Chapter 6
Insights into the Holocene Environmental History of the Highlands of Central Mexico

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Abstract With the aim of highlighting the present stage of development in the scenario of environmental and climate research during the Holocene in central Mexico, we present a synthesis of relevant events preserved in continental records. Climate conditions and intricate topography of this region led to the development of lake basins, whose records were the sources for several paleoecological studies. These records suggest higher moisture during the early Holocene, although the high insolation promoted higher evaporation. Toward the mid-Holocene, the southward displacement of the ITCZ led to drier conditions in the area. During the Late Holocene, environmental change and human activities are intertwined, with the latter expanding over the last 2000 years. A review of paleoecological signals such as cultural pollen taxa, microcharcoal, deforestation, and erosion reveals human activities during the Late Holocene. Understanding the past climate of central Mexico is important for predictions of global warming, as a large part of the Mexican population reside in this region. Additionally, changes in forest composition and hydrological conditions observed in this region provide important ecological and climatic information to characterize the Trans-Mexican Volcanic Belt.

Keywords Late Holocene · Trans-Mexican Volcanic Belt · Droughts · Pollen records

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This chapter is dedicated to Dr. Jerzy Rzedowski

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Introduction

Past landscape dynamics can be reconstructed by analyzing the terrestrial archives preserved in lacustrine sequences. These archives provide valuable information regarding limnological conditions, plant communities, and climate change. Environmental changes as well as their relationship with the archaeological history of central Mexico have been important research topics because of (a) a complex physiographic context due to the Trans-Mexican Volcanic Belt (TMVB) hosting important elevations and intermountain basins with sediments deposited over thousands of years which open the possibility of reconstructing past environments; (b) the fact that climate change has been an important driving force controlling species distribution and migration along the altitudinal gradient defined by the complex topography of the region; (c) the historical context of the region, as the TMVB is part of the core area for the development of the Mesoamerican cultures and was the cradle of maize domestication (Piperno et al. 2009).

Paleoecological data obtained from the analysis of lacustrine sediments allows the identification of ecosystem's responses to climate variability during different time frames. Geochemistry and diatom analysis are two proxies used in lake sediments that can give detailed information about changes in the hydrological balance, allowing the identification of either wetter or dryer intervals (ej. Metcalfe et al. 2010; Rodríguez-Ramírez et al. 2015; Bhattacharya et al. 2017). On the other hand, the palynological record has been used to reconstruct the vegetation history and the responses of plant communities to natural disturbances such as fires, volcanic activity, and climate change (Lozano-García et al. 1993, 2013, 2015; Lozano-García and Ortega-Guerrero 1994, 1998; Ortega-Guerrero et al. 2000; Torres-Rodriguez et al. 2015; Sedov et al. 2010; Correa-Metrio et al. 2012; Figueroa-Rangel et al. 2008; Castillo-Batista et al. 2016).

In this chapter, we present an overview of Holocene paleoecological records and available paleolimnological data from central Mexico to estimate past changes in temperature and episodes of increased aridity in the region. An emphasis is given to the review of previously published records providing evidences of changes in the vegetation communities and their altitudinal distribution that can be related with climatic changes or anthropogenic impacts.

Central Mexico

Geological Scenario

The Trans-Mexican Volcanic Belt (TMVB) (Fig. 6.1) extends between 19° and 21° N latitude from the Gulf of Mexico to the Pacific coast, with an E–W direction (Gomez-Tuena et al. 2005). This geological province is a continental magmatic arc that developed in the mid-Miocene (ca. 19 Ma) as result of the subduction of the Cocos and Rivera plates below the North America plate, and its activity continues

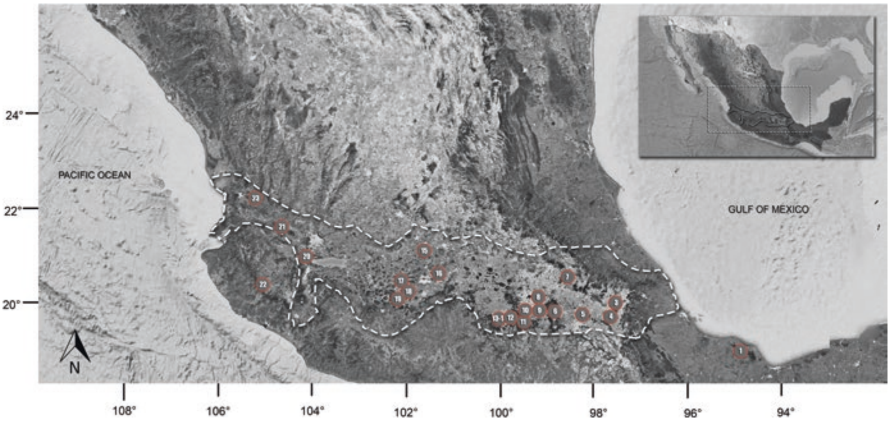

Fig. 6.1 The TMVB is marked with dotted line in the map of Mexico, and the numbers indicate the sites discussed in the text (Table 6.1)

up to modern times (Ferrari et al. 2012). Intense volcanic activity in the region led to the formation of the highest mountains like Iztaccihuatl (5286 m), Popocatepetl (5452 m), and Pico de Orizaba (5675 m). Extensional tectonic regimes during the Pliocene and the Quaternary developed several closed basins (Ferrari et al. 2012).

