Environmental variability during the last three millennia in the rain shadows of central Mexico

Variabilidad ambiental durante los últimos tres milenios en las sombras de lluvia de México central

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ABSTRACT

The last three millennia have been characterized by global temperature oscillations of around one Celsius degree, and high frequency variability on precipitation. Two main temperature anomalies have been reported worldwide, the Medieval Warm Period (MWP) and the Little Ice Age (LIA), characterized by higher and lower than average temperatures, respectively. Precipitation variability has been mostly associated with El Niño anomalies in the Equatorial Pacific. These global variability modes have been modulated by regional factors such as sea surface temperatures and their interaction with continental landmasses. Understanding regional responses to these anomalies would shed light on ecosystem response to environmental variability, a paramount tool for conservation purposes on the light of modern climate change. Here we present a 3,000-year sedimentary record from Lake Metztitlán, located in a Biosphere Reserve under the rain shadow of the Sierra Madre Oriental. Cladoceran and geochemical analyses were used to reconstruct lacustrine dynamics through the time period encompassed by the record. Our record points to highly dynamic lacustrine systems, coupled with global and regional climatic variability. In Metztitlán, the MWP was associated with low lake levels and a high torrentiality of the precipitation reflected in high-frequency peaks of detrital material. The LIA was associated with an enlarged water body, probably as a result of lower evapotranspiration. Overall, global climatic variability resulted in high variability of regional precipitation and detrital input in the Metztitlán region, in turn associated with changes in lake morphometry and depth. Our record highlights the vulnerability of the area to changes in sea surface temperature of the Gulf of Mexico, and to changes in the frequency of El Niño events. Although the effects of global climate change in the region are inescapable, our results emphasize the importance of controlling anthropogenic activities as an additional source of pressure on the regional ecosystems.

Keywords: Medieval Warm Period, Little Ice Age, Cladocera, late Holocene, rain shadow, Barranca de Metztitlán Biosphere Reserve.

RESUMEN

Los últimos tres milenios se han caracterizado por oscilaciones en la temperatura global alrededor de un grado Celsius, y una variabilidad de alta frecuencia de la precipitación. Dos principales anomalías de temperatura han sido reportadas mundialmente, el Periodo Cálido Medieval (PCM) y la Pequeña Edad de Hielo (PEH), caracterizadas por temperaturas más cálidas y más frías que el promedio, respectivamente. La variabilidad de la precipitación ha estado estrechamente relacionada con las anomalías de El Niño en el Pacífico Ecuatorial. A nivel regional, estos modos de variabilidad han sido modulados por factores como la temperatura superficial de los océanos y su interacción con las masas continentales. El entendimiento de las respuestas regionales a estas anomalías ayuda a comprender la respuesta de los ecosistemas a la variabilidad global, un elemento crítico para la conservación en vista del cambio climático moderno. En este trabajo se presenta un registro sedimentario de 3000 años del lago Metztitlán, ubicado en la Reserva de la Biosfera en la Sierra Madre Oriental. Se empleo un análisis geoquímico y cladócero para reconstruir dinámicas lacustre en el período de tiempo que abarca el informe. Nuestro registro apunta a sistemas dinámicos lacustres, asociados con la variabilidad climática global y regional. En Metztitlán, el PCM estuvo asociado con bajos niveles lacustres y una alta torrencialidad de la lluvia, reflejada en picos de alta frecuencia en los indicadores de aporte detrítico. La PEH estuvo asociada con un cuerpo lacustre más extenso, probablemente resultado de una menor evapotranspiración. En general, los efectos de la variabilidad climática global se reflejaron en una alta variabilidad de la precipitación y entrada de detríticos (detrital input) en la región de Metztitlán, a su vez asociada con cambios en la morfometría y la profundidad del lago. En nuestro registro resalta la vulnerabilidad del área a cambios en la temperatura superficial de mar en el Golfo de México, y a cambios en la frecuencia de los eventos El Niño. Aunque los efectos del cambio climático en el área son inevitables, nuestros resultados enfatizan la importancia de controlar las actividades antropogénicas como una fuente adicional de presión sobre los ecosistemas regionales.

Palabras clave: Periodo cálido medieval, , pequeña edad de hielo, cladóceros, Holoceno tardío, sombra de lluvia, Reserva de la Biósfera Barranca de Metztitlán.

1. Introduction

Environmental and ecosystem dynamics are strongly influenced by the interaction of global and regional climatic variability with local processes at diverse spatial and temporal scales (Delcourt and Delcourt, 1991; Bradley, 2015). Through the Holocene, climatic variability has been expressed mainly through changes in regional precipitation regimes, but also through variability in regional temperatures (Mayewski *et al.*, 2004; Bradley, 2015). Throughout the Holocene, changes in precipitation have been mostly associated with precessional changes in insolation, generating millennial-scale patterns of progressive increases or decreases of precipitation (Haug *et al.*, 2001; Bradley, 2015).

Within the last two millennia, the Medieval Warm Period and the Little Ice Age represent the two main changes in global temperatures (Mann *et al.*, 2009) that are reflected by sea surface temperatures and therefore by regional hydrological cycles (Richey *et al.*, 2007). The sub-decadal changes in the temporal distribution of El Niño anomalies in the equatorial Pacific have been an additional source of climatic variability that manifests in regional hydrologic anomalies across the globe (Cane, 2005). The effects of these variability modes on regional environments depend on mechanisms that couple regional and global mechanisms of energy redistribution (Bradley, 2015). At a local scale, ecosystems represent envelopes that encompass biological communities and their interactions with constantly changing environmental conditions (Delcourt and Delcourt, 1991; Bush, 2003).

In recent decades, numerous paleoenvironmental studies have focused on understanding the successional development of lacustrine environments and their relationship with global and regional climatic variability (e.g. Cuna *et al.*, 2014; Rodríguez-Ramírez *et al.*, 2015; Correa-Metrio *et al.*, 2016; Vázquez-Molina *et al.*, 2016; Escobar *et al.*, 2020; Franco-Gaviria *et al.*, 2020). A general property of lake development is the sedimentation process that, in the long term, transforms aquatic environments into terrestrial realms through the gradual infilling of the lacustrine basin (Wetzel, 2001). This process is the result of the interaction between the lithosphere and the atmosphere, modulated by climatic and biological factors.

The eutrophication of freshwater ecosystems is closely associated with these factors and has been a major topic of interest, as the availability of water for ecosystem functioning and human consumption is highly dependent on this process. Eutrophication implies a change on lake trophic status of lacustrine environments as a result of the input of exogenic materials producing an increase in autotrophic productivity (Wetzel and Likens, 2000; Wetzel, 2001). This process can be driven by natural causes and varies depending on lake morphometry, regional climates, and characteristics of the catchment basin such as size and vegetation cover (Carpenter *et al.*, 1998; Wetzel, 2001).

However, during the late Holocene, this process has been accelerated by anthropogenic input of nutrients derived from intensive and extensive human activities (e.g. Carpenter *et al.*, 1998; Franco-Gaviria *et al.*, 2020). Sediment accumulations in lacustrine environments contain biological, chemical, and physical evidence of lake development through time (Cohen, 2003). The study of this sedimentary evidence offers an opportunity to understand processes and factors involved in lake development through time scales beyond the historic observations.

