A 12,000 Year Diatom-Based Paleoenvironmental Record from Lago De Zirahuén, Mexico

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Abstract The volcanic dammed Zirahuén Lake is one of the least eutrophic lakes in the state of Michoacán in the central Mexican highlands. Diatom-based records from two cores – one littoral in a water column of 15 m deep and one from the center of the ca. 40 m-deep lake – provide a sequence of environmental change spanning the last c. 12 ky. Diatom assemblages during the late Glacial are representative of shallow water or marsh-type environments, indicating lower lake levels in the lake margin. Fluctuating conditions occurred in the early Holocene, as evidenced by diatom assemblages in the central core, while an unconformity was observed in the littoral core between 12.1 and 7.2 ka BP associated with the damming of the lake as product of the development of the Magueyera volcano. The cores recorded a lake deepening and more stable lake levels between ca. 8.8 and 2 ka BP, with the planktonic *Aulacoseira ambigua* dominating the diatom assemblages. The lake

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deepening is associated with the last two La Magueyera lava flows that caused the final damming of the lake. These volcanic events increased hydrothermal activity and eutrophic conditions in the lake and favored increased silica availability for the *Urosolenia eriensis* blooms, with almost monospecific diatoms at c. 10.2 ka BP and again between 6.8 and 6.6 ka BP. Anthropogenic influence on the lake ecosystem is evident from c. 3.6 cal ka BP as increased catchment erosion. Significant changes from the mid-eighteenth century associated mainly with colonial copper smelting, deforestation, and recent intensification of land use in the catchment for avocado production are responsible for lake eutrophication.

Introduction

The state of Michoacán in the highlands of western-central Mexico contains numerous Neogene-Quaternary lakes formed by volcanic and tectonic activity (Fig. 1). These basins are ideal for the investigation of climatic and paleoenvironmental change in the region over the Late Pleistocene and Holocene, providing the focus for some of the first paleolimnological research in Mexico (e.g., Hutchinson et al. 1956). Over the last few decades, multiple paleolimnological investigations of lakes in the highlands of Michoacán have revealed complex patterns of environmental change related to climate, volcanic, and human activity (Metcalfe 1995; Davies et al. 2004; Vázquez-Castro et al. 2008; Israde-Alcántara et al. 2010; Lozano-García et al. 2013). Deciphering a clear climatic signal has been problematic, particularly during the last 3–4 thousand years when human activity has intensified in the region.

Paleolimnological records indicate sedentary agriculture was established in the highlands of Michoacan from ca. 3.5 cal ka BP, based on palynological evidence from the Pátzcuaro lake (Watts and Bradbury 1982) located 12 km at NE of Zirahuén Lake (Fig. 2a, b) The archaeological record has provided evidence of Pre-Classic settlements (2000 BCE to 250 CE; 3950–1700 cal ka BP), with dense, urban settlements since the Classic (250 CE to 900 CE; 1700–1050 cal ka BP). The region formed the heartland of the Post-Classic (900 CE to 1521 CE; 1521–429 cal ka BP) Purepecha culture which had its maximum development before the arrival of Spaniards to the region in 1521 CE (Fisher et al. 2003; Pollard 2000).

The first paleolimnological record from Lake Zirahuén focused on a series of short cores covering the last ~1000 years (Davies et al. 2004). These provided evidence of responses to changing human activity in the basin during the Post-Classic Purepecha settlement and through Colonial expansion and settlement, particularly from the eighteenth century. A rapid response to recent land-use intensification was also identified (Davies et al. 2005). Two longer cores were retrieved in 2003 (Fig. 2c,
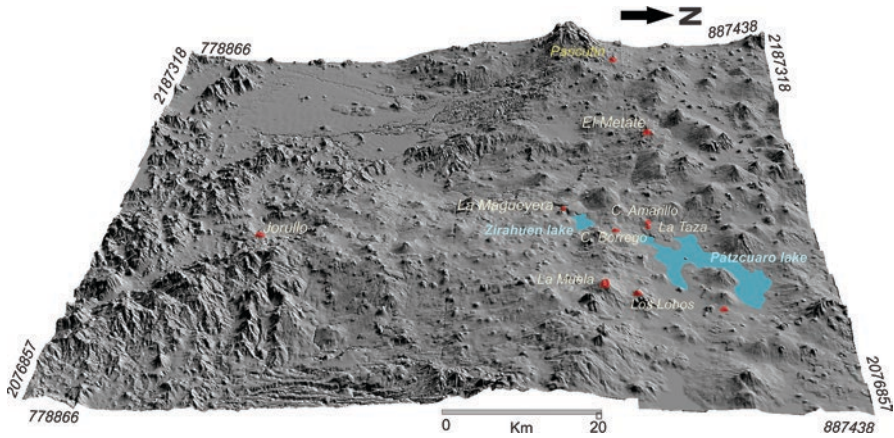
Fig. 1 (**a**) Location of Zirahuén Lake in the TMVB (Trans Mexican Volcanic Belt within the monogenetical Michoacán Guanajuato volcanic field). Elevation model showing the volcanic highlands surrounding the study area, with lakes Pátzcuaro and Zirahuén and a high elevation area between the lakes
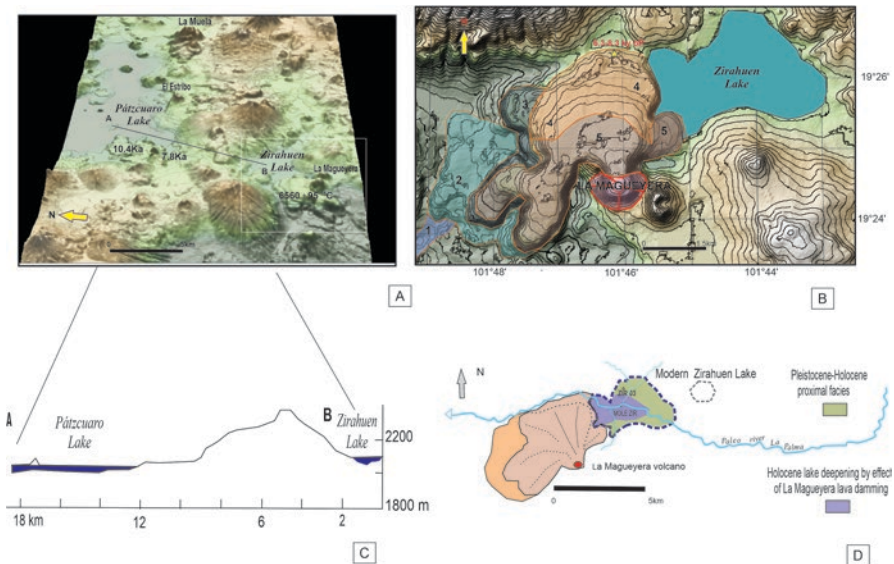

Fig. 2 (**a**) Altitudinal relationship between Lake Patzcuaro and Lake Zirahuén, observed in section A–B, A being the southern shores of Lake Patzcuaro. (**b**) La Magueyera volcano and its relationship with Lake Zirahuén and the La Palma River, as well as the location of MOLE ZIR 03 central core and ZIR 03-01 littoral core. The arrow shows the direction of the paleo river flow toward the Balsas basin; (**c**) main stages of the dome construction of the La Magueyera volcano. Lava flows 1, 2, and 3 are the oldest flowing toward the Balsas basin. Lava flows 4 and 5 emissions dammed the lake

d). The first, 6.61 m in length, was retrieved in approximately 12 m of water in littoral northern sector (ZIR 03 01). It spans the last ca. 17 cal ka, with a hiatus observed between 12.1 and 7.2 cal ka BP (Ortega et al. 2010). The second (MOLE ZIR 03), obtained from the deepest part of the lake in the central north sector, in 36.5 m of water, provides a continuous record of the last 11.6 cal ka BP.