Topography is the most significant feature of this geological province, and large areas have altitudes of between 1000 and 2500 m asl. The regional altitudinal gradient is evident from an E-W profile (Fig. 6.2). The lower western sector has mean altitudes of <2000 m asl, and warmer climates and the higher central and eastern basins have higher altitudes, up to ~2600 m asl, and cooler climates (Castellano de Rosas 2007; Caballero et al. 2010). The hydrology of the region is closely related with the active volcanic and tectonic environments, which favors the presence of closed basins with the development of lacustrine systems. The lakes in the area vary from extensive and shallow systems like Texcoco (EdoMex) and Cuitzeo (Michoacán) to smaller and deeper crater lakes like Santa María del Oro (Nayarit) and Aljojuca (Puebla) (Sigala et al. 2017).

Climate Scenario

The climate is characterized by a summer rainy season with most of the precipitation concentrated between June and September. It occurs when the trade winds bring moisture from the Caribbean Sea and the Gulf of Mexico and the intertropical convergence zone (ITCZ) reaches its northerly position. Tropical storms and hurricanes in both the Atlantic and the Pacific Oceans are also an important source of summer moisture for the region. Besides, the western basins along the TMVB are part of the core area of the Mexican Monsoon system (Metcalfe et al. 2015), and therefore they also receive summer monsoon style precipitation from the Pacific

Table 6.1 Palaeoecological sites of central Mexico

Site name	Map key	Elevation (m)	Lat.	Long.	References
Lake Verde	1	100	18° 03′ N	95° 20′W	Lozano-García et al. (2010)
Cofre de Perote	2	3717	19°30′N	97°09′W	Caballero-Rodríguez et al. (2018)
Oriental Jalapasquillo	3	2400	19°13′N	97°25′W	Ohngemach (1977); Straka and Ohngemach (1989)
Aljojuca crater lake	4	2376	19°05’N	97°32’W	Bhattacharya et al. (2015)
Tlaloqua II crater lake	5	3100	19°13′N	98°02′W	Ohngemach and Straka (1983); Straka and Ohngemach (1989)
Valle Agua el Marrano	6	3860	19°12′N	98°39′′W	Lozano-García and Vazquez-Selem (2005)
Lake Chalco CHAB	7	2240	19°15′N	19°15′N	Lozano-García et al. (1993), Caballero and Ortega (1998), Caballero et al. (2019)
Lake Chalco CHAD	7	2240	19°15′N	19°15′N	Lozano-García and Ortega-Guerrero (1998)
Lake Chalco CHAE	7	2240	19°15′N	19°15′N	Sosa-Nájera (2001), Correa-Metrio et al. (2013)
Lake Xochimilco	8	2240	19°13′N	99°08′W	Ortega-Guerrero et al. (2018)
Lake Texcoco	9	2210	19°28′N	99°58′W	Lozano-García and Ortega-Guerrero (1998), Sedov et al. (2010)
Lake Tecocomulco	10	2500	19°51′N	98°23′W	Caballero et al. (1999)
Lake Lerma SCA	11	2570	19°10′N	99°32′W	Caballero et al. (2002), Lozano-García et al. (2005)

(continued)

Table 6.1 (continued)

Site name	Map key	Elevation (m)	Lat.	Long.	References
Lake La Luna	12	4200	19°06′N	99°45′W	Cuna et al. (2014)
Lake Zempoala	13	2800	19°03′N	99°18′W	Almeida el al. (2005)
Quila	14	3100	19°04′N	99°19′W	Almeida el al. (2005)
Hoya Rincon de Parangueo, Hoya San Nicolas	15	1800	20°23′N	100°50′W-101°19′W	Park et al. (2010), Domínguez et al. (2019)
Lake Cuitzeo	16	1880	19°53′N-20°04′N	101°15′W	Israde et al. (2002, 2010)
Lake Zacapu	17	1970	19°50′N	101°40′W	Xelhuantzi-López (1994)
Lake Zirahuen	18	2075	19°26′N	101°44′W	Ortega-Guerrero et al. (2010), Lozano-García et al. (2015)
Lake Patzcuaro	19	2035	19°36′N	101°39′W	Bradbury (2000), Metcalfe et al. (2007)
Lake San Marcos	20	1352–1346	20°17′N-20°05′N	103°34′W-103°30′W	Castillo et al. (2017)
Etzatlan-Magdalena Basin	21	1360	20°47′N	104°39′W	Vázquez et al. (2017)
Sierra Manantlan Forest hollow	22	2570	21°23′N	103°52′W	Figueroa-Rangel et al. (2008)
Lake Santa Maria del Oro	23	750	19°42′N	104°35′W	Rodríguez-Ramírez et al. (2015)

Ocean. By the end of autumn and during winter, the ITCZ migrates southward, while the high-pressure cells over the North Pacific and North Atlantic cause dry conditions to most of Mexico.