Numerous lakes are distributed across Central Mexico, offering the opportunity to study lake formation and its development in a highly complex landscape, marked by an intricate history of human occupation and natural environmental variability (Caballero-Rodríguez *et al.*, 2017). Here we present the environmental history of Lake Metztitlán, located in the Biosphere Reserve of the same name. Understanding the temporal environmental dynamics of the region is crucial for its conservations as it has been classified as one of the most vulnerable biosphere reserves in the light of ongoing global climate change (Esperon-Rodriguez *et al.*, 2019).

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We retrieved a sediment core and analyzed it for geochemical composition and cladoceran remains. Our aim was to understand regional and local environmental variability through time, and their coupling with global environmental variability through the late Holocene. Overall, we intend to investigate the effects of climatic variability of the last three millennia on regions that are today characterized by an arid climate. Also, we wanted to evaluate the effects of regional climatic variability on the development of local lacustrine conditions.

2. Study area

Lake Metztitlán is located within the Barranca de Metztitlán Biosphere Reserve (20°42' - 20°39' N, 98°53' - 98°49' W, at an elevation of 1,253 m asl), State of Hidalgo, on the western flank of the Sierra Madre Oriental, Mexico (Figure 1). The regional geology is composed of Mesozoic marine sedimentary rocks, particularly limestones and turbidites overlaid by clastic and basaltic materials of Neogene igneous origin, as well as alluvial Quaternary deposits (Carrasco-Velázquez *et al.*, 2008).

The regional relief is composed of parallel ranges and plateaus delimited by faults, constituting a highly dissected landscape with evidence of multiple slumps and detrital flows (García Arizaga *et al.*, 1996). Lake Metztitlán is a large (~2,949 ha) and shallow (^{z}mean = 11 m) water body originated by a massive slump of one of the flanks of the valley of the Metztitlán River that resulted in a natural dam (Suter, 2004).

Two regional, E-W striking, south-dipping normal faults feature pronounced scarps at the northeastern margin of the lake which seem associated with the damming slump (Suter, 2004). According to Suter (2004), the damming of the river occurred between 500 and 1,100 years BP. Currently, the slumped material covers an area of approximately 2.5 km^2 (Figure 1).

The lake is an eutrophic freshwater body of low transparency, with a polymictic mixing regime that hinders the formation of either a thermocline or an oxycline (Sigala *et al.*, 2017). The lake is fed by Metztitlán River, whereas the main drainage of water occurs by infiltration through the debris of the slumping with a resurgence of water by the northeast side of the lake, around 250 m below the level of the lake water (Suter, 2004).

The regional climate is warm and dry with pronounced torrential summer rains. Generally dry conditions are associated with the rain-shadow effect of the Sierra Madre Oriental. On the other hand, the seasonal precipitation regime derives from the northerly displacement of the Intertropical Convergence Zone during the boreal summer (CONANP, 2003). Additionally, during the hurricane season of the Atlantic, moisture from tropical storms ascends along the eastern flank of the Sierra Madre Oriental, bringing additional precipitation. Around the lake, moisture deficit persists throughout the entire year with an annual precipitation of 406 mm, and a mean evapotranspiration of 1,788 mm (Figure 1; Servicio Meteorológico Nacional, 2020).

The lake maintains water throughout the year because of permanent water input from the higher areas of the catchment basin. Mean annual temperature is 20.7 °C, with monthly mean minimum and maximum of 16.5 and 23.5 °C in January and May, respectively (Figure 1; Servicio Meteorológico Nacional, 2020). The steep altitudinal gradient and the highly dissected landscape have created the conditions for a complex mosaic of arboreal vegetation and shrublands. The mean vegetation types are tropical deciduous forests (1100-1500 m asl), lower montane shrublands (1500-1800 m asl), xerophytic shrublands (1000-1800 m asl), and coniferous forests (1800-2500 m asl) (CONANP, 2003; Rzedowski, 2006).

3. Methods

In May 2017, a 5.32-m-long core was retrieved from Lake Metztitlán using a modified Livingstone piston corer (Colinvaux *et al.*, 1999). The core was stored at the Instituto de Geología at a temperature

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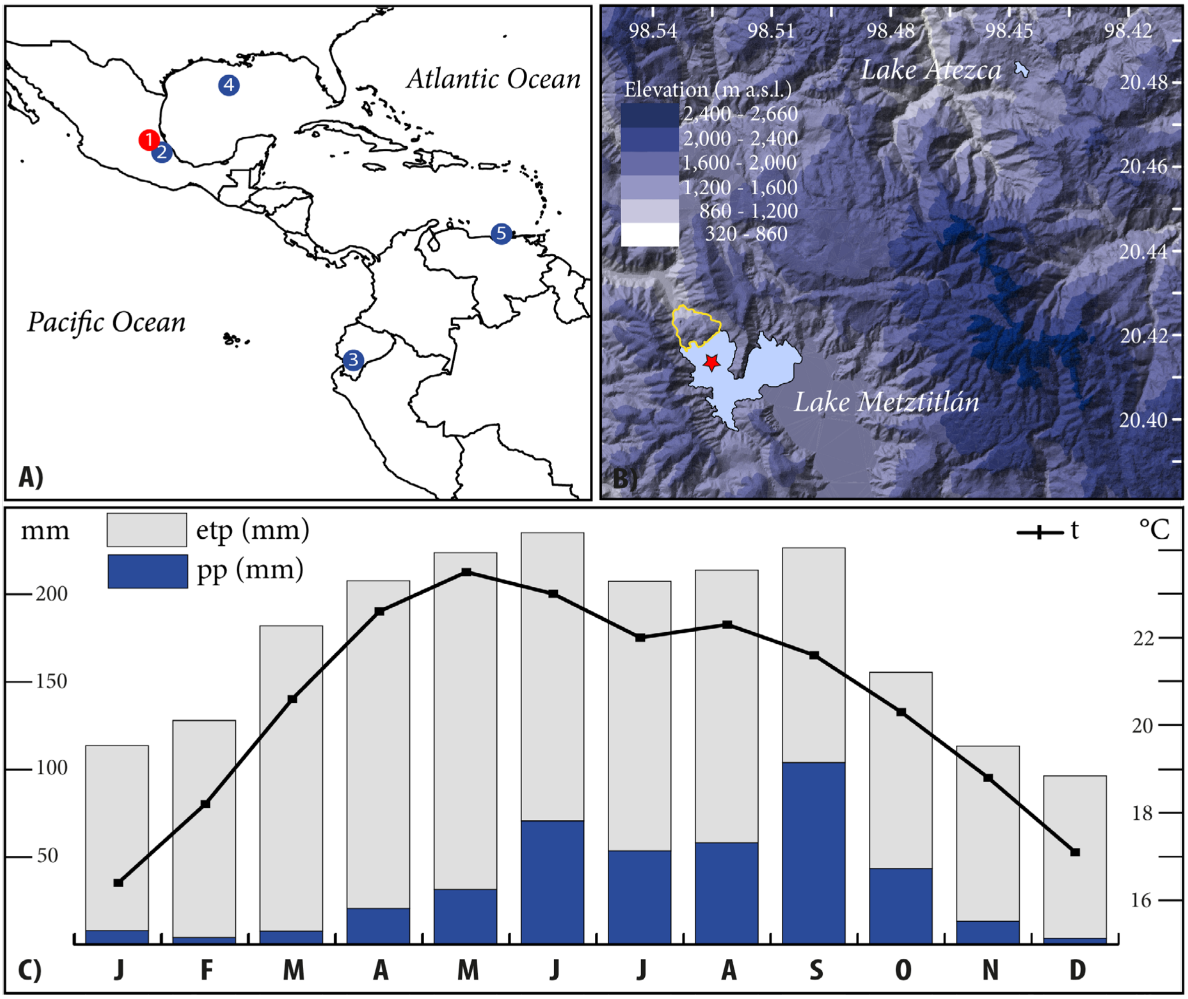

