

Holocene paleoenvironmental reconstruction of Laguna Babícora, Chihuahua, Northern Mexico, based on Ostracode Ecology and Shell Chemistry

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Abstract

Fossil ostracodes from the Las Vacas trench measured in Laguna Babícora, Chihuahua, Mexico were analyzed taphonomically, and the shells of *Limnocythere bradburyi* were tested for trace-elements. Chronological control of the sediments was established using two calibrated ¹⁴C ages placing plant material at 9250 and 990 years B.P. Ostracode association is represented by *Candona caudata*, *Eucandona patzcuaro*, *Cypridopsis vidua*, *Limnocythere platyforma* and *Limnocythere bradburyi*. Population structure and taphonomy indicate a biocenosis living in a low energy lake, fluctuating from fresh to hyposaline water. Ostracode abundances in the studied interval ranged from 698 to 2 valves/g of sediment. Water salinity was established between 100 – 5000 ppm. Shell Mg/Ca molar ratios were used to interpret changes in lake temperature, with calculated temperatures ranging from 11.9 °C to 7.3 °C, revealing a low-temperature trend during the early to late Holocene. Our data contributes to the completion of the paleoenvironmental scenario for the Early to Mid-Holocene based on evidence that is consistent with other paleoclimatic reconstructions from the Babícora area.

Keywords: ostracode, trace-element shell chemistry, Holocene climate.

Resumen

Se analizaron tafonómicamente los ostrácodos fósiles obtenidos del perfil Las Vacas de la Laguna de Babícora, Chihuahua, México y las valvas de *Limnocythere bradburyi* se analizaron para elementos traza. El control cronológico de los sedimentos se estableció con base en dos edades calibradas obtenidas por ¹⁴C en materia vegetal, con edades de 9250 y 990 años A.P. La asociación de ostrácodos está representada por *Candona caudata*, *Eucandona patzcuaro*, *Cypridopsis vidua*, *Limnocythere platyforma* y *Limnocythere bradburyi*. La estructura de la población y los atributos tafonómicos indican la presencia de una biocenosis bajo condiciones de baja energía, con fluctuaciones de salinidad entre dulceacuícola a aguas hiposalinas. La abundancia total de ostrácodos osciló entre los 698 a 2 valvas/gr. de sedimento. La salinidad del agua varió entre 100 – 5000 ppm. La relación molar Mg/Ca medida en las valvas fue empleada para interpretar los cambios en la temperatura del lago, con temperaturas calculadas entre los 11.9 °C a 7.3 °C, con lo que se interpreta que las condiciones durante el Holoceno temprano a tardío fueron frías. Los datos obtenidos contribuyen a afinar el escenario paleoambiental del Holoceno con base en un registro que es consistente con reconstrucciones previas del área de la Laguna Babícora.

Palabras clave: ostrácodos, tafonomía, elementos traza, Holoceno.

1. Introduction

The last 11700 years (Holocene) have been recorded worldwide as a period of relatively low climate variability. This global variability is mainly attributed to orbital forcing (Kutzbach and Otto-Bliesner, 1982; COHMAP, 1988, Mayewski *et al.*, 2004). For the Northern Hemisphere, factors like El Niño Southern Oscillation (ENSO) and North Atlantic Oscillation (NOA) are what control the climate (Wanner *et al.*, 2008). The Northern Hemisphere contains much evidence of this variability with high-resolution records (see compilation by Wanner *et al.*, 2008), including ice cores from Greenland (Yiou *et al.*, 1997), pollen and plant macrofossils from China (Yu *et al.*, 1998), and cave speleothems from Israel (Bar-Matthews *et al.*, 2003).

Quaternary paleoclimate reconstructions for northern Mexico and southwestern USA are extensive due to the sensitivity of the area to the different regional climate controls: the North American monsoon, jet stream, trade winds and westerlies (Metcalf *et al.*, 2000; Metcalf, 2006; Roy *et al.*, 2013). In addition, the wide availability of lacustrine (Castiglia and Fawcett, 2006; Metcalf *et al.*, 1997 and 2002; Palacios-Fest *et al.*, 2002; Chávez-Lara *et al.*, 2012) and non-aquatic terrestrial records (Waters and Haynes, 2001; Menking and Anderson, 2003; Van Devender, 1990a and b) have allowed the reconstruction of past local and regional climate trends.