Central Mexico is a sensitive region to recurrent atmosphere-ocean climatic oscillations like El Niño-Southern Oscillation (ENSO). The negative ENSO events (warmer tropical Pacific conditions during El Niño) are expressed as warmer and relatively dry summers and slightly cooler and wetter winters, while the positive ENSO events (cooler tropical Pacific conditions during La Niña) are related with higher than average summer precipitation (Pavia et al. 2006; Bravo et al. 2010; Magaña et al. 2003; Magaña 2004; Caballero et al. 2013)

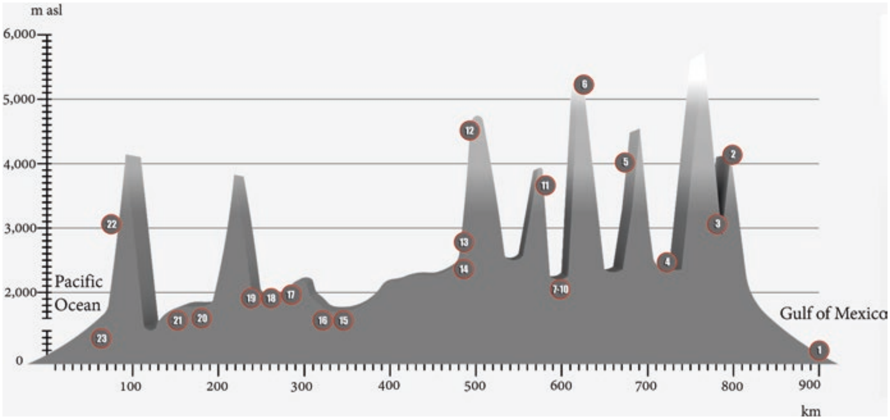

Fig. 6.2 Elevation profile of central Mexico showing the sites mentioned in the text (Table 6.1). Mountain name abbreviations from the east (E) to west (W) are as follows: CP Cofre de Perote, PO Pico de Orizaba, LM La Malinche, IZ Iztaccihuatl, AJ Ajusco, NT Nevado de Toluca, TA Tancitaro, NC Nevado de Colima

Plant Communities

Several vegetation types are present across these diverse landscapes. Alpine grasslands are generally found on the highest altitudes above the timberline and at lower elevations, and the montane forests, coniferous forests, and oak forests account for 60% of the vegetation (Luna et al. 2007). The timberline in the mountains of central Mexico varies in altitude from about 3800–4100 m asl, and the highest treeline in the world is at Pico de Orizaba, at 4200 m (Beaman 1962; Lauer 1978; Lauer and Klaus 1975). Below the treeline, the high elevation, sub-alpine *Pinus hartwegii* forest occurs from 3650 to 4200 m asl forming monospecific stands at the ecotone with alpine grasslands, under extreme temperatures (Perry 1991).

The coniferous forests are abundant as this kind of vegetation is favored by the acidic (pH 5–7), volcanic-derived soils common in the TMVB (Rzedowski 2006). *Pinus* forests (with ~48 species) are widely distributed, and except for *P. hartwegii*, they are present at elevations between 1500 and 3000 m asl, in temperate sub-humid climates, with annual average temperatures of 6–28 °C. The most common species in the area is *Pinus montezumae*, and it is substituted by *P. pseudostrobus* in less humid conditions and below 2000 m asl by *P. rudis* and *P. teocote*. *Pinus cembroides* (piñon pines) are generally found in the dryer areas with precipitation of less than 350 mm/yr. The volcanic history of central Mexico is linked with the evolutionary history of this genus, providing microhabitats that favored hybridization and adaptive radiation (Styles 1993). *Abies religiosa* forests in central Mexico are present at elevations from 2400 to 2600 m asl, with mean annual temperatures varying between 7 and 15 °C and precipitation of >1000 mm/yr. or in ravines protected from the high insolation (Rzedowski 2006).

Other prominent montane forests in the highlands of central Mexico are the *Quercus* forests, with 161 species, a highly diverse vegetation type. It occurs at elevations from 350 to 2000 m asl, with mean annual precipitation of 600–200 mm/yr. and annual average temperature of 10–26 °C, but more frequently in areas with temperature between 12 and 20 °C (Rzedowski 2006). The mesophytic or cloud forests develop in the coastal slopes at mid-elevations (1000–2500 m asl) above the lowland tropical vegetation and below the *Pinus*, *Pinus*-*Quercus*, and *Quercus* forests (Villaseñor 2010). Cloud forests are located at areas with mean annual precipitation higher than 1000 mm/yr., usually between 1500 and 3000 mm/yr., and the mean annual temperatures vary between 9 and 12 °C. This plant community presents high species diversity (Rzedowski 2006).