Figure 1 Study area. A) Continental context: 1. Lake Metztitlán; 2. Lake Aljojuca (Bhattacharya and Byrne, 2016); 3. Lake Pallcacocha (Moy *et al.*, 2002); 4. Pigmy Basin (Richey *et al.*, 2007).; 5. Cariaco Basin (Haug *et al.*, 2001). B) Regional topographic context of Lake Metztitlán, showing the coring site (red star), and the damming slump (yellow polygon). C) Regional climatology of the region from Metztitlán meteorological station, showing monthly evapotranspiration, precipitation, and mean temperature (data from Servicio Meteorológico Nacional, 2020).

of 2 °C for preserving the sedimentary evidence. The core was longitudinally sectioned for lithological description that included description of sediment color, qualitative description of sediment texture, and sediment reaction to HCl. Seven samples were extracted at different depths along the core for chronological control of the sedimentary sequence. Organic matter from each sample was dated by analyzing radiocarbon through accelerator mass spectrometry (AMS). Radiocarbon ages were calibrated using the IntCal20 curve (Reimer *et al.*, 2020), and a Bayesian age-depth model was constructed using bacon (Blaauw and Christen, 2011). All ages were expressed in calibrated years before 1950 CE (cal BP, hereafter).

Every two cm along the core, a one-cm^3 sample was extracted for geochemical analyses. Samples were freeze-dried and ground to silt texture using a mortar and pestle. Elemental concentrations were determined using X-Ray fluorescence with a Thermo Scientific Niton XL3t, making three repeated measurements per sample. Elemental concentrations of Ti and Zr were transformed to ratios using Ca, accounting for dilution effects and variability associated with elements undetected by the XRF (Löwemark *et al.*, 2011). Elemental concentrations of Fe and Mn were transformed to ratios using Ti, aiming to detect possible post-depositional alterations of these elements, as they are sensitive to changes in oxygen availability in the mud-water interface (Tribovillard *et al.*, 2006; Algeo and Liu, 2020). Also, the ratio Rb/Ti was calculated, aiming to an indicator of dominant sediment grain size, whereas the Sr/Rb ratio was calculated as an indicator of dominance of chemical weathering (Kylander *et al.*, 2011).

The sedimentary sequence was sampled every 10 cm for analysis of cladocerans. From each selected depth, a one-cm^3 sample was extracted and treated according to standard protocols (Frey, 1986; Szeroczyńska and Sarmaja-Korjonen, 2007). Whereas 10% KOH was used for deflocculating the samples, excess of carbonates in samples was removed by washing them with 10% HCl. The remaining material was sieved through a 35-μm mesh, taken to a 5 ml volume and tainted with safranine to better observe the morphology of cladoceran remains. For each sample, remains were counted until 200 individuals were reached by assembling headshields, shells, postabdomens, and postabdominal claws. Counts of cladocerans were transformed to concentrations (individuals/cm^3). Taxa were identified at species level using illustrated taxonomic guides (Elías-Gutiérrez *et al.*, 2008; Wojewódka *et al.*, 2020a, 2020b).

The geochemical dataset was submitted to a principal component analysis (PCA), aiming to summarize the variability of the dataset and determine the relationships among elemental concentrations and ratios (Jolliffe, 1986). This technique redistributes the variability of the dataset through new orthogonal components that are linear combinations of the original attributes. Attributes are represented by vectors in the newly ordinated space, with vector magnitude representing variability of the original attribute and angles among vector representing association among attributes. Sample scores along PCA axes were used to infer environmental changes through time. All analyses were performed using R (R Core Team, 2020), especially the vegan package (Oksanen *et al.*, 2019).

4. Results

4.1. LITHOLOGICAL PROFILE AND AGE-DEPTH MODEL

The core was mainly composed of a massive layer of clays overlying two thinner layers of sand and lime (Figure 2). The sediments were characterized by a moderate reaction to HCl, indicating a relatively high content of carbonates in the sediment. According to the texture of sediments, the sequence was divided in three units: U1, from 532 to 441 cm below lake floor (blf, hereafter), characterized by dark silt; U2, from 441 to 398 cm blf, composed by coarse dark sands; and U3, from 398 cm blf to the top of the record, composed of homogeneous bands of light clays.

According to the age-depth model, from 398 cm blf to the top , the sequence comprises a record of the last ~3000 years through the upper 398 cm. Calibrated radiocarbon dates on units 1 and 2 showed reversals and were therefore excluded from the analyses (Figure 2 and Table 1).

Given the contrasting nature of the sediments and the high instability of the hillsides (Suter, 2004), as well as the torrentiality of the regional climate, it is likely that units 1 and 2 were product of an instantaneous event. Thus, we based our temporal reconstruction exclusively on the sediments of U3. The landslide that dammed the river and created the lake was a mass remotion process that extended for more than 2 km across the valley (Figure 1; Suter, 2004).

This landslide was probably followed by instability of the hillsides and of the removed landmass, creating subsequent mass movements inside the lake, mixing detritus flows with older sediments from the bottom of the lake. Furthermore, the coarser sediments that characterized U1 and U2 suggest these sediments were deposited by processes of more energy than lacustrine progressive sedimentation.

Whereas one of the radiocarbon dates within U1 was statistically undifferentiable from the basal age, the other was younger (Figure 2), probably as a result of illuviation of organic matter through

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Table 1. Radiocarbon dates for the sediments of Lake Metztitlán.

Depth (cm)	Laboratory ID	Material	Age (^{14}C years)	Error (±)
0	Surface	bulk sediment	-67	5
152	UBA-34346	bulk sediment	864	32
251	UBA-34347	bulk sediment	1928	40
345	UBA-34348	bulk sediment	2364	29
501	UBA-34349	bulk sediment	2365	31
500	UBA-36487	bulk sediment	2002	31

the coarser materials of U1 and U2. Given that with our results we cannot offer a reliable explanation for units U1 and U2, from this point on, we will base our results and discussion only on U3.

4.2. GEOCHEMISTRY

Repeated measurement of Ca, Fe, K, Mn, Pb, Rb, Sr, Ti, Zn, and Zr were statistically consistent and showed significant variability through time. Concentrations of Ca, Sr, K, and Rb were highly variable through the record, showing a general increasing trend towards present (Figure 3). Ti and Zr concentrations were also highly variable, showing an abrupt decrease from 236 to 209 cm blf (from ~1620 to 1350 cal BP).

On the other hand, Fe and Mn concentrations showed little variability through the record, with the latter showing a substantial increase from 46 cm blf to the top of the record (last ~250 years). Pb and Zn concentrations were highly variable from the bottom of the record to 283 cm blf (from ~3000 to 2000 cal BP), whereas they showed relative stability from 283 cm blf to the top of the record (last ~2000 years).

PC1 and PC2 explained 41.0 and 20.8% of the variance of the geochemical dataset, respectively, and both were statistically significant under the broken-stick model (Figure 4). Althrough PC3 and PC4 were also statistically significant, we decided to exclude them from the interpretation as they were associated to very low amounts of variance (Figure 4).

Concentrations of Fe, Pb, Ti, Zr, and Zn were positively correlated and independent from the Fe/Ti ratio, Rb concentrations were positively associated with K, Mn, and Fe/Ti ratio. Ca and Sr concentration showed a positively association between them, and were in turn negatively associated with Fe, Pb, Ti, Zr, and Zn.