Laguna Babicora is a body of water located in the Chihuahuan Desert (Figure 1), where several paleoclimate studies have been carried out. Ortega-Ramírez (1995), Ortega-Ramírez *et al.* (1998, 2000), Metcalf *et al.* (2002), Palacios-Fest *et al.* (2002) and Chávez-Lara *et al.* (2012) have reconstructed the Pleistocene and Holocene environments based on sedimentological, geochemical, stratigraphic and biological proxies. Recently, Roy *et al.* (2012), using elemental concentrations and magnetic susceptibility, inferred several millennial scale paleohydrological changes during the last 27 cal ka, culminating with the basin drying at the cal. 3 ky B.P. For the last 80000 years, Roy *et al.* (2013) used a multi-proxy approach to interpret how the summer monsoon precipitation and winter storms have controlled the climate of the region. These authors considered the last 40 ky B.P. as a period with an unstable rainfall regime.

The climatic history for the Holocene of this basin continues to be unclear since distinct proxies show variable patterns and climate control. Metcalf *et al.* (2002) report a humid Pleistocene under the influence of winter storms and a Holocene marked by the absence of diatom record which they interpret as the establishment of dry conditions. Palacios-Fest *et al.* (2002), using the ostracode record of the basin, infer the presence of a permanent lake during the Pleistocene, and an intermittent lake from the early Holocene to the present. Roy *et al.* (2012, 2013) attribute the main origin of the precipitation in this region to the summer monsoon and in less magnitude to the winter storms, finding several dry episodes for the Holocene.

Ostracodes are microcrustacean, reputed to be extraordinary indicators for biodiversity and paleoenvironmental proxies. Due to a benthic character, as well as high and restricted environmental affinities, they are a reliable index of the any physical or chemical variation occurring in a freshwater body. Therefore, it is important to evaluate the population structure, since their preservation and carapace, or valve abundance, throughout a sedimentary column are indicative of valve-remains transport (term adopted by Zhai *et al.*, 2015, instead of post-mortem transport (Whatley, 1983a, b). Evaluation of the richness and diversity of the recorded assemblages certainly provides relevant information on water temperature, total dissolved solutes, pH, turbidity and vegetation (Rodríguez-Lázaro and Ruiz-Muñiz, 2012). Several researchers have proposed a relation between the chemical composition of ostracode shells and the water hosting at molting time, proving that the Mg/Ca ratio of valves correlates well with water temperature (Chivas *et al.*, 1986; Ito and Forester, 2009). Palacios-Fest (1996) produced standard coefficients to convert ostracode Mg/Ca ratios into paleotemperatures. These coefficients were calibrated using natural populations of *Limnocythere staplini* and *L. ceriotuberosa* from Utah and in subfossil specimens from the Hohokam Indian irrigation channels in the USA. Later, Palacios-Fest and Dettman (2001) used data from *Cypridopsis vidua*, El Yeso Lake, Magdalena Basin, Sonora; and those provided by cultured *Limnocythere staplini*, Antero Pond, South Park, Colorado USA to generate standard coefficients and, therefore, paleotemperatures were calculated for the *C. vidua* and redefined the equation for *L. staplini*. Based on these results, it is assumed that the Mg/Ca ratio of the ostracode shell can broadly indicate water temperature under which the shells were formed.

Palacios-Fest and Dettman's (2001) regression model as well as the paleosalinity index (PI) (Palacios-Fest *et al.*, 1993, 2001) were applied in three profiles from Laguna Babicora, using the shell chemistry of *L. ceriotuberosa* and *L. platyforma* (Palacios-Fest *et al.*, 2002). Mg/Ca ratios from individual valves of *Limnocythere staplini* and *Cyprideis castus*, recovered from the LS04-1 well, Laguna Salada, Baja California, were analyzed for the last 44000 years and relative high-resolution paleotemperatures were obtained only for *L. staplini* (Romero-Mayén, 2008).

In spite of the extensive and well preserved proxy records for the Babicora Basin, the Holocene climate and environmental history for the basin is still incomplete, mainly because of the scarce fossil record for this period. In this sense, the goal of this paper is to contribute to the knowledge of the Holocene environmental and climatic changes in northern Chihuahua, Mexico and lake-water conditions using a combination of ostracode paleoecological and trace-element interpretation, based on the premise that the Mg/Ca ratio in ostracode shells is dependent upon water temperature. In order to contribute to the knowledge of the paleoclimatic evolution of this area during the Holocene,