Holocene Environment

The present interglacial, the Holocene (11.7 cal ka BP to present), is characterized by an increase in global temperature after the cooler last glaciation. Based on estimations of terrestrial and marine temperature proxies, the beginning of the Holocene (11.7 cal ka BP) is marked by an increase in global temperature of 3–8 °C compared with the temperature of the last glacial maximum (21 ka cal BP) (Rehfeld et al. 2018). Besides, a lower global temperature variability led to relatively more stable climates over the Holocene. Temperature changes during this epoch promoted hydrological changes that affected plant community composition and distribution. The Holocene epoch is divided by two cold events at 8.2 ka cal BP and 4.2 ka cal BP (Walker et al. 2012) into the Greenlandian (11.7–8.2 cal ka BP), Northgrippian (8.2–4.2 cal ka BP), and Meghalayan (4.2 cal ka BP to today) ages.

Estimates of Past Temperature in Central Mexico

Important temperature changes have been reconstructed from different proxies during the transition from the Late Pleistocene to the Holocene. However, few of them provide quantitative estimates of these changes (Caballero et al. 2010, 2019). The temperature reconstruction based on equilibrium line altitudes (ELAs) of the mountain glaciers of central Mexico, particularly at the Iztaccihuatl Volcano, is one of them (Vazquez-Selem and Heine 2011). Other sources of quantitative estimates of the past temperature in the region are pollen- and diatom-based transfer functions, which allow estimating changes in temperature by calibrating fossil assemblages with modern ones present at different sites along a temperature gradient. Pollen- and diatom-based temperature transfer functions in central Mexico are available only for Lake Chalco, located at the southern part of the Basin of Mexico (Correa-Metrio et al. 2013; Caballero et al. 2019).

The lowest ELAs recorded between 20 and 14 cal ka BP infer that temperature decreased by 7.6–6.2 °C in central Mexico during the last glaciation (Vazquez-Selem and Heine 2011; Caballero et al. 2010). Pollen- and diatom-based transfer functions on the other hand suggest slightly lower maximum temperature decrease (4–5 °C, Correa-Metrio et al. 2013; Caballero et al. 2019). Deglaciation at the end of the Pleistocene generally led to the retreat of mountain glaciers, but several smaller re-advances are documented. The first one, dated at 12.0–10.0 cal ka BP, overlaps with the Younger Dryas cold event (12 cal ka BP) and the onset of the Holocene (11.7 cal ka BP), with an estimated temperature decrease of 4.4–5.4 °C. For the Younger Dryas, the pollen- and diatom-based transfer functions suggest smaller temperature decrease (about 1.5–2 °C). However, during the Greenlandian, they reconstructed important temperature increases, for example, warmer conditions were evident since ca. 11.5 ka cal BP from the diatom data, with a maximum warming (+3 °C) from 10.5 to 8.5 cal ka BP. The pollen data recorded this temperature increase at a slightly later date, that is, between 9 and 5 cal ka BP. Another glacial advance was recorded from 8.5 to 7.5 cal ka BP, contemporary with the 8.2 cal ka BP cold event that marks the transition between the Greenlandian and the Northgrippian. The ELAs estimated a temperature decrease of 2.6–3.3 °C during this event. This cold event is not clear in the pollen- and diatom-based transfer functions from Lake Chalco, which on the other hand show that temperatures reduced during the Northgrippian. Finally, a last glacial advance was recorded during the Meghalayan, which was correlated with the Little Ice Age (AD 1400–1900), but without a precise dating (Vazquez-Selem and Heine 2011).

Estimates of Past Moisture in Central Mexico

Paleolimnological records allow inferring past changes in available moisture during the Holocene. This kind of records can identify dry periods from intervals of reduced lake levels, increased in salinity, or reductions in the surface runoff. Along the TMVB, the lacustrine basins with paleolimnological records are distributed along an E-W altitudinal transect from the Gulf of Mexico to the Pacific Ocean (Fig. 6.2). The reviewed records for this section are also included in Table 6.1, where the corresponding bibliographic references are listed. For the sake of clarity, in this compilation, the names of the sites are mentioned in parenthesis, and an emphasis is given on the general trends.

During the Greenlandian (11.7–8.2 cal ka BP), many lacustrine records along the TMVB show sedimentary hiatuses (Tecocomulco, Texcoco, Zirahuen), saline environments (Chalco, Xochimilco, Cuitzeo), and trends to lower lacustrine levels (Upper Lerma, Patzcuaro, San Marcos, Etzatlan) that culminate during the 8.2 cal ka BP cold event that marks the end of this age. This trend to saline environments and generally low lake levels can be explained by the maximum values of summer insolation that promoted higher evaporation in the region. This trend is present in the lakes on the central and western sections of the TMVB. However, there is no paleolimnological information from the eastern sector of the TMVB for this interval.