The negative association between Ca with Ti/Ca and Zr/Ca ratios (Figure 4), implies diluting effects by high concentrations of these elements in their original concentrations (Löwemark *et al.*, 2011).

Ti/Ca and Zr/Ca ratios were high from ~2800 and 1620 cal BP, and from ~1350 and 900 cal BP, whereas they showed low values between ~3000 and 2800 cal BP, ~1620 and 1350 cal BP, and through the last ~900 years. The Rb/Ti ratio was in antiphase with Ti/Ca and Zr/Ca. Fe/Ti and Mn/Ti ratios showed low variability throughout the record, yet showing a progressive increase through the last ~900 years.

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4.3. CLADOCERA REMAINS

Nine Cladocera taxa where found in 54 samples analyzed through the entire record. These taxa were classified in three and six planktonic and littoral species, respectively. Whereas the plankton group was composed of *Daphnia* sp. (Müller, 1785), *Liederobosmina* sp. (Brtek, 1997), and *Bosmina* sp. (Baird, 1845), the littoral was composed of *Alona* sp. (Baird, 1843), *A. ossiani* (Sinev, 1998), *Ovalona glabra* (Sars, 1901), *Chydorus* cf. *sphaericus* (Müller, 1776), *Leydigia* cf. *louisi louisi* (Jenkin, 1934), and *L.* cf. *striata* (Birabén, 1939). Two of *Leydigia* species, *L.* cf. *louisi louisi* and *L.* cf. *striata* are benthonic bottom dwellers. *Liederobosmina* sp. and *Bosmina* sp. were the most abundant taxa through the record, reaching concentrations higher than 2,000 individuals per cm^3, with an abrupt increase from 150 cm blf to the top of the record (last ~800 years) (Figure 5). *A. ossiani* and *Daphnia* sp. were present only from 381 to 347 and from 145 to 120 cm blf (~2750 to 2500 and ~750 to 650 cal BP, respectively). Samples from 236 to 209 cm blf (~1550 to 1350 cal BP) were barren for Cladocera.

5. Discussion

5.1. DETRITAL AND AUTHIGENIC INPUT

Concentrations of K, Rb, Ti, and Zr in sedimentary deposits are usually associated with the input of detrital materials, mainly associated to erosive processes (Rothwell and Rack, 2006; Kylander *et al.*, 2011). Rb, Ti, and Zr are conservative elements that, after deposited, maintain a signal of the provenance, as most of their abundance corresponds to detritus from parental rocks (Rothwell and Rack, 2006; Boës *et al.*, 2011; Algeo and Liu, 2020). In our record, whereas Ti and Zr were pos-

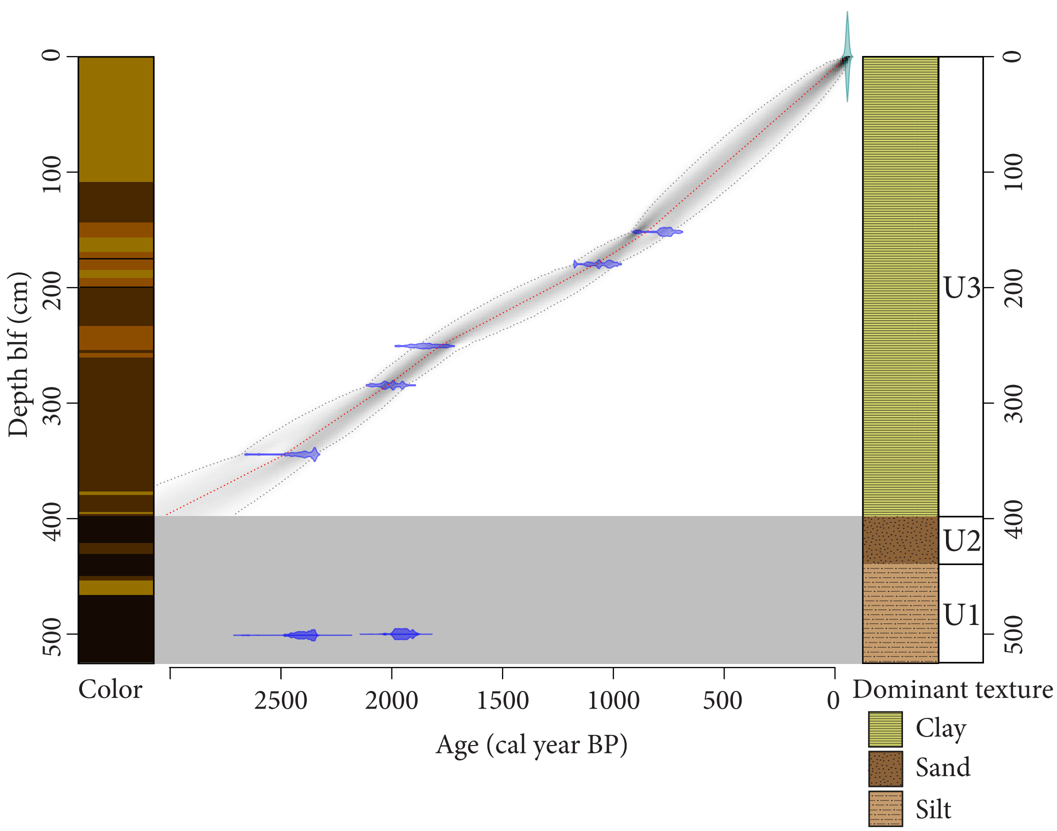

Figure 2 Stratigraphy and age-depth model of the sediment core. The gray rectangle highlights the sediment that represents a probable instant deposit after the damming of the lake.

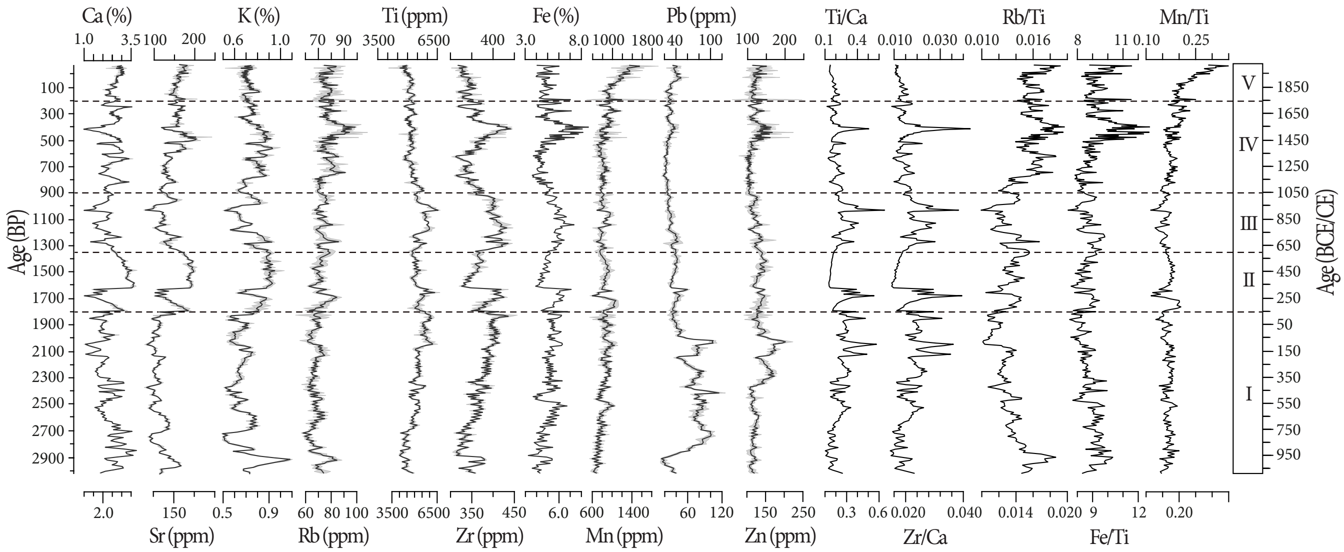

Figure 3 Elemental concentrations and elemental ratios of the sedimentary record of Lake Metztitlán.