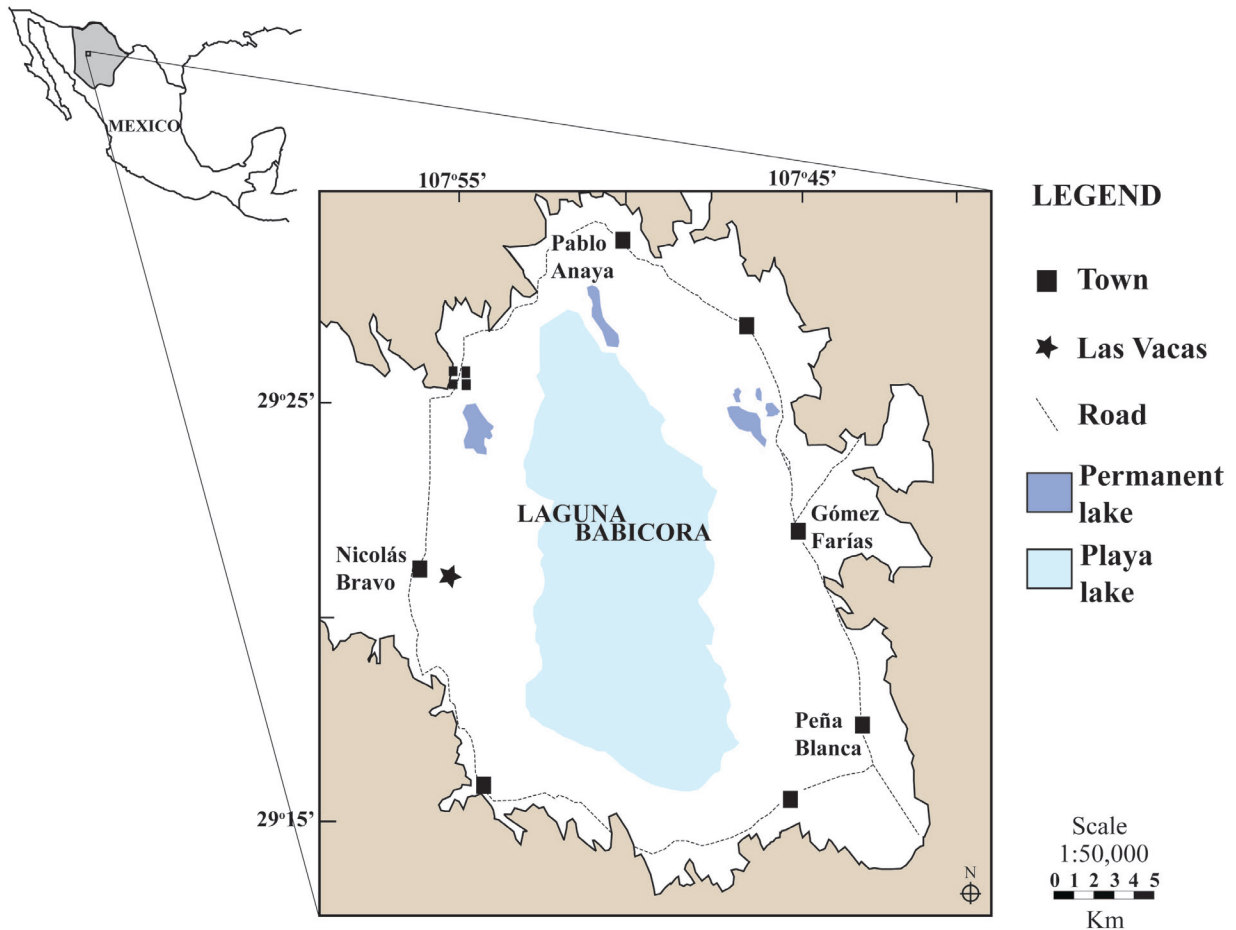


Figure 1. Las Vacas profile location within Laguna Babicora, Chihuahua, Mexico (modified from Palacios-Fest *et al.*, 2002).

we supplement our investigation with the incorporation, as extensive as possible, of the results of earlier studies on sedimentology and radiocarbon chronology (Ortega-Ramírez *et al.*, 1998), and by comparing ostracode Mg/Ca ratio data from Palacios-Fest *et al.* (2002).

2. Study area

Laguna Babicora is an endorheic basin (Ortega-Ramírez *et al.*, 2011) located in the northwest of the State of Chihuahua, Mexico (29° 15' 29° 30' N, 107° 40' 108° 00' W) (Figure 1). The lake has an area of 1896 km² and lies at 2100 m.a.s.l with a NE-SE orientation. It is surrounded by hills and peaks that reach altitudes ranging from 2500 to 3195 m.a.s.l. It is bounded to the north by the Sierra de Chalchihuites and Cerro El Sombrerillo; to the South by El Cerro de la Cebolla, El Cerro de la Copa and El Cerro del Venado; to the West the Sierra Madre Occidental; and to the East by Sierra Grande. These mountain ranges are mostly composed of Miocene-Pleistocene rhyolitic rocks, intercalated with andesites and ignimbrites, and covered by rhyolitic tuffs and basaltic lava flows of Pliocene-

Pleistocene age. Most of the sediments within the basin are of fluvial or lacustrine origin (Ortega-Ramírez *et al.*, 2000).