The Northgrippian (8.2–4.2 cal ka BP) began, as explained in the previous paragraph, with generally low lake levels. Many of the records showed a recovery (Texcoco, Tecocomulco, Upper Lerma, Zirahuen, Etzatlan) or a transition from saline toward fresher conditions (Chalco, Xochimilco, Cuitzeo) by 6–5 cal ka BP. However, the records showed another dry period (Patzcuaro, Cuitzeo, Upper Lerma, Etzatlan) correlating with the cold event that marks the end of this age. Again for this period, there are no paleolimnological records from the eastern sector of the TMVB.

For the Meghalayan (4.2 cal ka BP to present), the number of paleolimnological records increased. These records covered the full extent of the TMVB for the last 2 cal ka BP. Some of these records (Upper Lerma, Patzcuaro, Etzatlan) showed that the dry spell that started by the end of the Northgrippian extended until about 3 to 2 ka cal BP. Lake levels recovered by that time, but soon they gave way to a new dry interval dating at around 1.5 cal ka BP (AD 600) to 0.8 cal ka BP (AD 1100). This dry period correlates with the demise of the Mesoamerican cultures during the Late Classic (AD 600–900) and is identified in nearly all the paleolimnological records from the region (Verde, Aljojuca, Upper Lerma, Patzcuaro, Zirahuen, Etzatlan, Juanacatlán, Santa María del Oro), from the Gulf Coast to the Pacific Ocean, representing the most important paleolimnological trend for the Meghalayan (Rodríguez-Ramírez. et al. 2015).

During the cooler climates of the Little Ice Age, several records showed evidences of dry conditions (La Luna, Juanacatlan, Santa Maria del Oro, Patzcuaro). However, the dates slightly differ between sites, and in some it shows a two-phase cooling pattern, that is, AD 1400 to 1600 and/or AD 1660 to 1770. Only at the lowland tropical site of Lago Verde, in Los Tuxtlas, a twofold increase in lake levels is evident. This two-phase behavior during the Little Ice Age that has also been recorded at other sites has been correlated with the Spörer (1450–1550) and Maunder (1650–1750) solar minima (Lozano et al. 2007).

Archaeological Background

Archaeological data regarding the peopling of the Americas is a controversial issue. Recent archaeological research suggests that Beringia could have been populated as early as 20 cal ka BP (Bourgeon et al. 2017). However, other archaeological data point to a later date, that is, 14 cal ka BP, during the deglacial. The early human migrations into America could have taken place through different routes, for example through an ice free corridor in North America between the Laurentide and Cordilleran ice sheets (Dixon 2001) or an alternative, that has become relevant in the recent decades, is the migration route through the Pacific coast, facilitated by the exploitation of coastal resources (Dixon 2001; Dillehay et al. 2008).

The transition from hunters-gatherers to agricultural villages was a gradual process that started during the Greenlandian, that is, 10 cal ka BP (Ranere et al. 2009), and consolidated during the so-called Archaic period (9–4 cal ka BP). Mexico has been identified as one of the main centers in the development of agriculture, with maize (*Zea mays* ssp. *mays*) as the most important crop in the region. Maize was domesticated from teosinte (*Zea mays* ssp. *parviglumis*) in the central Balsas region (Piperno et al. 2009; Ranere et al. 2009) by ca. 9 cal ka BP, and the molecular studies of maize landraces by Matsuoka et al. (2002) allowed to establish that there was a single domestication event after which diversification took place, extending from the Balsas region to the highlands of central Mexico, and from there, it spreads to the rest of Mesoamerica and surrounding regions.

Vegetation Paleorecord

Paleoecological research documented the vegetation history, lake levels, and erosion rates and related them to climate variability and other drivers. Some of these records cover the Last Glacial Maximum, as well as the transition from the Late Pleistocene to the Holocene (Caballero et al. 2010). Because of the region's intricate topography, climate change promoted variations in species distribution along the altitudinal gradient, and species migrations resulted in new configurations in plant communities. The climatic fluctuations over the Pleistocene, together with volcanic and tectonic activities, promoted topographic changes. A model of sky-island vegetation dynamics has been proposed to explain the biodiversity observed in the mountainous regions of Mexico (Mastretta-Yanes et al. 2015). Past changes in montane vegetation composition emerged from the various palynological studies carried out in the sedimentary sequences collected from lakes and bogs (Table 6.1).