itively associated, Rb was decoupled from these elements, even when concentrations were standardized to Rb/Ti (Figure 4). This observation suggests that concentrations of these elements in our record could have been associated with the energy of the transporting agents causing a size sorting of the transported materials. Whereas Ti and Zr are usually associated with relative coarse and heavy grains, Rb mainly associates with finer and lighter sediment fractions (Rothwell and Rack, 2006; Calvert and Pedersen, 2007; Kylander *et al.*, 2011). Given its high capacity of sorption in clay minerals, Rb is an element of low mobility, but it also replaces K in feldspars of variable grain size (Rothwell and Rack, 2006; Calvert and Pedersen, 2007; Kylander *et al.*, 2011). Thus, the positive correlation between K and Rb in the sediments of Lake Metztitlán (Figure 4) suggests these elements were associated with the input of fine material into the sedimentary deposit.

Ca and Sr concentrations in lacustrine sediments are the result of both clastic input from the erosion of parental materials and authigenic precipitation of carbonates (Rothwell and Rack, 2006; Algeo and Liu, 2020). Carbonate precipitation occurs when dissolved minerals in water reach saturation concentrations, and physical, chemical and biological processes facilitate their deposition in the lake floor (Cohen, 2003). These conditions often associate with low lake levels. In our record, negative correlations among detrital elements (Ti and Zr) and Ca and Sr (Figure 4), indicate that these latter elements are mainly result of authigenic precipitation of carbonates. Thus, whereas Ti/Ca and Zr/Ca ratios reflect the detrital input, incorporating the Ca diluting effect, the authigenic flux is represented by Ca, reflecting increased regional evapotranspiration, and probably low lake levels.

The evident separation of elements, associated with authigenic and detrital flows in the PCA (Figure 4), suggests that PC1 directly reflects erosive processes. Overall, erosion is controlled by weathering and mechanisms of detrital transport, the latter mainly associated with the erosive action of precipitation and wind (Sageman and Lyons, 2003). Rainfall and wind represent the main erosive agents in humid and arid areas, respectively (Rose, 1985; Ahnert, 1998). Although, through the late Holocene, both erosive agents might have played a role in Metztitlán, aeolian erosion in the area was probably diminished by the regional geomorphology, whereas the torrential precipitation regime has surely been associated with large amounts of

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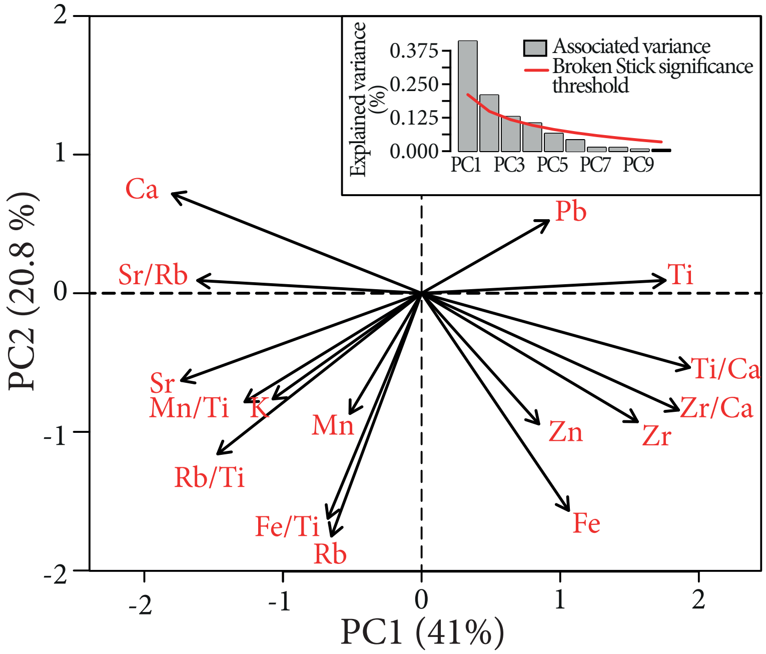

Figure 4 Correlation biplot of the principal component analysis of the geochemical record of Lake Metztitlán. The inset shows the variance associated with each component (grey bars), and the null variance associated with the broken-stick model.

pluvial laminar and linear erosion (Ahnert, 1998). Thus, detrital input into our record is most likely associated with regional precipitation, and positive scores of PC1 are a result of phases of a wetter and/or a more torrential regional climate. Given the sparse vegetation associated with the regional climate (Rzedowski, 2006), wetter periods would be associated with more regional erosion. Transport and deposition of a high load of sediments would result in a faster infilling of the lacustrine basin, impeding the deepening of the water body. PC2, on the other hand, was negatively correlated with Fe, Fe/Ti, Mn, Rb, Rb/Ti (Figure 4), suggesting it was also an indicator of detrital input, although it was probably associated with finer materials.

5.2. REDOX CONDITIONS

Fe and Mn can be affected by processes of reduction and oxidation that take place after deposition (Boës *et al.*, 2011). Under conditions of oxygen availability in the water column, Mn and Fe precipitate in the sediments as oxyhydroxides of magnesium and ferric iron. On the other hand, under anoxic conditions, these elements redissolve and are liberated back to the water column (Algeo and Liu, 2020). Given their detrital origin, an unaltered signal of these elements would imply positive associations with detrital elements that are not prone to post-depositional processes. In our record, both Fe and Mn are decoupled from Ti and Zr concentrations, implying a large amount of variance caused by diagenetic processes. Thus, the Fe/Ti and Mn/Ti ratios could be used as indicators of post-depositional processes, with low values pointing to redissolution of these elements caused by anoxic conditions (Algeo and Liu, 2020). Additionally, in the record of Lake Metztitlán, peaks of Mn/Ti and Fe/Ti ratios were in phase with high concentrations of Ca, suggesting enrichment and fixation of Mn and Fe through authigenic precipitation of carbonates (Cohen, 2003). Overall, changes in Mn/Ti and Fe/Ti ratios can be interpreted as changes in the oxygen content of the mud-water interface, or as changes in the precipitation of carbonates. These processes are closely related as carbonate precipitation usually takes place under low lake levels, which in turn would improve oxygenation of water by wind mixing.

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5.3. LAKE SURFACE, LITTORAL DEVELOPMENT, AND LAKE PRODUCTIVITY

Cladocerans are a highly specialized biological group, systematically distributed across lacustrine environments (Whiteside and Swindoll, 1988; Korhola and Rautio, 2001). Overall, the lake environment can be divided in the littoral and limnetic or open water zones (Wetzel and Likens, 2000), and the distribution of Cladocera species across these areas is driven by their ecological affinities (Korhola and Rautio, 2001). Thus, the turnover of taxa in our record offers elements to reconstruct environmental dynamics of the lake through the time period spanned by our record. Members of the Chydoridae family are mainly distributed across shallow littoral areas with preferences for particular microhabitats such as rocks, mud, and aquatic vegetation (Korhola and Rautio, 2001; Adamczuk, 2014). Contrastingly, open waters are colonized by planktonic species that mostly belong to the families Bosminidae and Daphniidae (Whiteside and Swindoll, 1988; Korhola and Rautio, 2001). Thus, changes of relative abundant of littoral vs. planktonic taxa are informative of changes in factors that modify the habitat of cladocerans, such as lake morphology (Hofmann, 1987). Given the morphology of Lake Metztitlán, abundance increases of planktonic taxa are probably not associated with a deepening of the lake, but more likely an enlargement of the open water area of the lake.