Laguna Babicora is located within the semi-cold climate region (García, 1973). Modern mean annual precipitation is 450 mm, with rains clustered in the summer months, and a mean annual temperature of 11.5 °C (Ortega-Ramírez *et al.*, 1998), ranging from 4 °C in January to 20 °C in July (Ortega-Ramírez *et al.*, 2011). The presence of water within the basin depends directly on the rainfall, with major periods clustered in summer and with the consequent water runoff into the basin (Chávez-Lara *et al.*, 2012).

3. Methods

Twelve samples were collected from a 120-cm-deep trench called Las Vacas (Figure 1) at the northwestern edge of the lake. The profile consists of a monotonous succession of silty-clays and clayey-silts (Figure 2).

Due to the low abundance of suitable material for dating, the profile was dated with two ¹⁴C ages obtained in plant debris and calibrated with OxCal v3.5 (Table 1): 9250 years B.P. at a 115 cm depth (sample Las Vacas 1) and 990 cal.

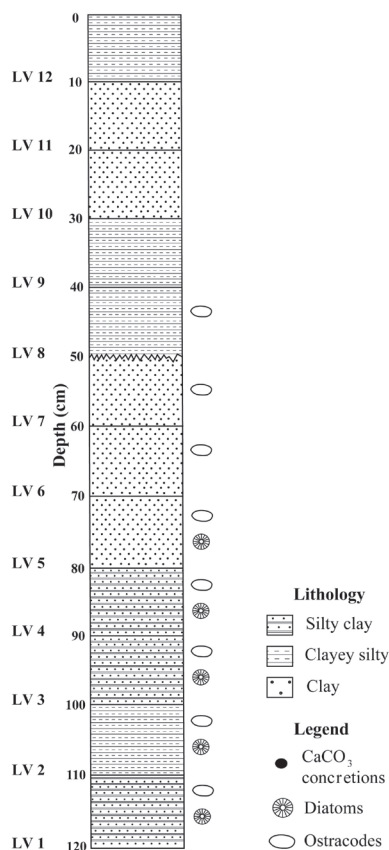


Figure 2. Stratigraphic column of the Las Vacas profile taken at Laguna Babicora, Chihuahua, Mexico.

years B.P. at a 35 cm depth (sample Las Vacas 9) (Ortega-Ramírez, personal commun.) (Figure 2).

Table 1. Chronological control from the profile Las Vacas from Laguna Babicora, Mexico.

Depth (cm)	Laboratory code	Material	Radiocarbon date (BP)	Cal. Date (BP)
115	INAH-VACAS1	Plant debris	9587 ± 112	9250
35	INAH-VACAS7	Plant debris	836 ± 108	990

Ten grams of dry sediment from each sample were washed following standard micropaleontological techniques (Danielopol *et al.*, 2002). Separation of adult ostracode valves from those of instars was done by sieving 1 gram of the treated sample at 106 and 63 mm, respectively. Counting of caparaces and valves also was done in 1 gram of sediment. Species identification was conducted using the taxonomy set by Liebau (2005), and for the recognition at the specific level we followed Delorme (1971a, b and c), Forester (1985) and Carreño (1990). The ostracodes are housed in the Colección Nacional de Paleontología, María del Carmen Perrilliat Museum of the Instituto de Geología, Universidad Nacional Autónoma de México, under the catalog number IGM-822-Mi to IGM-842-Mi

Taphonomy and population structure were established based on both fossil preservation and the absolute and relative abundances of fossil ostracodes. These features were calculated in dry sediment. Preservation of valves was assessed using color, chemical overgrowth, dissolution, and the degree of mechanical breakage (BD). Since valves are generally well preserved, we only considered BD0 for intact valves and 20 – 30 % area broken away, BD2 for the 30 – 50 % area broken away, and BD3 with over 50 % area broken away. BD degree was applied when more than 80 % of the ostracode valves per sample presented one of the three conditions. Abrasion and BD were used as indicators of post-depositional transport, whereas valve/carapace and juvenile/adult ratios were used as indicators of changes in the hydrodynamic condition within the water body.