According to studies of glacial advances in the mountains of central Mexico, most of the glaciers continued to have ELAs similar to those at the LGM until about 14 cal ka BP (Vazquez-Selem and Heine 2011; Caballero et al. 2010). This is consistent with the pollen record at the Tlaloqua II crater (3100 m asl), where the alpine grasslands were present during this period and the upper timberline was at ca. 3000 m asl, nearly 1000 m below its modern values (Ohngemach 1977; Straka and Ohngemach 1989). In the mid-elevations, pollen spectra from Lake Zirahuen (2075 m asl) showed changing vegetation during the deglacial, when dry and cold environments favored the dominance of *Pinus* forest. By the end of the Pleistocene (ca. 13.5 cal ka BP), the glaciers retreated (Vázquez-Selem and Heine 2011), and a rapid vegetation turnover was recorded (at 13.3 cal ka BP), with the presence of *Quercus* and *Alnus* and more diverse montane forests (Lozano-García et al. 2015). Similar palynological trends have also been documented in other records from mid-elevations (ca. 2000–2600 m asl). For example, increases in pollen percentages of *Quercus, Abies*, and *Fraxinus* are recorded at the western sector of central Mexico (lake Zacapu; Correa-Metrio et al. 2012), and pollen indicative of dry forest and shrublands was reported from Rincon de Parangueo (Dominguez-Vázquez et al. 2019).

For the Greenlandian (11.7–8.2 cal ka BP), insolation was the main forcing that affected precipitation and seasonality in central Mexico. The strength of summer insolation was at its highest during the beginning of the Holocene at ca. 12 cal ka BP. The high seasonality declined over the course of the last 10 ka, reaching its lowest values over the last 4 cal ka. Paleotemperature changes during the Late Pleistocene and Holocene were reconstructed using other proxies. Cooler conditions continued into the earliest Greenlandian (11.7–10 ka cal BP) according to the glacial history of the central volcanoes and the pollen-based transfer functions, even though diatom-based transfer functions recorded an earlier warming (since 11.5 cal ka cal BP). The high elevation pollen records showed periglacial conditions at the Agua El Marrano (3860 m asl) and Cofre de Perote (3717 m asl). However, alpine grasslands developed at the lower elevation site Tlaloqua II crater (3100 m asl) (Ohngemach 1977; Straka and Ohngemach 1989). The increase in temperature at ca. 10 cal ka BP, with higher than present summer insolation, promoted the establishment of alpine grasslands in all the high elevation sites. For example, the vegetation cover at the Agua El Marrano (3860 m asl) located in the NE slope of the Iztaccihuatl (Fig. 6.3) was alpine grasslands with the timberline at 500–700 m below its present position from 10.5 to 7 cal ka BP (Lozano-García and Vázquez-Selem 2005), and it continued up to 8.5 cal ka BP in the Tlaloqua II crater (Ohngemach 1977; Straka and Ohngemach 1989). At Lake Quila (3100 m asl), *Alnus* forest with low percentages of *Pinus* was present from ca. 11.6–10.6 cal ka

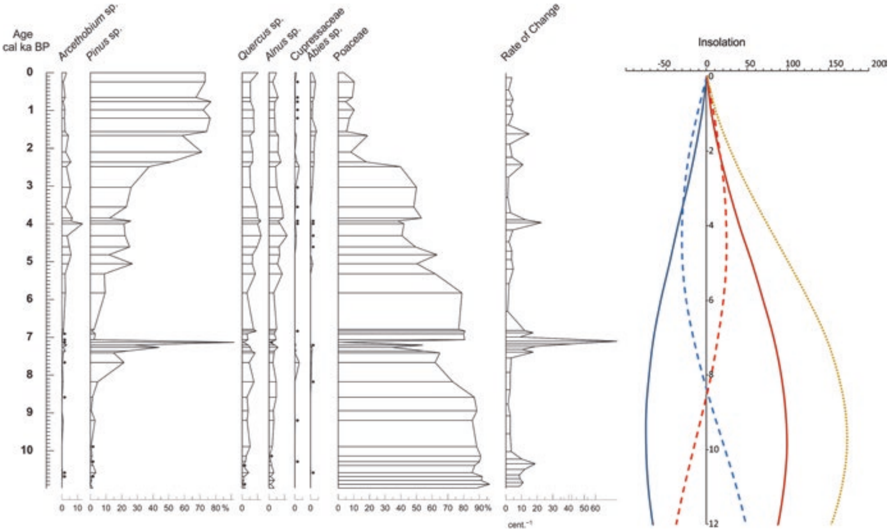

Fig. 6.3 Summary pollen diagram of the Agua El Marrano site (Lozano-García and Vázquez-Selem 2005), selected taxa, and rate of change. Seasonal insolations (W/m^2) at 20° N (Berger and Loutre 1991) are shown (continuous blue line, December; dotted blue line, March; dotted red line, September; continuous red line, June; dotted yellow line, June–December)

BP, and the contribution of *Pinus* forest increased afterward (Almeida-Leñero et al. 2005).

At mid-elevations sites, the forest composition changed between 12.5 and 9.5 cal ka BP. *Pinus* forests developed but the pollen spectra of Lake Patzcuaro, Lake Zirahuen, Lake Zacapu, Lake Chignahuapan, and Lake Chalco revealed increase in *Quercus, Alnus*, and *Abies* (Watts and Bradbury 1982; Xelhuantzin-López 1994; Lozano-García and Ortega-Guerrero 1998; Lozano-García et al. 2005, 1993; Torres-Rodríguez et al. 2012). This ecological turnover in vegetation is illustrated with the pollen diagram of Lake Zirahuen, where the rate of change remains below 20, then increases to 60, and becomes lower again (Fig. 6.4). By the end of the Greenlandian, at ca. 8 cal ka BP, *Pinus-Quercus* mix forests were present at several sites: Chalco, Zirahuen, Patzcuaro.