The higher Bosminidae biomass often reflects increase of nutrients (Bays and Crisman, 1983) while the turnover of bosminid taxa is usually associated as an indicator of changes in the trophic status of lakes (Korhola and Rautio, 2001). However, species of *Liederobosmina* appearing in the region may inhabit, both, environment poor (*Liederobosmina tubicen*) and rich in nutrients (*Liederobosmina hagmanni*); and some species (*Liederobosmina huaronensis*) did not show prominent relation with trophic state, whereas *Bosmina* sp. is more commonly found under eutrophic conditions (Beaver ***et al.***, 2018). On the other hand, independently of trophic status, species group of Bosminidae can coexist in open water environments (Hofmann, 1987; Szeroczyńska, 2002). The aforementioned lack of species turnover among bosminid taxa suggests abundances of *Liederobosmina* sp. and *Bosmina* sp. through the record were more associated with the expansion of the open water zone than with changes in the trophic status of the lake. Aquatic vegetation increases the diversity of cladocerans as they offer shelter for taxa adapted to littoral environments (Adamczuk, 2014). Littoral macrophytes can regulate the trophic state of lakes as they retain nutrients, favoring clear waters (Sand-Jensen and Borum, 1991). The Cladocera genus *Alona*, and *O. glabra* are commonly associated with aquatic vegetation (Korhola and Rautio, 2001). On the other hand, *C.* cf. *sphaericus* is a dualistic species, as it can be found under conditions of low nutrient concentration and also associated with macrophytes (Korhola, 1999). Thus, in our record, littoral species (*Alona* sp., *A. ossiani*, *C.* cf. *sphaericus*, and *O. glabra*) are indicating the development of mature littoral areas, probably resulting from advances of the water surface across the southern alluvial plain of Metztitlán valley. During times of expansion of the lake, the alluvial plain was probably covered by a shallow water layer that allowed the establishment of mats of aquatic vegetation that promoted the growth of populations of *Alona* sp., *A. ossiani*, *C.* cf. *sphaericus*, and *O. glabra*. Lastly, the benthic species found in the record of Lake Metztitlán, *L.* cf. *striata* and *L.* cf. *louisi louisi*, have been reported for turbid environments with high nutrient input (Kotov ***et al.***, 2003; Kotov and Elías-Gutiérrez, 2004; Wojewódka ***et al.***, 2016; Sigala ***et al.***, 2017). In our record, these taxa were probably associated with a highly productive environment, which was in turn promoted by nutrients brought by the river together with the detrital input.

5.4. THE LAST 3,000 YEARS AT LAKE METZTITLÁN

According to a visual inspection of the variability of geochemical ratios, we identified five main stages in the evolution of the lake. These stages were characterized by relatively homogeneous conditions and were apparently dominated by changes in the regional moisture availability. The high variability of Cladocera assemblages through time allowed for the identification of an additional stage towards the end of the record. This discretization of the record was supported by PCA scores, which show consistency between the geochemical and biological signals (Figure 6).

5.4.1. ZONE I (398-256 CM BLF; ~3000-1800 CAL BP)

Through this time interval, higher abundances of *L.* cf. *louisi louisi* and *L.* cf. *striata* suggest a shallow environment with rather weakly developed submerged vegetation and probably low water transparency (Figure 6). This zone overlays the instantaneous deposit of coarse material that characterizes the bottom of the core (Figure 2). Such instantaneous event filled the bottom of the lake bringing a high load of nutrients derived from the fresh material recently eroded. Decreasing Rb/Ti ratios (Figure 3) suggest that progressively coarser materials were deposited into the lake, coinciding with the succession of cladoceran assemblages from littoral to benthic and planktonic species. Indeed, the progressive decrease of the Rb/Ti ratio indicates progressively increasing of grain size in the sediments, whereas the slight increase in lake level probably caused anoxic conditions in the mud-water interface, reflecting in the decrease of the Fe/Ti ratio (Figure 6). Increasing PC1 scores reflect the progressive increase of Ti/Ca and Zr/Ca ratios (Figures 3 and 6), suggesting relatively wet conditions.

Relatively wet conditions have been reported for the region (Bhattacharya *et al.*, 2015), which would have allowed the infilling of the lake after the landslide damming. From ~2550 to 1800 cal BP, as benthonic Cladocera taxa diminished, pelagic and littoral taxa increased (Figure 6). Increasing concentrations of *Liederobosmina* sp. and *Bosmina* sp. suggest a slight increase in lake extension at that time.

Overall, this stage shows the initial development and progressive infilling of the lacustrine basin, which could have been associated with the damming of the river by the massive landslide in the context of relatively high moisture availability in the region (Bhattacharya *et al.*, 2015).

Nevertheless, as we do not have elements to associate U1 and U2 to the landslide, it is also possible that the lake was much older than the time spanned by our sedimentary record. The relatively wet conditions could be associated with a low frequency of El Niño events in the equatorial Pacific (Moy *et al.*, 2002). Today, El Niño events are a major contributor to precipitation variability in Mexico (Magaña *et al.*, 2003), bringing pronounced droughts to the Metztitlán region (CONANP, 2003). According to the record of Lake Pallcacocha (Moy *et al.*, 2002), El Niño frequency was apparently low through most of zone 1 of our record, probably producing a low frequency of droughts that facilitated the progressive infilling of the lake. Superimposed on the trend towards wetter conditions, peaks of Ti/Ca and Zr/Ca suggest a high variability in the input of detrital material, that could have been associated with either short lived intermissions of even wetter conditions or torrential events.

High variability of Cladocera assemblages further support our interpretation of high variability of lake level and extension. These erosive peaks were probably associated with the high frequency variability mode of the Intertropical Convergence Zone revealed by the Cariaco basin Ti record (Haug *et al.*, 2001).

5.4.2. ZONE II (256-209 CM BLF, ~1800-1350 CAL BP)

The bottom of this zone (~1800-1620 cal BP) showed an abrupt decrease of Cladocera remains, accompanied by low detrital input, reflected in low scores of PC1 (Figure 6). The peak of terrigenic input identified between ~1750 and 1620 cal BP probably corresponds to torrential events with high erosive capacity given the generally dry regional climate. Such torrentiality could be associated with reinvigoration of the El Niño frequencies recorded in lake Pallcacocha (Moy *et al.*, 2002). Although our PC1 peak predated the increase of El Niño frequency, the mismatch could be associated with the uncertainty of our age-depth model.

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From ~1700 to 1400 cal BP, samples were barren of cladocerans and Ti/Ca, Zr/Ca, and PC1 decreased (Figure 6), indicating low detrital input to the lake, and probably an almost complete desiccation of the water body. This period coincides with an abrupt onset of dry conditions that have been reported for the basin of Serdán Oriental at ~1600 cal BP (Bhattacharya *et al.*, 2015). This same pattern has been reported for other sites at elevations above 1000 m asl (e.g. Metcalfe *et al.*, 2010; Park *et al.*, 2019), thus, indicating a regional drought.