A detailed stratigraphic correlation between the two cores, age model and sedimentary evolution of the lake, was presented by Vázquez et al. (2010). Ortega et al. (2010) focused on the paleoenvironmental record of the last 17 cal ka based on diatom, geochemical, and physical properties of the littoral core, ZIR 03 01. The palynological and microcharcoal records from MOLE ZIR 03 and ZIR 03 01 were reported by Lozano-García et al. (2013), identifying the multiple influences of climate and anthropogenic disturbance on the landscape, vegetation, and fire regime.

Here, we present the diatom record from MOLE ZIR 03, building on previous paleolimnological investigations at Lago de Zirahuén. The new data provide insights into aquatic responses to volcanic activity and climate change during the early Holocene which are not captured in the littoral core (Lozano-García et al. 2013; Ortega et al. 2010). More recent anthropogenic impacts on the aquatic ecology can be placed within the longer term context of the evolution of the lake through the Holocene.

Site Description

Lago de Zirahuén is located on the Trans Mexican Volcanic Belt (TMVB), Michoacán state, Mexico (19° 26′ N, 101° 45′ W), at an altitude of 2075 m asl at the limit of the watershed between the Lerma and the Balsas basins (Fig. 1) (Israde-Alcántara et al. 2011). The drainage basin has an area of 260.8 km² (López 1982) and the lake area is 9.86 km² (Vázquez 2012). The lava dammed lake is hydrologically closed with a principal stream, the Rio de la Palma, flowing into the lake from the east (Fig. 2c). The lake has a maximum depth of 42 m, but may be two meters lower during dry periods. It is one of the most dilute bodies of water in central Mexico, with an average electrical conductivity of 75.0 μS/cm with Ca-Mg-HCO₃ as the dominant ions (Armienta et al. 2008; Tavera and Martínez-Almeida 2005). The surface water pH of lake water varies, with recorded values of 8.4 in 1997 (Davies et al. 2002) and 6.5 in 2013. Lago de Zirahuén is a tropical oligo-mesotrophic lake and one of the least eutrophic lakes in Michoacán state. However, in the 1980s, a trend toward nutrient enrichment was observed in the recent sedimentary record (Davies et al. 2004, 2005) which was attributed to an increase in agricultural and tourist activities within the basin, in combination with the lack of water treatment facilities, increasing the concentration of nutrients. Since the summer of 2002, *Mycrocystis aeruginosa* has been observed in the north and south sectors of the lake. Analysis from June 2013 indicates a lake clearly in the process of eutrophication,

with a Secchi disc transparency of 2.26 and an oxygen concentration of 5.70 mg/L^{-1} compared with 2010 measures with Secchi disc transparency of 3.70 m and oxygen concentration of 7.82 mg/L^{-1}, respectively (Bernal-Brooks et al. 2016). Toward the Rio de La Palma, the oxygen concentration decreases to 1.82 ± 1.17 mg/L (Gomez-Tagle et al. 2013). Lago de Zirahuén is a monomictic lake, thermally stratified with a December–January mixing regime (Tavera and Martínez-Almeida 2005).

The basin is covered by numerous lava emissions and pyroclastic materials (Fig. 1) extruded over the last 8 million years (Osorio-Ocampo et al. 2018). The continued emissions of those volcanic materials in the region have noticeably changed the configuration of the basin during the Neogene-Quaternary. Like many sites in the region, the principal volcanic products observed are Quaternary basaltic-andesitic lava flows forming large semi-shield volcanoes (Cerro Cumburinos to the NW and Cerro Zirahuén to the NE). Based on volcanic and geomorphologic relations (Fig. 2c), it has been suggested that La Magueyera Lava Flows (LMLF), to the SW, were produced around 6560 ± 950 BP (Ortega et al. 2010) modifying the morphology of the lacustrine basin, contributing to the change of lake level. Nevertheless, through a detailed morphological analysis, five lava flows have been identified (Fig. 2c). The dated lava flow (Ortega et al. 2010) belongs to the fourth lava flow event. The age of the lake is not yet known and could originate in the initiation of La Magueyera lava flow in the area, damming the perennial Rio de la Palma River during the late Pleistocene–Early Holocene.

Around the lake there is a thick layer of paleosols which are the main sources of detritus for the lake. One of them is a reddish Luvisol with the characteristic coloration of the region (Fig .3). To the SW, covering the LMLF there is a more recent ochric andosol of yellow to brown color (Vázquez 2012). To the N and SE of the lake the landscape has some flat areas that have been used for agriculture; the continued deforestation has caused marked erosion which is intensified during the rainy months. The dominant vegetation in the upper elevations of the basin (3300–2800 m) is fir forest, replaced at lower elevations by oak and pine forest (Lozano-García et al. 2013). The forest at lower levels has been increasingly replaced with the expansion of avocado cultivation. Areas below 2400 m asl are largely covered with grassland and scrub vegetation (Tavera and Martínez-Almeida 2005).

The climate of the region is temperate subhumid (Cw$_2$), with annual mean temperature of 16 °C. The annual rainfall is between 800 and 1200 mm with a mean of 891 mm (Servicio Meteorológico Nacional). The climate is markedly seasonal with a concentration of rainfall in summer between June and October with the arrival of humidity from the Gulf of Mexico and Pacific Ocean, controlled by variations in atmospheric circulation of the High Pressure Subtropical Cells and the Intertropical Convergence Zone. These changes in effective moisture are reflected in Lago de Zirahuén through changes in lake level and chemical composition and aquatic ecology.
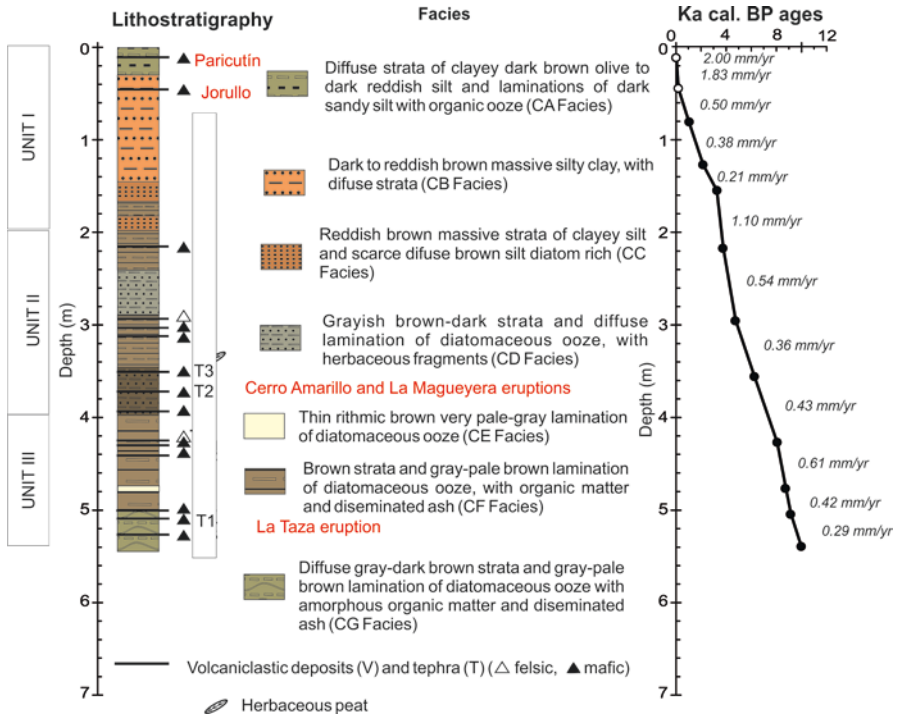
Fig. 3 Stratigraphic column of MOLE ZIR 03 core record showing the main facies along the core. Diagram showing age model (ka) using IntCal20. Black circles are the midpoint of 2 σ calibrated ^{14}C and open circles are the known tephra ages of Paricutin (TP) and Jorullo (TJ). Sedimentation rates are shown in mm/year. Other evidence of nearby volcanic activity around the lake are La Taza, La Magueyera, and Cerro Amarillo