A significant palynological signal of warming during the Greenlandian was the disappearance of *Picea* (spruce) in pollen spectra at the high elevation basins (>2000 m asl), located in the eastern sector of the TMVB. The last record of *Picea* pollen at Tlaloqua II crater was at ca. 10 cal ka BP, and it was observed at ca. 7 cal ka BP and at ca. 10 cal ka BP in Lake Texcoco and Lake Chignahuapan, respectively. However, no *Picea* pollen has been reported in pollen sequences of the Late Pleistocene from the lower eastern basins (i.e., Patzcuaro, Zirahuen, Zacapu and Cuitzeo) that have records extending into the last glacial. This absence is indicative that the climate in these lower basins was not cold enough to sustain this conifer. Today, relict populations of *Picea chihuahuana* can be found at sites 700 km north from the Basin of Mexico, with mean annual temperatures from 9 to 12 °C and precipitations of 600 a 1300 mm/yr. It has been suggested that the high seasonality of the Greenlandian, with cold winters and warmer summers, compared with present conditions favored the ITCZ to shift toward a northern position carrying more

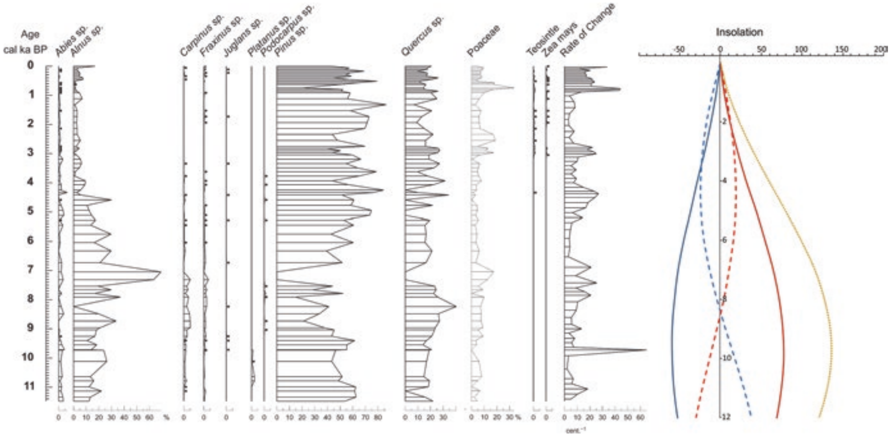

Fig. 6.4 Summary pollen diagram of Lake Zirahuen (Lozano-García et al. 2013), selected taxa, and rate of change. Seasonal insolations (W/m^2) at 20° N (Berger and Loutre 1991) are shown (continuous blue line, December; dotted blue line, March; dotted red line, September; continuous red line, June; dotted yellow line, June–December)

precipitation to the region (Metcalfe et al. 2015). However, the presence of hiatuses, low lake levels, and saline conditions is indicative of high evaporation that dominated the hydrological balance.

A transition from high to lower seasonality occurred during the Northgrippian, and it was translated into variable climatic conditions for central Mexico (Metcalfe et al. 2015). A compositional change in vegetation was recorded between 7.5 and 7.1 cal ka BP at Agua el Marrano (Fig. 6.3). The presence of a pollen assemblage similar to the modern pollen rain of *Pinus hartwegii* forest suggests that this community was established close to this site. The rate of change increased abruptly up to 70, and the pollen indicators of swampy conditions reduced, suggesting the establishment of drier conditions during this time. Afterward, from 7.1 to ca. 3 cal ka BP, the alpine grasslands reestablished in the site, and the rate of change values remained lower.

It was possible to detect significant changes in the forest composition from the high-resolution Zirahuen record, located at mid-elevations. A sudden collapse in *Alnus* was probably linked to the 8.2 ka cal BP cold oscillation. Another period of change was recorded between 7.3 and 7.1 cal ka BP with increases in *Alnus* pollen and reduction in other pollen trees such as *Pinus* and *Quercus*. An increase of the rate of change occurred between 7.9 and 7 cal ka BP indicating a compositional change in the community. A pulse of wetter conditions might explain this variation in the plant community. At other pollen records near Zirahuen, the increases in *Alnus* pollen were also recognizable. It occurred in Patzcuaro from ca. 7 to 6 cal ka BP (Watts and Bradbury 1982) and also in Zacapu (Xelhuanzti-López 1994), although the resolution in the last record was lower than Zirahuen.