5.4.3. ZONE III (209-164 CM BLF, ~1350-900 CAL BP)

A recovery of the water body was evidenced by the recolonization of cladocerans and the increase of indicators of detrital input, Ti/Ca, Zr/Ca, and PC1 (Figure 6). Whereas *L.* cf. *louisi louisi* suggests a relatively shallow lake, moderate concentrations of *Liederobosmina* sp. and *Bosmina* sp. suggest a large open water area. Three consecutive and relatively evenly spaced peaks of indicators of detrital input suggest a high-frequency mode of variability of the regional hydrological cycle. A similar mode of variability of successive centennial droughts for this time period has also been reported for the Yucatan Peninsula (Hodell *et al.*, 2001), possibly implying solar activity as a common driver. Peaks of detrital materials (Ti/Ca and Zr/Ca) could also have been associated with torrential rains in a matrix of generally dry conditions. Indeed, absence of littoral taxa in most of the samples could have been caused by the massive input of sediments causing frequent disturbances to the littoral environment, impeding the establishment

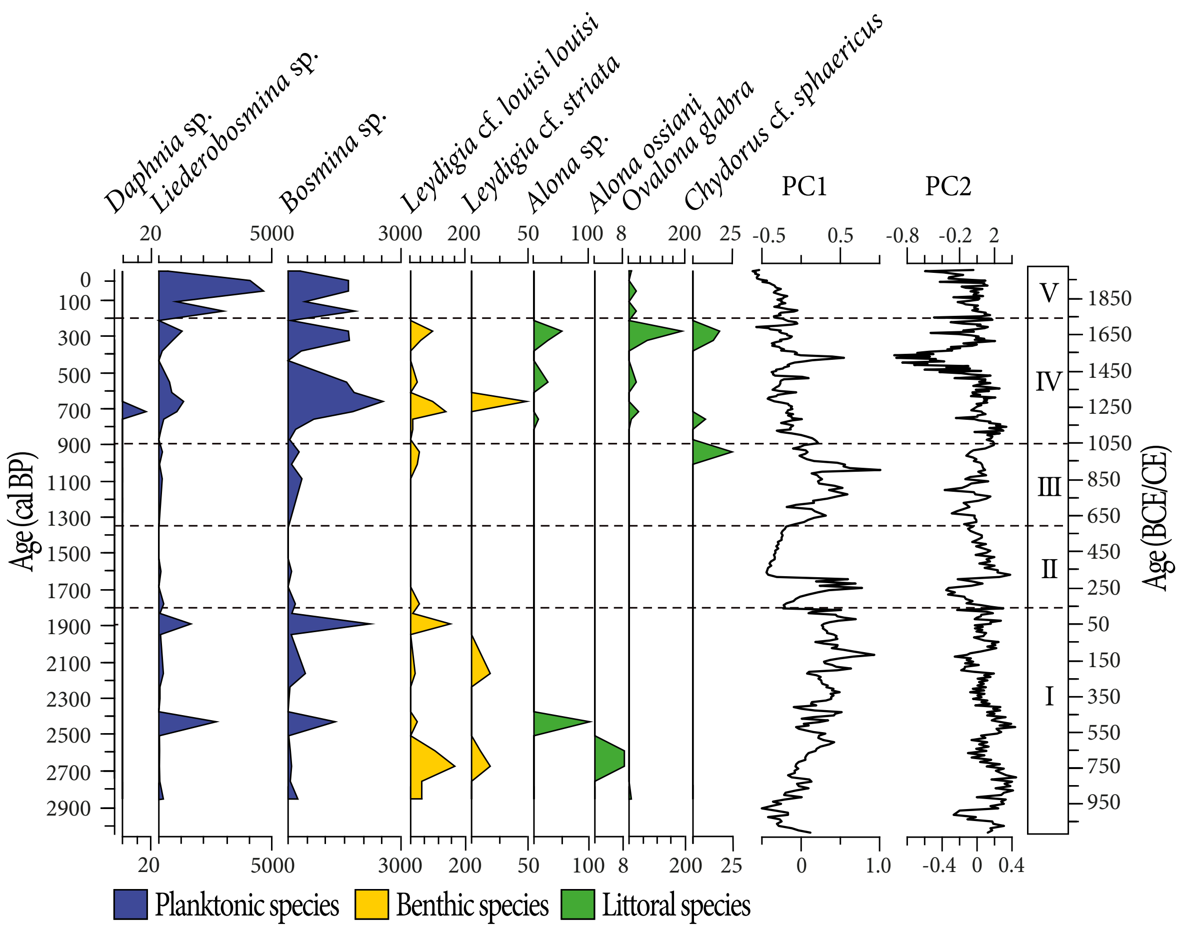

Figure 5 Cladocera concentrations in the sedimentary record of Lake Metztitlán. Sample scores of the principal component analysis along axes 1 and 2 are shown.

of littoral vegetation and, thus, preventing the establishment of a community associated with these areas.

The time period comprised by this zone roughly coincides with the Medieval Warm Period, a time when global temperatures were around one degree higher than those that characterized the 20th century (Mann *et al.*, 2009). In Central Mexico, this time period was characterized by an intensification of the regional droughts (Metcalfe *et al.*, 2010; Rodríguez-Ramírez *et al.*, 2015; Bhattacharya *et al.*, 2015; Park *et al.*, 2019), however, the Metztitlán record shows conditions that seem more erosive. Such high erosion was probably associated with an intensification of the regional summer rains and therefore an accentuation of precipitation seasonality. Today, the main source of moisture for the Metztitlán region are the easterlies that bring humid air from the Gulf of Mexico (Douglas *et al.*, 1993). During the MWP, sea surface temperature in the Gulf of Mexico was around 2 °C higher than modern (Richey *et al.*, 2007), producing higher regional convective activity, and thus explaining the high erosive activity reflected in the sedimentary record of Lake Metztitlán.

5.4.4. ZONE IV (164-47 CM BLF, ~900-200 CAL BP)

The increase of all Cladocera species suggests higher water levels in the lake with a higher diversity of habitats. Substantial increases of *Liederobosmina* sp. and *Bosmina* sp. (Figure 5) suggest a relative deepening of the lake environment, as well as a widening of the lake surface. Regional records suggest an increase of regional moisture availability that coincides with the onset of this stage of the lake (Bhattacharya *et al.*, 2015). The development of mature littoral areas is evidenced by permanent presence of both benthic and littoral Cladocera species. Indeed, historic accounts report that the lake occupied much of the southern areas that are today occupied by towns and extensive crops (Acuña, 2017). Relative flat and diminishing ratios of Ti/Ca, Zr/Ca and PC1 scores suggest that moisture availability was low but constant (Figures 3 and 6). Increasing Rb/Ti ratios suggest a progressive increase of finer material in the detrital input. Authigenic precipitation of carbonates is suggested by low values of the Ti/Ca and Zr/Ca ratios together with increasing ratios of Fe/Mn (Cohen, 2003). Overall, under generally dry conditions suggested by carbonate precipitation, moisture availability was enough for maintaining a large lake size that allowed the development of littoral areas. Most regional records show high variability through the time period comprised by this zone (Metcalfe *et al.*, 2010; Cuna *et al.*, 2014; Rodríguez-Ramírez *et al.*, 2015; Bhattacharya *et al.*, 2015; Park *et al.*, 2019; Wogau *et al.*, 2019). Regional environmental variability during this time interval was closely associated with anthropogenic activity, as well as with changes in moisture availability caused by the Little Ice Age (LIA) (Mann *et al.*, 2009). In Metztitlán, the littoral community was established by the beginning of the LIA (~600 cal BP, Figure 6), suggesting that this anomaly in the region was associated with the enlargement of the water body.