Methods

During the Mesoamerican Lakes Expedition (MOLE) in October 2003, three cores were collected in the deepest central zone of Zirahuén Lake at ca. 36.5 m below the water surface using a modified Kullenberg coring system (Kelts et al. 1986; Kullenberg 1947) (Fig. 2c), obtaining a central sequence of 5.4 m length. The polycarbonate core tubes were sectioned longitudinally, photographed, and lithostratigraphy was described following standard protocols (Schnurrenberger et al. 2003). The sediment was packed into weakly diamagnetic resealable plastic cubes (8 cm^3) for magnetic analyses (251 samples were taken continuously). Mass-specific low-field magnetic susceptibility (χ_{lf}) was measured in a Bartington system. To correct for the presence of paramagnetic minerals, ferrimagnetic susceptibility (χ_f) was calculated by subtracting the paramagnetic contribution (χ_p) estimated from the high field slope of the hysteresis loops. Total inorganic carbon (TIC) was measured on 94 freeze-dried samples on a UIC 5030 coulometer, and total carbon (TC) in a UIC 5020. Total organic carbon (TOC) was obtained from the difference between TC

and TIC for each sample (Myrbo 2004). In order to complement the study, we made use of scanning electron microscopy observations (SEM) and X-ray diffraction in a Phillips 1130/96 diffractometer (Vargas et al. 2007).

Diatom samples were taken at 5 cm intervals through the entire sequence. The samples were dried and processed for analysis in 1 cm³ volumes through digestion with 10% hydrochloric acid and 30% hydrogen peroxide to eliminate carbonates and organic matter. Once the diatoms were cleaned, 200 µl aliquots were taken and dried on a cover slip for mounting with Naphrax. Observations were made at 1000× magnification with an Olympus Bymax 50 microscope; taxa were identified using the works of Krammer and Lange Bertalot (1986, 1988, 1991a, b), Rumrich et al. (2000), Rott et al. (2006), Bradbury (2000), and reference to the standard floras of Geology Department at the INICIT (Instituto de Investigaciones en Ciencias de la Tierra) and previous studies on the lake (Ortega et al. 2010). A minimum of 400 valves was counted for each sample and 200 valves in samples of scarce diatom content. Percentages in samples, variation in abundance through time, and preferred habitat of diatoms were graphically represented by means of Tilia Graph software (Grimm 1987, 1992). Total diatom abundance is expressed in valves per gram of dry sediment. Only diatoms with an abundance >5% are shown in diagrams (Figs. 4 and 5).

The age model for the central core was provided by 10 AMS ¹⁴C dates determined on bulk organic sediment and pollen extracts (Table 1). Radiocarbon dates were calibrated to calendar years BP, with the northern hemisphere terrestrial calibration curve (IntCal 20, Reimer et al. 2020) using the midpoint of the 2σ probability interval of calendar ages. The age model also incorporates two tephras of known origin, Jorullo at 0.43 m depth (1759–1764 CE) and Paricutin (1943–1945 CE) at 0.2 m depth (Vázquez et al. 2010).
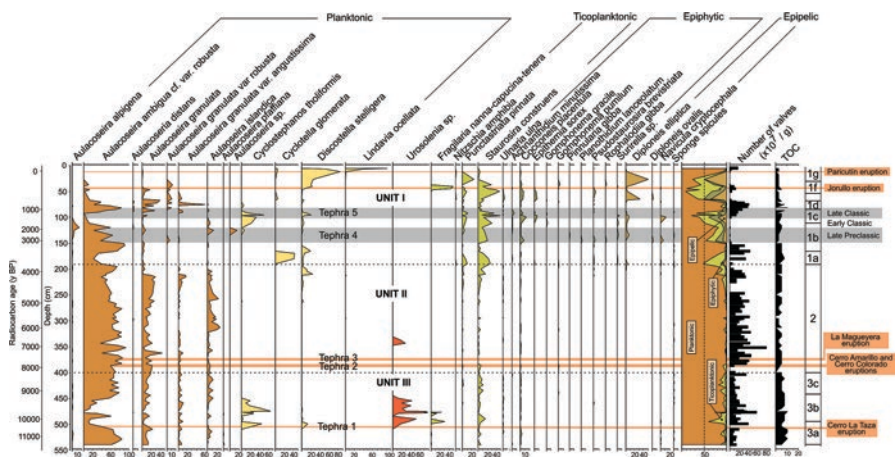

Fig. 4 Diatom record from MOLEZIR 03 sequence showing the main zones: selected taxa as percentages of total counts, and total counts grouped by ecological habitat, plotted versus core depth. Model age is in cal ka BP
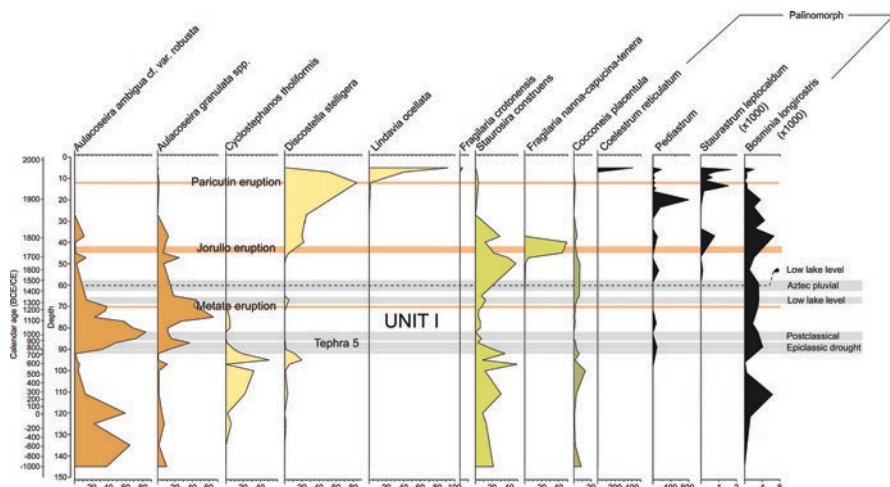
Fig. 5 Detailed diatom and palinomorphs record of the past 2000 years and the associated historical events during this time: Epiclassic drought, Postclassic, Aztec pluvial, El Metate, Jorullo, and Paricutin Eruptions

Table 1 AMS ¹⁴C dates for the MOLE ZIR 03 sequence

Lab. Code	Depth (m)	AMS ¹⁴C yr BP	2 δ range (cal yr BP)	Mean value
Beta – 221711	0.80	990 ± 40	793–956	874 BP
Beta - 221712	1.25	2090 ± 40	1943–2289	2116 BP
Beta - 223997	1.55	3230 ± 40	3379–3559	3469 BP
SUERC − 8106	2.15	3732 ± 26	3984–4152	4068 BP
SUERC − 8103	2.97	4725 ± 27	5326–5577	5451 BP
SUERC − 8102	3.56	6235 ± 38	7010–7254	7139 BP
SUERC − 8104	4.27	8014 ± 48	8651–9014	8832 BP
Beta – 223999	4.76	8710 ± 40	9545–9887	9716 BP
Beta – 223998	5.03	9130 ± 40	10221–10410	10350 BP
Beta – 221711	5.39	10020 ± 100	11242–11871	11556 BP
La Taza		9300 ± 40	10302–10647	10475 BP
Cerro Amarillo		6970 ± 40	7694–7924	7709 BP
La Magueyera		6560 ± 950	5593–9661	7627 BP
El Metate			1250 CE	
Jorullo			1759–1764 CE	
Paricutin			1943–1945 CE	