During the Meghalayan, the last 4.2 cal ka cal, a general trend toward drier conditions was associated to the southward migration of the ITCZ (Metcalfe et al. 2015). The paleolimnological records for the region identify two long dry periods: the first one from 4.2 to 3 or 2 cal ka BP and the second one from 1.5 to 0.8 cal ka BP (AD 600 to 1100). Two shorter dry spells were observed during the Little Ice Age (i.e., AD 1400–1600 and 1660–1770). High-elevation sites showed the establishment of modern conditions at the Agua El Marrano. The record of alpine grasslands decreased, and *Pinus* pollen increased steadily until the *Pinus hartwegii* forest reached its modern range at ca. 3 cal ka BP. *Abies* forests were established at Quila, after a dry period from 5 to 2.5 cal ka BP, with mixed *Pinus-Quercus* forests (Almeida et al. 2005). A drought between 4.5 and 4.2 cal ka BP has been reported from Zirahuen, and it was related to the end of the orbital-controlled early Holocene warm period. Events of high erosion occurred after 4 cal ka BP with more unstable conditions linked to the ENSO forcing (Lozano-García et al. 2015). Dominance of *Pinus* forest, which is the main montane communities in the highlands of central Mexico, has been linked to drier climates. Evidence of *Pinus* forest expansion and its relationship with climatic changes has been documented in the pollen record of Manantlán, in particular with the arid intervals between 4.2–2.5 cal ka BP, 1.2–0.85 cal ka BP (AD 750–1100), and 0.5–0.2 cal ka BP (AD 1450–1750) (Figueroa-Rangel et al. 2008).

In central Mexico, the paleoecological records for the Meghalayan contained not only a climatic signal but also the imprint of human activities. This Late Holocene climatic signal was not evident in all the mid-elevation records, as some of them were perturbed by past human activities around the lakes. New hypothesis regarding the early distribution of gatherers and cultivators in Mexico suggests that agriculture and domestication dispersed inland from western Mexico through river basins such as the Santiago-Lerma and Balsas-Mezcala (Zizumbo-Villareal and Colunga 2008) and settled in numerous lakes of central Mexico with plentiful resources. The most distinctive evidences of human activity in the pollen records across central Mexico are a) the presence of maize pollen in the lacustrine sequences, b) reduction of tree pollen which marks deforestation events in the area, and c) abundant charcoal deposition probably related to the slash and burn practices characteristic of land clearing for agriculture.

Generally, the occurrence of cultigens has been reported, mainly maize, in the pollen records from central Mexico (Watts and Bradbury 1982; Goman and Byrne 1998; Sluyter and Domínguez-Vázquez 2006; Lozano-García et al. 2005; Lozano-García et al. 2007). These grains are not frequent in the lacustrine records because their large size (70–120 m) limits their dispersal. The identification of maize pollen is based on its size as well as its axis/pollen ratio; however, this criterion has been debated because *Zea mays* ssp. *parviglumis* and *Zea mays* subsp. *mays* overlap. An example of an early record of maize pollen comes from the crater lake of Rincon de Parangueo and at La Hoya San Nicolás. This record suggested small agriculture activities at ca. 5.7 cal ka BP, and these assumptions were based on the minor increases of *Zea* and Amaranthaceae (Park et al. 2010), with intensification of human activities at 2.4 cal ka BP. In other sites (e.g., Patzcuaro), the signal of agriculture was tracked by the presence of larger pollen grains attributable to *Zea* (at 3.6 cal ka BP; Watts and Bradbury 1982). In order to disentangle past land-use practices, a multiproxy approach with a combination of terrestrial pollen records including the sporadic presence of cultigen (maize), deforestation data, and charcoal records can be useful. For example, pollen of *Zea mays* ssp. *parviglumis* was found at ca. 6 cal ka BP at Lake Zirahuen. However, no other change in the pollen spectra indicated evidence of food production in the area. Extensive and intensive land use since the last 3 cal ka BP was inferred not only from the maize pollen but also by an increase in the herbaceous pollen assemblage (i.e., Amaranthaceae and Poaceae). All these, along with increases in magnetic susceptibility indicating higher erosion rates and abundant charcoal particles suggesting anthropogenic fires, provided evidence of land-use changes in the area.

In some paleoecological records that covered the last 2.8 cal ka, it was possible to unravel the climate variability imprint, in spite of the increasing intensity of anthropogenic impact. An example of this is the Lago Verde record in the eastern lowlands. A combination of proxies showed prehistoric human occupation with presence of maize and disturbance pollen such as Poaceae and Asteraceae throughout the mid-Classic (ca. BC 250 to 800 AD). Forest regeneration after 800 AD is inferred from the pollen spectra in response to abandonment with the highest tropical forest diversity during the Little Ice Age (Lozano-García et al. 2010;

Lozano-García et al. 2007). All these paleoecological research contributed to improve the understanding of changing environments in central Mexico, an area with a great proportion of the Mexican population. Multiple evidences of climate change, hydrological balance, vegetation history, and earlier human impacts provided indications of the environmental variability over the last 11,700 years. The past climate variability of central Mexico is relevant for understanding the environmental problems associated with the global warming.

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