Under regional colder conditions, evapotranspiration probably decreased, ameliorating the effects of the relatively drier climate. The most important event that took place through this stage was marked by a peak of indicators of terrigenic detrital input between ~450 and 400 cal BP (1500-1550 CE, Figure 6).

This peak is preceded by the Spörer solar minimum (Bard *et al.*, 2000), which in the region was associated with dry conditions (Bhattacharya *et al.*, 2011; Rodríguez-Ramírez *et al.*, 2015) that were probably associated with a low vegetation vigor in the catchment basin of Lake Metztitlán. Thus, once dry conditions were overcome, there was a temporal invigoration of the hydrological cycle that strengthened the erosive capacity of rain, acting on a more erodible landscape.

5.4.5. ZONE V (47 CM BLF TO THE TOP, THE LAST ~200 YEARS).

The disappearance of almost all benthic and littoral taxa and rebounding of planktonic species (Figure 6) indicate a relatively deep and open

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lacustrine environment, with a weakly developed littoral zone. After the LIA, global temperatures rebounded and as a consequence, evapotranspiration rates probably increased, implying the retraction of the water body from the alluvial plain previously covered by water. General low moisture availability is reflected in low Ti/Ca and Zr/Ca ratios, with high Rb/Ti ratios suggesting a preferential deposition of fine materials in the coring site. As the valley was infilled by sediments, the influence of the mouth of the river on the coring site was probably progressively lower.

However, during the 19th and 20th centuries, the regional hydrology was highly modified by hydraulic infrastructure (Waitz, 1947). Although infiltration through the obstruction created by the landslide continued to be the main control of water level (Suter, 2004), man-made infrastructure probably played a major control on the deposition process that took place through this time period.

Indeed, besides natural process, the disappearance of littoral communities was probably also promoted by the occupation of the alluvial plain by productive activities.

6. Conclusion

Our multiproxy reconstruction based on the sedimentary record of Lake Metztitlán shows a history of high environmental variability through the last 3,000 years. The chronological model suggests that Lake Metztitlán has been in place for at least three millennia, shedding new light on the age of the ecosystem, formerly located at between ~1100 and 500 cal BP (Suter, 2004). Within this time

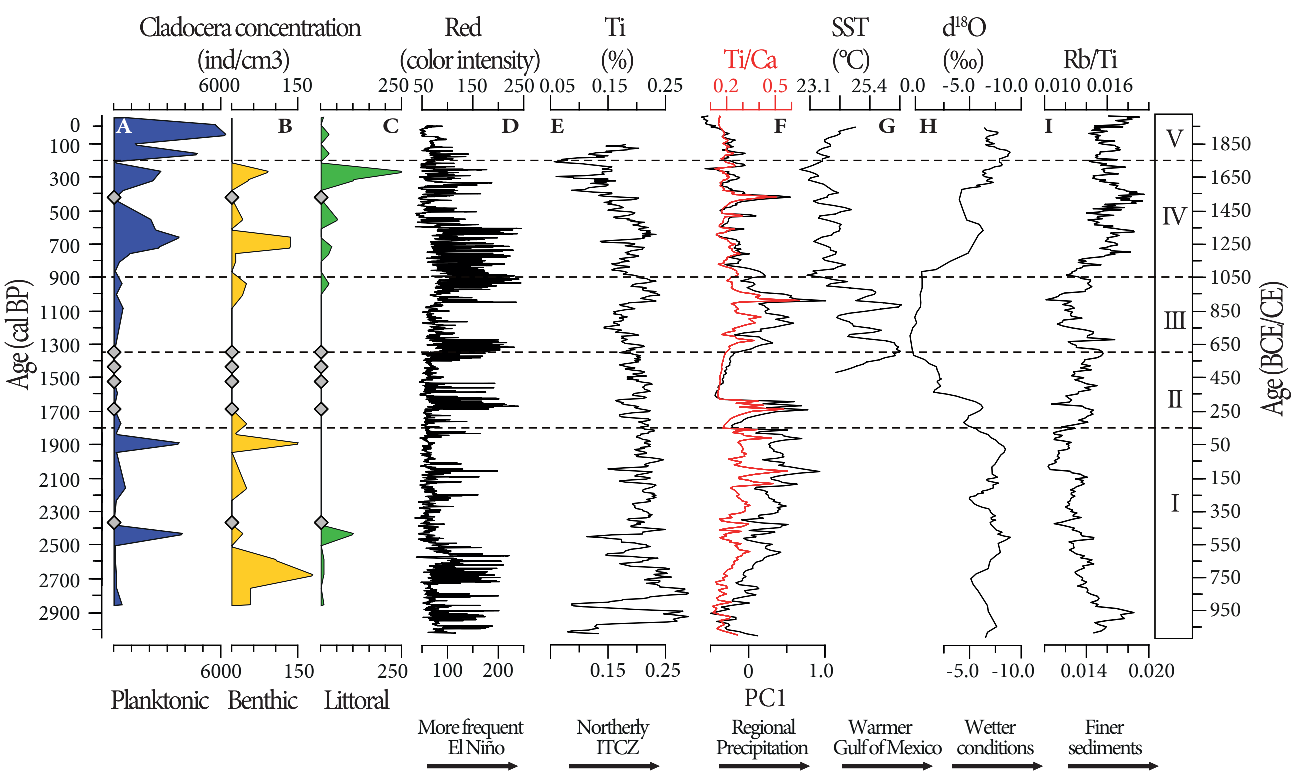

Figure 6 The paleoenvironmental record of Lake Metztitlán in the regional and continental context. A, B, and C, concentrations of planktonic, benthic and littoral Cladocera taxa, respectively, in the sediments of Lake Metztitlán; samples barren of cladocerans are represented by gray diamonds. D. Red intensity of the sediments of Lake Pallcacocha, Ecuadorian Andes, as a proxy of El Niño frequency (Moy *et al.*, 2002). E. Ti concentration in the sediments of Cariaco Basin (Haug *et al.*, 2001). F. Ti/Ca ratios (red) and PC1 sample scores (black) of the sedimentary record of Lake Metztitlán. G. Sea surface temperatures of the Gulf of Mexico reconstructed from the sediments of Pigmy Basin (Richey *et al.*, 2007). H. d18O in the sedimentary record of Lake Aljojuca, Serdán Oriental Basin (Bhattacharya and Byrne, 2016). I. Rb/Ti ratios in the sediments of Lake Metztitlán.

frame, our results demonstrate that, although the regional climate has always been arid, it has been subjected to multiple forcings that have resulted in a highly dynamic system. Whereas the millennial scale trend in the regional climate does not seem to follow a specific pattern, the effects of decadal-to centennial drivers are evident.

Our results suggest that the local environmental evolution reflected by the cladoceran assemblages was highly conditioned by changes in the regional hydrological cycle. Changes in the regional precipitation regime conditioned the productivity and morphology of the water body, producing cycles of high erosion associated with lake infilling and development of littoral areas.

During the MWP, the lake was shallow, whereas the regional climate was characterized by successive peaks of drought and wet conditions. Contrastingly, the LIA was characterized by a relatively wet climate and an expansion of the lake surface, with a very wet period during the intermission between the solar minima of Maunder and Spörer. Overall, our record demonstrates the close association between local and regional environmental conditions. Through the last three millennia, the region of the Barranca de Metztitlán Biosphere Reserve has been submitted to a high environmental variability.

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