Calibration based on IntCal 20 (Reimer et al. 2020) program, calculated between consecutive data. *TP* Paricutín Tephra (1943 CE), *TJ* Jorullo Tephra (1762 CE), and other nearby eruptions

Results

¹⁴C Dating and Stratigraphy

The stratigraphy of MOLE ZIR 03 has been described in detail in Vázquez et al. (2010). To summarize, it is composed of three main units (Fig. 3): Unit III (5.40–3.98 m, 11.5–8.1 ka BP) is characterized by laminated gray diatom oozes with disseminated organic matter and six volcanic ashes, with a mean sedimentation rate of 0.44 mm/yr; Unit II (3.98–1.98 m, 8.1–3.91 ka BP) is characterized by diffuse laminations of black organic-rich diatom ooze and seven volcanic ashes, with a mean sedimentation rate of 0.57 mm/yr; and Unit 1 (1.98–0 m, 3.91 ka BP-2003 CE) composed mainly of clastic sediments of black-reddish silty clay and silty sand, with few organic and diatomaceous layers and a mean sedimentation rate of 2.0 mm/yr. Unit 1 contains the historic tephras of Jorullo and Paricutin volcanoes (Fig. 1). Sedimentation rates calculated from the revised age model indicate a range of 0.21–2.00 mm/yr through the c. 11.5 kyr record.

Magnetic Susceptibility and TOC

Magnetic susceptibility (Fig. 6) shows a clear relationship to the stratigraphy of the core. The bottom and middle of the sequence have a very low concentration of magnetic minerals with little variability. Unit III has the lowest values with $\chi_f \approx 0.02 \times 10^{-6}$ m³/kg on average, and for Unit II intermediate values $\chi_f \approx 0.1 \times 10^{-6}$ m³/kg. The highest magnetic concentration is present in Unit I with the maximum values of $\chi_f \approx 5 \times 10^{-6}$ m³/kg. In all cases χ_f was high when tephras occur. The TOC values (Fig. 4) show downcore variations clearly related to stratigraphy too (Fig. 6). TOC is highest in Unit III (highest value at the base 12.36 wt%). TOC shows a clearly decreasing trend from Unit III to I with a stable trend in Unit II, and some high values at the top of the core. TIC is interpreted as a measure of carbonate precipitation in the lake sediments as no detrital carbonates enter in the lake. Higher values would therefore be related to changes in ionic concentration during drier conditions (Eugster and Hardie 1978). TIC values are very low, ranging from 0% to 0.05%, with very low amplitude variations, and are not discussed further.

Diatom Assemblages

The diatom record from MOLE ZIR 03 (Figs. 4 and 5) is almost complete, with diatoms well preserved throughout except between 0.65 and 0.52 m. A total of 84 diatom taxa were identified.
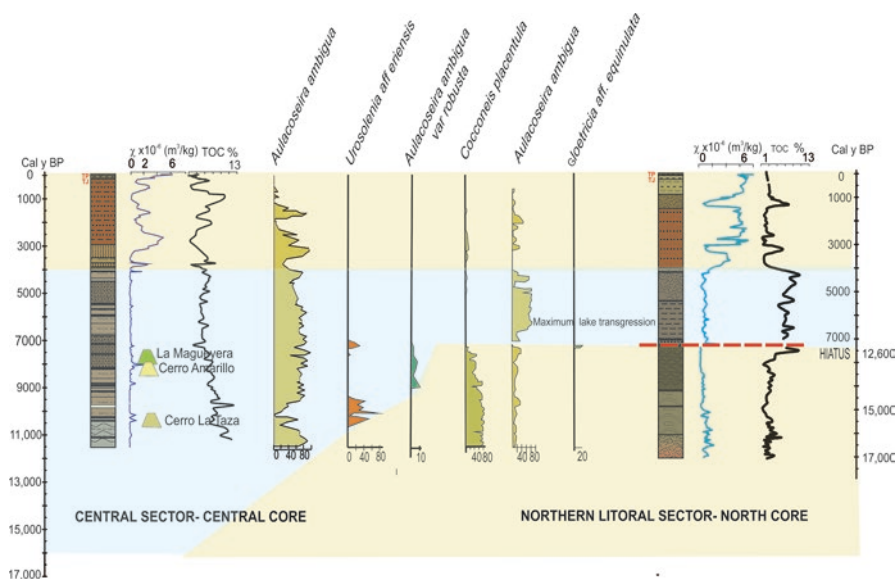
Fig. 6 Stratigraphic units. Correlation between the central coring site, MOLEZIR 03 core, and the northern littoral site, ZIR03 01 core based on lithology, magnetic susceptibility, TOC (Total Organic Carbon), and selected diatom taxa. Maximum lake stages and associated volcanism in relation to main organisms are shown in blue. The red dotted line highlights the discordance in the littoral core

The base of the core to 3.98 m depth, corresponding to stratigraphic Unit III is split into three subzones. The lower part (Subzone 3c, 5.40–4.99 m; 11.6–10.26 ka BP) marks the start of the Holocene and is dominated by *Aulacoseira ambigua* cf. var. *robusta* and *A. granulata* (over 80% of total species), followed by *Staurosira construens* and *Cocconeis placentula*. Diatom abundance is 20×10^7 vgds (valves per gram of dried sediment). Above this, in subzone 3b (4.99–4.49 m; 10.26–9.22 ka BP), a significant decline in the percentage of *Aulacoseira* spp. is observed, which is substituted by the planktonic *Urosolenia* aff. *eriensis*, which increases to over 80% of the assemblage at 4.8 m. Diatom abundance increases to 41×10^7 vgds through subzone 3b. The appearance of *Urosolenia* is accompanied by *Cyclostephanus tholiformis*, which reaches values of over 60%. The group *Fragilaria nanana*, *F. capucina*, *F. tenera* is present at up to 30% of the total diatom count above 4.95 m in depth. *Staurosira construens* also appears in small numbers, coinciding with clear laminations in the core, mainly between 4.78 and 4.70 m. The upper part of the zone (Subzone 3a, 4.49–3.98 m; 9.22–8.20 ka BP) is characterized by a return to an assemblage dominated by *Aulacoseira ambigua* cf. var. *robusta*, along with *A. granulata* and *A. islandica*. *Staurosira construens* is present at c. 10–15% of the count, with *Cocconeis placentula* and *Ulnaria ulna* also present in small amounts.

In Unit II (zone 2, 3.98–1.98 m; 8.20–3.92 ka BP), the diatom abundance increases relative to zone 3, with values between 20 and 40×10^7 vpgds and a short-

lived peak of 80×10^7 vpgds at 3.5 m. The assemblage continues to be dominated by *Aulacoseira ambigua* cf. var. *robusta*, and *Aulacoseira granulata, Aulacoseira islandica* is present at lower abundances but does increase from 3.25 m to 2.5 m. *Urosolenia* makes a brief reappearance between 3.43 and 3.37 m at c. 30% of the count. Overall, species diversity is low.