The Mg/Ca atomic ratios of ostracodes were measured on well-preserved, adult valves of *Limnocythere bradburyi*, using one to five specimens per sample. The samples were first immersed in ultrapure water (18.2 MΩ, Barnstedt Nanopure System), and then dissolved in sub-boiling HNO₃. All procedures were carried out under a clean hood in the Laboratorio de Química Ultrapura at the Instituto de Geología, UNAM. Analyses were performed using an Agilent 7500 ce ICPMS following the methodology of Rosenthal *et al.* (1999), but adapted for analysis using a quadrupole mass filter and a long-dynamic range dual detector (pulse and analogue modes). Briefly stated, the methodology was based on measuring the ²⁶Mg/⁴⁸⁻⁴⁶Ca intensity ratios for each sample, and comparing them with those measured for a gravimetrically-prepared solution with a known Mg/Ca molar ratio. Care was taken to measure all isotope ratios using the same detector section (pulse or analogue) to avoid any possible bias caused by pulse/analogue cross-calibration. The Mg/Ca standard solution was analyzed after 5 – 7 samples, and Mg/Ca ratios were obtained by interpolating the analytical response of the solution throughout the analysis period. This allowed simultaneous correction for mass discrimination induced by differences in ion transport efficiency by the ICPMS, as well as by signal drift produced by sample deposition onto the sampling cones and ion-lenses. The reported Mg/Ca ratio for each level corresponds to the average, when available, of five valves. The uncertainty in the Mg/Ca ratio is less than 1 %, limited by counting statistics.

The geochemistry work was performed in 2005, as part of the calibration process of the ICPMS used (IGL-UNAM) for the ostracodes shell trace-element/Ca ratios method.

Based on the results of Palacios-Fest and Dettman (2001), it is assumed that the Mg/Ca ratio of the shell can broadly indicate the water temperature under which ostracodes molted their shells. This relation between the valve Mg/Ca molar ratio and water temperature is defined in the following equation:

$$T(^{\circ}\text{C}) = ((\text{Mg}/\text{Cav}) + 0.0035) / 0.00089 \text{ Equation [1]}$$

where Mg/Cav is the Mg/Ca ratio of each *Limnocythere bradburyi* valve. This equation was used to estimate the water temperature based on each Mg/Ca molar ratio obtained by ICPMS.

4. Results

Based on the two calibrated ^{14}C ages and extrapolated ages and depth, we infer a sedimentation rate of 0.009 cm/y for the seven lower units (Las Vacas 1-Las Vacas 7). Unfortunately, the ^{14}C age of Las Vacas 9 is above an unconformity involving a change in the sedimentary regime. Therefore, the sedimentation rate calculated from the two ^{14}C ages and subsequent time intervals inferred is not reliable to permit an age model; nevertheless, it does provide a relative frame for this time interval. Hence, the calculated ages are used here with caution.

Not surprisingly, five of the seven ostracode species that were recorded by earlier works (Palacios-Fest *et al.*, 2002; Chávez-Lara *et al.*, 2012) were recovered from strata 1 to 8 at the Las Vacas profile with well documented ecological parameters (Table 2; Figure 3): *Candona caudata* Kaufmann, 1900; *Eucandona patzcuaro* (Tressler, 1954); *Cypridopsis vidua* (O.F. Müller, 1776); *Limnocythere bradburyi* Forester, 1985 and *Limnocythere platyforma* Delorme, 1971c.

Horizons with fossil ostracode records were deposited during the Early to Late Holocene. Samples LV1 and LV2 belong to Early Holocene. From LV3 to LV6, sediments were deposited during the Mid-Holocene, and LV7 and LV8 are dated as Late Holocene. Absolute abundance of ostracodes varied along the profile attaining its maximum at Las Vacas 1 (LV1) with 698 valves/gram and decreasing upwards with 198 valves/gram at Las Vacas 3 (LV3). At Las Vacas 4 (LV4), the assemblage records a peak reaching 423 valves/gram. From this level towards the top, the total valves/gram decreases and the fossil record disappears at Las Vacas 8 (LV8). No specimens were found in any of the strata above Las Vacas 8 (LV8) (Table 3; Figure 4).

Table 2. Ecological and salinity tolerances of the five species described for the profile Las Vacas, Laguna Babicora. 1. Bachhuber and Catto, 2000; 2. Palacios-Fest, 1994; 3. Palacios-Fest and Dettman, 2001; 4. Chávez-Lara *et al.*, 2012; 5. Forester, 1985; 6. Bradbury *et al.*, 1990; 7. Cohuo *et al.*, 2016; 8. Delorme and Donald, 1969; 9. García *et al.*, 2014.

Species	Salinity tolerance (ppm)	Water preferences
<i>Candona caudata</i>	20-2054 ¹	Oxygenated water ⁶
<i>Eucandona patzcuaro</i>	20-5000 ²	Shallow, turbid water ⁷ ; Seasonal drying ⁸
<i>Cypridopsis vidua</i>	10-10000 ³	Ephemeral and permanent water ³
<i>Limnocythere platyforma</i>	100-1000 ⁴	Shallow, dilute water ⁹
<i>Limnocythere bradburyi</i>	1000-100000 ⁴	Shallow, turbid water ⁵

Good valve preservation was observed throughout the column (Table 3): BD was relatively low and abrasion was not observed. From LV1 to LV5 we observed a BD0, indicating an 80 % or more of valves with low or no area damage by post-depositional breakage. In the upper samples with ostracode presence (LV6-LV8), we observed a BD1.

