press, 573–92.

Velázquez, D.R. 2003: Evolución paleoambiental del lago de Cuitzeo durante el Pleistoceno tardío: Historia de la vegetación e implicaciones paleoclimáticas. Unpublished M.Sc. thesis, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, México.

White, S.E. 1962: Late Pleistocene glacial sequence for the west side of Iztaccíhuatl, Mexico. *Geological Society of America Bulletin* 73, 935–58.

—— 2002: Glaciers of Mexico. In Williams, R.S. and Ferrigno, J.G., editors, *Satellite image atlas of the glaciers of the world – glaciers of North America.* U.S. Geological Survey Professional Paper 1386-J-3. J383–J405.

Wille, M., Hooghiemstra, H., Behling, H., van der Borg, K. and **Negret, A.J.** 2001: Environmental change in the Colombian subandean forest belt from 8 pollen records: the last 50 kyr. *Vegetation History and Archaeobotany* 10, 61–77.

Xelhuantzi-López, M.S. 1994: Estudio palinológico de cuatro sitios ubicados en la cuenca de Zacapu: fondo ciénaga, contacto Lomas ciénaga, pantano interno y Loma Alta. *Cuadernos de Estudios Michoacanos* 6, 81–93.

Zreda, M.G. and **Phillips, F.M.** 2000: Cosmogenic nuclide buildup in surficial materials. In Noller, J.S., Sowers, J.M., Lettis, W.M., editors, *Quaternary geochronology: methods and applications.* Washington DC: American Geophysical Union, 61–76.

Zreda, M.G., Phillips, F.M. and **Elmore, D.** 1994: Cosmogenic 36Cl accumulation in unstable landforms. 2. Simulations and measurements on eroding moraines. *Water Resources Research* 30, 3127–36.