Unit I, (Fig. 5) representing the uppermost 1.98 m of core, is split into seven subzones. It is characterized by the reduced dominance of *Aulacoseira ambigua* cf. var. *robusta* and increased species diversity, with greater contribution of tycho-planktonic, epiphytic, and epipelic taxa. Subzone 1a (1.98–1.70 m; 3.92–3.63 ka BP) sees an abrupt decrease in *Aulacoseira ambigua* var. *robusta* abundance and increase of *Cyclotella glomerata* in association with *Staurosira construens.* Between 1.70 and 1.11 m (Subzone 1b, 3.63–1.69 ka BP) the diatom assemblage *Aulacoseira* spp. again, reaching their maximum abundance in the diatom record (92% at 1.55 m). *Staurosira construens, Punctastriata pinnata,* and *Pseudostaurosira brevistriata* increase in this interval along with small numbers of *Diploneis elliptica*, *Cocconeis placentula*, *Planothidium lanceolatum, and Pinnularia* gibba are present. In the next interval (Subzone 1c, 1.11–0.80 m; 1.69–0.88 ka BP), *Aulacoseira* spp. almost disappear, with a corresponding increase in *Cylostephanos tholiformis*. The overall diatom abundance declines in subzone 1c, which also sees an increasing proportion of small fragilaroid species, *Cocconeis placentula* and *Epithemia sorex*. Between 0.80 and 0.65 m (Subzone 1d, 0.88–0.58 ka BP), *Aulacoseira granulata, A. granulata v. angustissima,* and *A. ambigua* reappear with an increase in the number of vpgs. The interval 0.65–0.52 m (Subzone 1e, 0.58–0.33 ka BP) has the lowest diatom abundance of the record; it is characterized by diatoms of robust, highly silicified diatoms such as *Diploneis* and *Aulacoseira ambigua* cf. var. *robusta*. From 0.52 to 0.37 m (Subzone 1f, 330 y −145 y BP), the *Fragilaria nanna, F. capucina,* and *F. tenera* group, together with *Diploneis elliptica,* form a distinctive assemblage. The upper part of Unit I (Subzone 1 g, 0.37–0 m; c. 145 y BP–2003 CE) is characterized by a major change in the diatom flora, with high percentages of *Discostella stelligera* and *D. pseudostelligera.* These taxa are rapidly replaced by *Lindavia ocellata* from 10 cm (1943 AD) to 5 cm depth (1982 AD), dominate the assemblage. In the last 5 cm of the sedimentary record (1982 CE) appear *Fragilaria crotonensis,* a characteristic cultural eutrophication diatom taxa (Reavie and Cai 2019).

Interpretation and Discussion

Paleoenvironmental Interpretation

At the base of the core to ~2 m depth (ca. 11.6–4 ka BP), low magnetic susceptibility values suggest minimal catchment erosion into the lake (Fig. 6). Occasional peaks in magnetic susceptibility are associated with tephra layers as described by

Vázquez et al. (2010). The highest % TOC values are found in the basal sediments, up to 4 m depth (11.6 ka BP – 8.2 ka BP), indicating a productive aquatic environment as catchment sources do not appear to be significant based on the magnetic signal. The diatom assemblage through this section (Unit III) is formed by the planktonic taxa *Aulacoseira ambigua* cf. var. *robusta* and *A. granulata*, particularly in subzones 3a and 3c. *A. ambigua* var. *robusta* was also found in Late Pleistocene sediments of nearby Lake Patzcuaro. These are heavily silicified species that require substantial water depth and deep circulation to remain buoyant (Bradbury 2000) and an abundant silica supply (Kilham et al. 1986). The presence of *A. granulata* also indicates nutrient-rich lake waters. Subzone 3b shows a change in diatom flora, *Aulacoseira* reduces its abundance and instead pioneer diatom *Urosolenia* cf. *eriensis* becomes abundant more so between 10.2 and 9.3 cal ka BP where it is associated with *Cyclostephanos tholiformis* suggests increased nutrients. Significant numbers of *Urosolenia* cf. *eriensis* and *Cyclostephanos tholiformis* are common in eutrophic lakes in North America (Stoermer et al. 1987) and Brazil Tremarin et al. (2015); *Urosolenia* is a delicate, lightly silicified diatom and its exceptional preservation within this section of core is notable. Its presence may suggest a higher degree of stratification in the water column as it commonly occurs in the late-summer autumn plankton bloom of moderately stratified temperate lakes (Rott et al. 2006). In this interval, the needle-shaped diatoms planktic group (*Fragilaria nanna*, *F. capucina, F. tenera*) appears for the first time by ca. 10 cal ka BP. Fragilaroid taxa commonly occur in association with volcanic ash deposition in lake sediments (T1), in response to increased nutrient inputs (Telford et al. 2004). These nutrient-rich conditions in the lake were possibly a consequence of the mafic tephra associated to the Cerro La Taza eruption. This diatom assemblage gives an indication of the status of the lake after the eruption, with a stratified water column in a warm climate. A productive aquatic environment is also consistent with the relatively high TOC values found in the basal sediments (11.6 cal ka BP–8.2 cal ka BP). The palynomorphs record in subzone 3b showed a *Pinus*-dominated landscape with low percentages of spores of *Pediastrum boryanum* var. *longirostrus* and *Botryococcus* (Lozano-García et al. 2013). The renewed dominance of *Aulacoseira* spp. in subzone 3c suggests a return to deeper circulation in the water column.

The continued dominance of *A. ambigua* cf. var *robusta* and *A. granulata* and other Aulacoseira species through Unit II, between ca. 8.2 and 3.8 cal ka BP, indicates relatively stable lake conditions, with only minor fluctuations in the assemblage through this period. A relatively deep mixing regime would have been required to enable these heavily silicified taxa to remain the major component of the diatom assemblage throughout this 4000 year period. The lack of epiphytic and periphytic forms throughout Unit II suggest minimal input of littoral material to the center of the lake, again supporting more stable conditions. A brief reappearance of *Urosolenia* cf. *eriensis* between 6.6 and 6.8 cal yBP suggests increased silica supply as this coincides with the highest diatom concentrations in the core (80×10^7 vgds). This occurs directly above a mafic tephra, which relates to the La Magueyera eruption dated to 6.9–7.1 cal. ka BP (Vázquez et al. 2010) and a mean of 7.6 cal y BP (intCal 20) and is likely a direct response to nutrients inputs and increased ionic concentra-

tion from this volcanic source. After this eruption, visible peat and the highest TOC percentages are recorded.

Above 1.98 m to the top of the core, the magnetic susceptibility values increase significantly, with several large peaks (Fig. 6). While a small peak is associated with the deposition of a tephra layer at 1.98 m, these high values are more sustained and are associated with the influx of reddish brown soil from the surrounding slopes (Vázquez et al. 2010). The sedimentation rate through Unit I is substantially higher than the rest of the core. The increase in the proportion of epiphytic and other periphytic diatoms and more variable diatom assemblages support the interpretation of episodes of increased catchment erosion.