Eucandona patzcuaro was the dominant species throughout the profile with the exception of LV8 in which *L. bradburyi* becomes the abundant species. *C. caudata* was only present in LV1, and *C. vidua*, *L. bradburyi* and *L. platyforma* show highly variable abundance throughout the profile, but in general, these species increase in abundance when *E. patzcuaro* diminishes. *L. bradburyi* is abundant

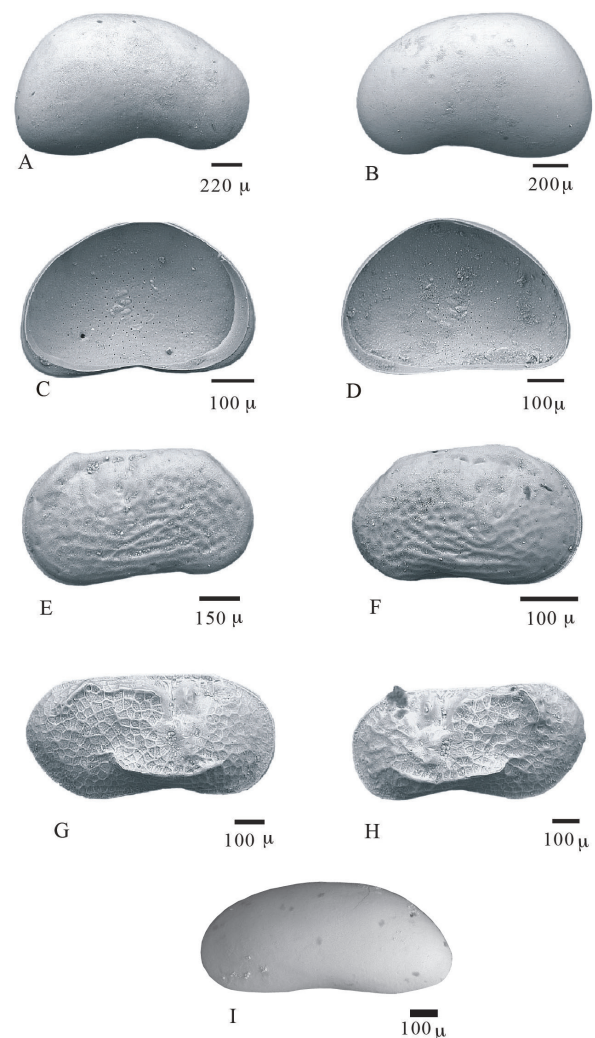


Figure 3. SEM photographs of the ostracode species from Las Vacas profile. A: RV of *Eucandona patzcuaro*, IGM-822-Mi; B: LV of *Eucandona patzcuaro*, IGM-823-Mi; C: RV of *Cypridopsis vidua*, IGM-828-Mi; D: LV of *Cypridopsis vidua*, IGM-829-Mi; E: RV of *Limnocythere bradburyi*, IGM-833-Mi; F: LV of *Limnocythere bradburyi*, IGM-834-Mi; G: LV of *Limnocythere platyforma*, IGM-838-Mi; H: RV *Limnocythere platyforma*, IGM-839-Mi; I: LV of *Candona caudate*, IGM-843-Mi (RV: right valve; LV: left valve).

Table 3. Ostracode taphonomic data throughout the Las Vacas profile. BD0 indicates an assemblage with more than 80 % of valves with good conservation (intact or 20 – 30 % of broken area); BD1 indicates an assemblage with more than 80 % of valves with 30 – 50 % of valves area broken away.

Sample	Cal. Years (B.P.)	Valves/gr (Dry sediment)	Adults vs. Instars	Carapaces vs. valves	BD	Accompanied fauna and flora
Las Vacas 12		0	-	-	-	Plant debris
Las Vacas 11		0	-	-	-	Roots
Las Vacas 10		0	-	-	-	-
Las Vacas 9	990	0	-	-	-	Bone fragments
Las Vacas 8		3	1	7	BD1	-
Las Vacas 7		2	15	8	BD1	-
Las Vacas 6		170	18	27	BD1	Diatoms, bone fragments
Las Vacas 5		303	33	19	BD0	Diatoms
Las Vacas 4		423	23	105	BD0	Diatoms
Las Vacas 3		182	33	12	BD0	Diatoms, bone fragments
Las Vacas 2		403	40	41	BD0	Diatoms
Las Vacas 1	9250	698	16	56	BD0	Diatoms