Subzone 1a (3.92–3.63 cal ka BP) shows an abrupt decrease of *Aulacoseira ambigua* var. *robusta* and an increase of *Cyclotella glomerata* in association with *Staurosira construens,* that indicates an increase in nutrient concentration but with a decrease in mixing. Subzone 1b (3.63–1.69 cal ka BP) sees a return to the dominance of *Aulacoseira ambigua* cf. var *robusta*. Above this, the increased importance of tychoplanktonic species *Staurosira construens* and *Pseudostaurosira brevistriata* along with periphytic taxa (e.g., *Planothidium*, *Pinnularia*), suggest increased inputs of material from the littoral zone, related to catchment disturbance and/or lower lake level. The trend of fluctuating conditions continues into subzone 1c (1.69–0.88 cal ka BP) as *Cyclostephanos tholiformis* dominates the planktonic taxa, suggesting lower mixing and nutrient enrichment. The associated increase in epiphytic forms represented by *Cocconeis placentula* and *Epithemia sorex* indicates an expansion of shoreline habitat suitable for macrophytes, possibly due to lower lake levels. A return to the *Aulacoseira* spp. dominated assemblage in subzone 1d (0.88–0.58 cal ka BP) suggests more turbid, well-mixed lake waters and an increase in lake level as epiphytic taxa decline. Increased catchment erosion is evident above this in subzone 1e (0.58–0.33 cal ka BP) from a further peak in magnetic susceptibility. The poor preservation coinciding with increase in catchment inputs indicates that sedimentation may have been more rapid, diluting the diatom component of the sediments. The occurrence of the Jorullo tephra (1764–1759 CE) at the boundary between subzones 1e and 1f at 43 cm depth marks the onset of a significant change in the diatom assemblage, with a short-lived spike in planktic *Fragilaria tenera-nanna-capucina* group. This is likely a response to the deposition of the tephra and consequent increase in nutrient availability in the lake waters. Above this, the increase in *Discostella stelligera* becomes the dominant component of the plankton, and was previously interpreted as being associated with increased anthropogenic catchment disturbance (Davies et al. 2002).

At the end of this phase in subzone 1f (0.33–0.24 cal ka BP) (ca 1830 CE–1880 CE), an increase in epipelic species (*Diploneis elliptica*) is observed, which may indicate a decrease in the level of water in the lake. Subzone 1g, from 37 cm to the top of the core (since ca. 1810 CE), indicates further catchment disturbance, with a peak in magnetic susceptibility and poor diatom preservation. The Paricutin tephra (1943 CE, at 20 cm depth) contributes to this signal. The rapid switch from *D. stelligera* to *L. ocellata* in the uppermost sediments in this core at 10 cm depth was also reported by Davies et al. (2004) in short cores and interpreted as a response to inten-

sification of agriculture since the 1980s. *Lindavia ocellata* is a common taxon in Lake Tacambaro, south of Lake Zirahuén and appears in the last 10 cm of the record (Sanchez 2007; Caballero et al. 2016). Its co-occurrence with *Fragilaria crotonensis*, a commonly used indicator species for mesotrophic conditions and the onset of eutrophication, supports this interpretation. The presence of epiphytic, epipelic, and aerophilous diatom species suggest the expansion of marginal habitat.

Correlation of MOLE ZIR 03 and ZIR03-1

Correlation of diatom evidence from MOLE ZIR 03 with the previously published 17 ka, 6.61 m record from the littoral zone (ZIR 03-1; Ortega et al. 2010; Vázquez et al. 2010; Lozano-García et al. 2013) provides an opportunity to examine the consistency between the diatom records from the two sequences. The correlation between ZIR 03-1 and MOLE ZIR 03 was established by Vázquez et al. (2010) and is based on the presence of five common tephra layers in the two cores. The oldest of the five common tephras is dated between 7.1 and 6.9 cal ka BP (Vázquez et al. 2010). This stratigraphic framework which links the cores over the last ca. 7 cal ka BP is supported by the magnetic susceptibility and pollen records from both cores (Lozano-García et al. 2013). The diatom assemblages recorded in MOLE ZIR 03 between ca. 7 cal ka BP and the base of the sequence at ca. 11.6 cal ka BP is not represented in ZIR 03-1. This covers a key time period as the North American Monsoon was becoming re-established over Mexico during the early Holocene (Metcalfe et al. 2015). Furthermore, there is evidence for significant volcanic activity at this time which may have impacted lake development. The diatom record therefore may provide insights into aquatic responses to these local and regional factors.

Volcanic Impacts on the Paleoenvironmental Record

In central Mexican lacustrine basins, paleoenvironmental records are influenced by episodes of volcanic activity (Telford et al. 2004). Results from tephrastratigraphy from nearby Lake Pátzcuaro shows a peak in activity from monogenetic volcanoes around the area between 15 and 10 ka BP (Newton et al. 2005). More recent research shows that this activity persisted into the early Holocene with the development of two monogenetic volcanoes close to Zirahuén: Cerro la Taza which erupted at 9300 ± 40 uncalibrated ^{14}C years BP (10.4 cal ka BP) and Cerro Amarillo dated at 6970 ± 40 uncalibrated ^{14}C years BP (7.8 cal ka BP), Osorio-Ocampo et al. (2018) was the source of the more recent emitted fall deposits this period (Fig. 1).

A direct influence on the morphology of Lago de Zirahuén was caused by eruptions of La Magueyera volcano (Fig. 2c) with lava flows produced in five stages. Only the second to last Magueyera lava (4) has been dated, and was erupted between

6.3 and 8.3 cal ka BP (Ortega et al. 2002). 7.6 cal ka BP (median probability IntCal 20).

The impacts of the early Holocene volcanic activity are recorded in specific changes in diatom assemblages as well as other proxies. In the littoral core (northern lake sector) (Figs. 2c and 4), the diatom record from 17 cal ka BP to 10 cal ka BP indicates that Zirahuén was a shallow lake with the epiphytic species *Cocconeis placentula* as the dominant diatom at abundances greater than 80%. This suggests that the earlier eruptions that created the La Magueyera volcano (lava 1 and lava 2, Fig. 2c) were not sizeable enough to produce a high enough lava to dam the lake. Lavas 3 and 4 finally dammed Lake Zirahuén resulting in the rise in lake level needed to produce a rapid change, from the shallow, aquatic environment with epiphytic diatoms *Cocconeis,* to a planktonic assemblage-dominated *Aulacoseira* ambigua cf. var. robusta (Fig. 4). As outlined earlier, this species and the others it occurs in association will require a deeply circulating water column to keep it buoyant (Bradbury 2000).

Maximum lake transgression is indicated by the appearance of *Urosolenia-Cyclostephanos* assemblage along with *Botryococcus* in the palynological record (Lozano-García et al. 2013). The peaks in *Urosolenia* are also associated with a decline in *Isoetes* between 10.2 cal ka BP and 9.6 cal ka BP, coincident with the end of the La Taza volcano eruption (Figs. 1 and 6) in correspondence with high valve abundance and an inverse relation with the lowest magnetic susceptibility values. The *Urosolenia* peaks are associated with a sharp decrease in *Aulacoseira* and *Isoetes* (Lozano-García et al. 2013) between 10.2 cal ka BP and 9.6 cal ka BP, suggesting a decrease in turbulence and an increase in water depth. This period is associated with the end of the La Taza volcanic eruption (Fig. 1).

In the littoral ZIR 03-01 core, an unconformity is marked by a high peak in magnetic susceptibility between 12 ka cal BP (Late Pleistocene) and 7.2 cal ka BP (Fig. 6). Prior to this, the presence of *Isoetes* that together with the presence of *Cocconeis* indicates a shallow lake of less than 18 meters (Lozano-García et al. 2013), compared with the present lake conditions of 42 m maximum depth and an area of 9.86 km^2. If we subtract an 18 m regression, during the late Pleistocene the lake could have had 24 m of maximum depth and be more restricted to the southern sector. The flood plain could be expanded by the sediment discharged from the La Palma River three kilometers inside the lake in the eastern delta of La Palma River (Fig. 2d).

A second lake transgression and final damming of the lake could be related to lava 4, dated between 8.3 BP and 6.3 ka BP (Ortega et al. 2002) when *Gloetrichia equinulata* (8.9 cal ka BP to ca. 6.8 cal ka BP) appears in the record (Lozano-García et al. 2013). This change is followed by a further *Urosolenia* peak. During this time another nearby volcanic center, Cerro Amarillo, also produces an eruption between 7.8 cal ka BP and 7.7 cal ka BP. Both the eruptions of Cerro Amarillo and La Magueyera contributed to high charcoal peaks, high percent carbon, and the disappearance of *Pinus* and *Quercus*, suggesting a period of significant disturbance in the basin.

In this volcanic context, the hydrothermal influence is a possible factor in influencing the lake chemical and thermal conditions and possibly produced the *Urosolenia* and *Cyclostephanus tholiformis* assemblages. However, nutrient enrichment and changes in lake configuration and water column dynamics could also explain the observed changes. *Cyclostephanus tholiformis* is common in eutrophic lakes and ponds (Davies et al. 2005) and in warm water lakes in North America (Stoermer et al. 1987). At Lake Kivu, an African volcano tectonic lake, *Urosolenia,* appears as a result of a rise in lake level during the Late Pleistocene as a result of subaquatic springs that maintained the thermohaline stratification of the lake (Ross et al. 2015). As at Kivu Lake, previous phreatomagmatic activity could have enhanced hot water infiltration via groundwater into the lake as hydrothermal pulses produce well-established lake stratification and diatom blooms (Sarmiento et al. 2006). At Zirahuén, a volcanic complex divides the Pátzcuaro basin (2042 masl) from that of Lake Zirahuén (2082 masl), this eruptive activity pulse could produce a rapid change in the lake conditions (probably associated with hydrothermal discharge into this alkaline volcanic lake).

The potential impact of more recent tephra deposition from the Jorullo and Paricutin eruptions on the diatom record from Lago de Zirahuén was investigated by Telford et al. (2004), who identified a very limited response to these historical eruptions. The high levels of catchment erosion over the last few hundred years coupled with anthropogenic eutrophication have likely been the stronger influence on the diatom record over this more recent time period (Telford et al. 2004), masking any minor impacts of tephra deposition.

Regional Paleoclimatic Record

Paleoenvironmental studies in northern Michoacán cover the last ca. 50 ka BP, with Late Pleistocene records from Pátzcuaro (Bradbury 2000; Metcalfe et al. 2007) and Cuitzeo (Israde-Alcántara et al. 2010) indicating contrasting conditions to the Holocene. Between 47 ka BP and 18 ka BP, Pátzcuaro was a more extensive and deeper and colder lake than at present (Bradbury 2000), while Zacapu (Metcalfe 1992) and Cuitzeo (Israde-Alcántara et al. 2010) were deep lakes before 28 ka BP, both lakes having conditions of more stability and depth than at present. During this time period, the landscape was also modified by either volcanic or tectonic activities (Pooja et al. 2016).

Younger Dryas to Early Holocene

From the interval between 13.5 and 12 ka BP, Lakes Pátzcuaro, Cuitzeo (Israde-Alcántara et al. 2012), and Parangueo (Domínguez-Vázquez et al. 2018) experienced wet conditions and high water levels, with a shallowing from 12 to 10 ka

BP. Generally dry conditions at the onset of the Holocene are observed in records across Central Mexico (Metcalfe et al. 2015). During the early Holocene in Lago de Zirahuén, a deep lake was established at the central core site but the littoral core records a hiatus. This could be indicative of lower lake levels than present but the hiatus is more likely related to the catchment disturbance linked to volcanic activity and subsequent establishment of the current lake configuration.

From 10.2 ka BP to 9.5 ka BP, the MOLE ZIR 03 core high percentages of *Urosolenia and Botryococcus* together with the highest TOC percentages (Fig. 3) and an *Isoetes* decrease suggests a deep, fresh, and nutrient-rich lake. The littoral core records a hiatus, which could be interpreted as low water level at that location, but is more likely related to the catchment disturbance linked to Holocene volcanism that led to the establishment of the present lake configuration.

The volcanic activity in the area at Pátzcuaro Lake 8 km NE from Zirahuén Lake continued from ca. 7 ka BP to 8.4 ka BP with the construction of Cerro Amarillo (7.7 ka BP) and emissions 4 and 5 of La Magueyera (8.3 cal ka BP to 6.3 cal ka BP) (Ortega et al. 2010) (Fig. 2c) with the emission of ash fall deposits. This caused an increase in the charcoal and magnetic susceptibility signal. As a result, *Pinus* and *Quercus* disappeared in the basin, replaced by a succession of atypical communities with the presence of *Gloetricchia equinulata* and *Tilia* (Lozano-García et al. 2013) and *Urosolenia-Cyclostephanus toliformis* (Fig. 4).

The pollen spectra at Zirahuén at 8.2 ka cal BP shows a sharp decrease in *Alnus* abundance that has been associated with a cold and dry episode caused by a glacial advance (Heinrich event). The nearly global expression of climate conditions at 8.2 cal ka BP indicates a short-lived cold and dry episode promoted by the reduction on the northward heat transport (Walker et al. 2019).

Toward 9 ka BP a decrease in water level occurred in Lake Pátzcuaro. Records of diatoms, pollen, and mineralogy indicate still wetter than present conditions that prevailed just a little after 4.5 ka BP (Bradbury 2000; Metcalfe et al. 2007). In Zacapu, the records of several paleoenvironmental indicators suggest a geography dominated by shallow marshes and somewhat deeper ponds between 9 ka BP and 7 ka BP. The diatom record from Zirahuén (between 11.6 ka BP and 8.2 ka BP) indicates fluctuating conditions during the lower Holocene, but the driest conditions occurred during the late Holocene too. Also in Zacapu, Xelhuantzi Lopez (1994) reported a temperate humid or subhumid environment between ca. 8.1 and ca. 6.7 ka BP. This is coincident with an inundation of the shore at Zirahuén between 7.3 and 7.1 ka BP.

Middle Holocene (7–4 ka BP)

In the period between 7 ka BP and 4 ka BP, the Zirahuén diatom record indicates a period of increased stability in the lake that is represented by the high abundance of diatoms characteristic of deep, freshwater lakes. During that period, the central MOLE ZIR 03 core displays diffuse lamination. In Lake Zacapu, 38 km north of

Zirahuén Lake, the diatom record between 6.9 ka BP and 5.8 ka BP (Metcalfe 1994) reveals a period of semidry temperate climate and after this at ca. 4.5 ka BP, Zacapu became an alkaline marshland, Metcalfe (1994) recorded the poor preservation of diatom valves as well as discontinuities in the diatom record, which following recent studies of Garduño et al. (personal communication) and Soria et al. (2020), we interpret as being associated with significant seismic activity. In the neighboring region of Cuitzeo, diatom associations between 8 ka BP and 4 ka BP suggest the establishment of more saline conditions. The deep, fresh, and stable lake through the mid-Holocene in Zirahuén is consistent with other records across the region that indicates generally wetter conditions and an enhanced summer monsoon (Metcalfe et al. 2015).

Late Holocene (4 ka BP to Present)

Toward the top of the Zirahuén cores (ca. 3.5 cal ka BP), significant changes are seen in the diatom preservation, abundance of diatoms, increasing diversity, and a noticeable increase in tychoplanktonic (*Staurosira*) and periphytic (*Cocconeis*, *Diploneis*) species (in both cores). Fluctuations of well-preserved and abundant diatoms were observed intercalated between the cycles of detrital input to the lake, marking periods of stability in contrast to unstable periods characterized by the common presence of detritus, phytoliths, sponge spicules, and fragmented diatoms such as *Surirella* and *Campylodiscus*, species indicating periods of increased ionic concentration and becoming gradually scarce until their disappearance from the record.