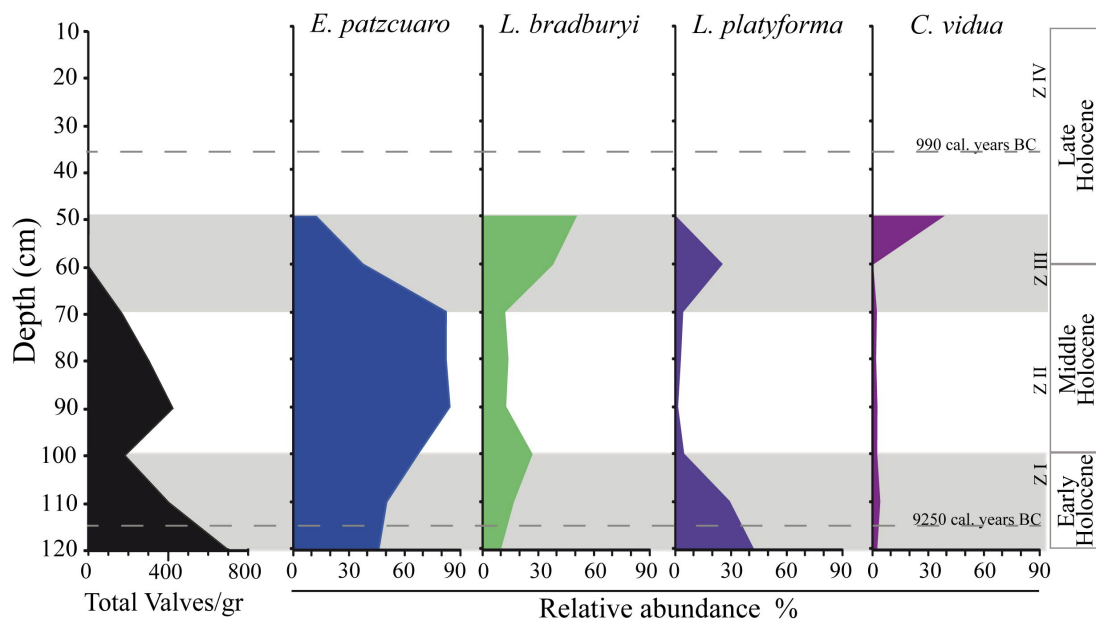


Figure 4. Total ostracode valves/gram and relative abundance for four species throughout Las Vacas profile. *Candona caudata* is not shown since its relative abundance is below 1 %. ZI-ZIV correspond to the established zones according to the assemblage composition.

in the upper part of the profile whereas *L. platyforma* is dominant in the lower part. *C. vidua* shows a low relative abundance throughout the profile, except in the LV8, where it becomes significant. Based on the assemblage composition, we established four zones (Figure 4): Zone I (LV1 and LV2), defined by the dominance of the genus *Limnocythere*, mainly by *L. platyforma*, a freshwater species; Zone II (LV3-LV5), where *E. patzcuaro* dominates the assemblage reaching nearly 90 % of the ostracode total abundance and *L. bradburyi* represents the second component of the

association with a diminished number of *L. platyforma*; Zone III (LV6-LV7), marked by the recovery of *L. platyforma*, an increase of *L. bradburyi* and the reduction in the assemblage of *E. patzcuaro*; and Zone IV (LV9-LV12), where the ostracode record disappears. Meanwhile, *Cypridopsis vidua* is a species that continues to have a low record along Zones I and II, but Zone III is marked by an increment in its abundance and *C. caudata* is a species recorded only in LV1 and LV2 (Zone I) with a negligible abundance (4 and 7 valves respectively).

Table 4. Values of Mg/Ca ratio analysis of *Limnocythere bradburyi* valves and Mg/Ca (mol) mean values per sample. Mean T (°C) was calculated applying Equation 1. Ages with * were calculated based on the yielded ¹⁴C dates.