Beginning at about 2 ka, the appearance of *Diploneis eliptica* in the diatom record of Zirahuén together with other epiphytic life forms such as *Gomphonema*, *Epithemia*, *Planothidium,* and C*occoneis*, and the abrupt oscillations in the abundance of *Aulacoseira* spp. The more diverse assemblages with increased inputs of periphytic taxa are coincident with such fluctuations in combination with high values of magnetic susceptibility represent episodes of catchment erosion in the basin. A general trend toward drier conditions was observed in the pollen record by Lozano-García et al. (2013). A drier and more variable climate suggests a weakening of the summer monsoon over the Late Holocene, with drier conditions associated with an increasing influence of the El Niño-Southern Oscillation (ENSO) mechanism in west central Mexico (Lozano-García et al. 2013; Metcalfe et al. 2015).

During the archaeological period between the Late Formative (0 a 100 CE) and the Terminal Formative (300 CE), corresponding to the top of subzone 1f of core MOLE ZIR 03, the presence of *Aulacoseira* spp. and the scarcity of epiphytic forms in association with high magnetic susceptibility values suggest humid conditions. During that period, the first appearance of *Zea mays* pollen recorded in the Pátzcuaro region was observed (Watts and Bradbury 1982) and in Zirahuén, *Zea mays* and *Teocinte* pollen (varieties of maize pollen) appear at ca. 3 ka (Lozano-García et al. 2013) indicating human occupation and cultivation within the basin. Due to the

influence of anthropogenic activity, interpretation of finer scale climatic variability is tentative. The generally drier climate evident from the paleoenvironmental record may have made the catchment more sensitive to erosion from anthropogenic disturbance.

The better-documented period is the Late Classic period between 300 and 900 CE, distinguished by the building of numerous ceremonial centers in central Mexico. In the state of Michoacán, the most relevant of such centers were located in Cuitzeo and Zacapu (Pollard 2000). During the period of 290 to c. 900 CE, in MOLE ZIR 03, sediments become darker and the diatom record provides evidence of a lake rich in nutrients and with fluctuating conditions.

Between ca. 900 and 1270 CE a slightly more humid condition than before is recorded by an increase in the frequency of *Aulacoseira ambigua*, although the values of magnetic susceptibility decrease significantly indicating the absence of high erosion rates in the basin. The increase in *Aulacoseira granulata* var *angustissima* around 1100 CE may indicate slightly increased ionic concentration and drier conditions. This period is coincident with the Medieval Climate Anomaly, during which wet conditions have been reported in Mexico from the eastern Yucatan Peninsula to the west at Santa Maria del Oro, Nayarit (Vázquez-Castro et al. 2008). Records from across the region indicate the possibility of a two-part MCA (Metcalfe et al. 2015).

In several sectors of E-W central Mexico between 19° and 20° of latitude, there is also evidence of an increase in water levels of lakes like Pátzcuaro around 750–1000 CE (Fisher et al. 2003), Zacapu at 760–1070 CE (Metcalfe 1995), southern Guanajuato (Metcalfe et al. 1989), and Zempoala at 650–850 CE (Almeida-Leñero et al. 2005).

Our record also confirms the decrease in the lake's water level and the widely fluctuating conditions with high peaks in the erosion rate between 1368 and 1620 CE, a period during which diatoms are absent from the sediments and the magnetic susceptibility values are high, indicating an interval of significant erosion. Between 1250 and 1550 CE, the pollen record is dominated by the cypress family (*Cupressaceae*) and toward 1600 CE the pollen of *Acacia* spp. and *Agave* spp. become characteristic of this interval.

In Lake Zirahuén and its surrounding area, besides the presence of *Teocinte* pollen in the core record there is no evidence of human occupation, even though historical documents between ca. 1460 and 1650 CE indicate a significant decrease in human population in the region associated with viral and bacterial epidemics introduced from the Old World to which native Americans had had no previous exposure. This made them more vulnerable to infectious diseases such as smallpox and measles causing high mortality and the abandonment of cultivated fields. Lake Pátzcuaro showed the highest water levels, during 1522 CE, a level that has not been surpassed since the Spanish Conquest in 1521 CE. During the colonial period land disputes were frequent during drought conditions, particularly where land was exposed due to lake level lowering (Endfield and O'Hara 1999).

The climatic record of the eighteenth and nineteenth century is characterized by numerous drought episodes recorded in historical documents. Over this time, we do

see evidence for lake level lowering, with increased presence of lake marginal diatom species, but the record is complicated by the increasing intensity of human impacts within the basin during the expansion of Colonial activities (Davies et al. 2004). The onset of this increased activity follows the deposition of the Jorullo tephra (1759–1764 CE). Diatom preservation is poor throughout as catchment inputs increase.

The concluding part of the environmental history of Lake Zirahuén comprises in the upper 0.37 m of the sediment core extending from the years 1805 to 2003 CE. Three types of events occurred during that period, the 1845 and 1858 CE earthquakes, the eruption of Paricutín volcano in 1943 CE, and the unequivocal signal of the development of the Spanish metallurgic industry for the processing of copper. Copper processing effluent was carried via the La Palma River to Lake Zirahuén, generating a peak in copper concentrations in the lake's sediments (Davies et al. 2004). In that interval of the sediment core, there is an increase in the presence of *Cyclotella stelligera* and *Cyclotella ocellata* together with *Fragilaria crotonensis*, which are a species indicative of eutrophication of the lake.

Conclusions

This chapter refines the age model and presents the diatom record that can be used to reconstruct the paleoclimate of Lake Zirahuén from 12 ka BP to the present. The data presented illustrate the following:

- Lake Zirahuén was dammed in early-middle Holocene as product of the Magueyera volcano lava flows located in the south sector of the lake.
- During the stages of eruptions and lava flows from La Magueyera volcano, five lava flows were produced, the first three lavas (lavas 1–3) were erupted some time before 12 ka BP, and lava flows 4 and 5 were erupted between ca. 8.3 ka and 6.3 ka BP. Lava flows 4 and 5 produced the maximum transgression in the lake leading to the deepening of the lake and the substitution of periphytic littoral diatoms assemblages by planktonic diatoms.
- The regional climatic system in this high volcanic plateau show dry conditions associated with a weak monsoon during the late Pleistocene-Early Holocene.
- From Early Holocene to 3.5 ka BP, the Zirahuén catchment shows the lowest erosion rates in the basin due to low volcanic activity and high lake levels. This was a period of stable lake conditions corresponding to a strengthening of the monsoon system.
- During the late Holocene, drier conditions than present prevailed from ca. 3.5 ka BP and the trend toward drier conditions has been observed at local and regional levels and was related to an increase in ENSO activity.
- The last 3 ka BP of Lake Zirahuén shows evidence of the combined impacts of drier conditions and human activity, periodic droughts, and constant fluctuations in regional volcanism.

- The past 900 years show a clear trend of decreasing water levels in the lake. Nonetheless, a peak of the planktonic diatom *Aulacoseira ambigua* between 800 and 1400 CE suggests an improvement of the environmental conditions, consistent with the Medieval Climate Anomaly that occurred between 950 and 1350 CE.

The volcanic activity in this sector of the Michoacán-Guanajuato volcanic field has been intense in the Pleistocene and along the Holocene, volcanism together with the climatic signal controls lake levels behavior in Zirahuén Lake, with increasing influence of human activity during the last 3000 years.

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