Sample number	Depth (cm)	No. valves	Valves Mg/Ca (mol)	Mean Mg/Ca (mol)	Mean T °C	Cal. years B.C.
LV6	65	1	0.003	0.003	7.3	4929*
LV5	75	2	0.004	0.006	10.9	5370*
			0.007			
LV4	85	2	0.006	0.007	11.9	6340*
			0.007			
LV3	95	2	0.005	0.005	10.1	7310*
			0.005			
LV2	105	5	0.005	0.006	10.7	8280*
			0.007			
			0.004			
			0.005			
			0.006			
LV1	115	6	0.007	0.006	11.5	9250
			0.005			
			0.007			
			0.007			
			0.006			
			0.005			

According to the ecological preferences of the four dominant ostracodes (Table 2) and data from several authors (Delorme, 1971a, b, c; Forester, 1985; Palacios-Fest and Dettman, 2001), two species are considered euryhaline (*Limnocythere bradburyi* and *Cypridopsis vidua*) while *Candona caudata*, *Limnocythere platyforma* and *Eucandona patzcuaro* are interpreted as stenohaline species. These ecological features and the relative abundance of the five species along the profile allow us to establish a water body ranging from fresh to hyposaline, with a salinity fluctuating between 100 to 5000 ppm, defined by the tolerances of *Eucandona patzcuaro* and *Limnocythere bradburyi*.

A monospecific population of diatoms represented by *Stephanodiscus niagarae* Ehrenberg co-occurs in the lower portion of the profile, gradually decreasing up-section with a last record at Las Vacas 6.

For shell chemistry, samples from LV1 to LV6 yielded ostracode valves suitable for Mg/Ca molar ratio analysis. A total of 18 valves of *Limnocythere bradburyi* were analyzed for Mg/Ca molar ratios, ranging from 1 to 6 analyzed valves/sample (Table 4). Mg/Ca molar ratios ranged from 0.003 to 0.005 mol. and calculated temperatures based on Mg/Ca ratios presented values from 11.9 °C at LV 4 to 7.3 °C at LV6.

The calculated temperature for the Las Vacas profile shows moderate to low temperatures oscillating from around 11.5 to 10.9 °C from the Early Holocene (LV1) to the middle Holocene (LV5), and with an abrupt decrease toward the beginning of the Late Holocene (LV6), where

the temperature diminishes around 3.6 degrees with a record of 7.3 °C (Table 4).

4. Discussion

Valves and carapaces of instars and adults recorded are 100 % white or translucent, suggesting that the ostracode lived or were deposited under normally oxygenated waters (Oertli, 1971). Throughout the profile, the structure of the population shows a dominance of valves over the carapaces as well as instars over adults. If we follow the interpretation by Whatley (1983a y b, 1988) for marine ostracodes, the assemblage recorded here might be considered as representing an autochthonous association.

The degree of mechanical breakage throughout the profile was BD0 to BD1; therefore, the magnitude and pattern of valve-remains transport can be considered negligible or nonexistent and thus is interpreted as a biocenosis living in a low energy environment.

Following Whatley *et al.* (1982) and Whatley (1983a, b, 1988), the low number of altered shells as well as the high frequency of instars over adults throughout the strata suggest the presence of a biocenosis living in a low energy environment with moderate to slow sedimentation rate and no or rare currents which favor valves to remain pristine.

The ostracode assemblage variation, reflected in the four established zones throughout the Las Vacas profile, allows inferring several paleoenvironmental trends for the

Early and Mid Holocene. According to the ostracode record, environmental conditions were highly variable, specifically those related to water input. Environmental conditions were optimal during the deposition of zones ZI to ZIII (LV1 to LV8) for the ostracode growing and hatching. These optimal conditions are related to the permanence of a water column. The shrinking of the water body drove the decline in ostracode abundance towards the top of the profile (Zone IV) with consequent salinity alterations. These variations drove the changes in assemblage composition (from Zone 1 to III) between fresh and hyposaline ostracodes, and finally the decline of the ostracodes.

From the Late Pleistocene, this lake is mainly influenced by the North American Monsoon, which brings rains that fill the basin during the summer and winter storms that bring less precipitation in the cold season (Roy *et al.*, 2013). This implies that the water level of the basin is rain-dependent, which means that the fossil record can be used as an indicator of the precipitation features.

Lake size was likely reduced as a result of the changes in the evapotranspiration/precipitation regime, and/or the decline in snowmelt runoff from the surrounding mountains. For the Babicora Basin, Chávez-Lara *et al.* (2012) report a lacking ostracode record for the last 12000 years B.P. Palacios-Fest *et al.* (2002) report a continuous record of ostracodes for the Don Beto profile in the depocenter of the Babicora Basin, with a time interval from 24 Ky B.P. to 1.3 Ky B.P. Since the Las Vacas profile is located at the edge of the paleolake, we infer that as the lake was shrinking, small isolated puddles remained, allowing the permanence of ostracodes, which may have been the case for this profile.

The presence of *Stephanodiscus niagarae*, a planktonic diatom, reflects an open and deep water body (Theriot and Stoermer, 1981); however, the Las Vacas ostracode association indicates shallow water conditions. As Palacios-Fest *et al.* (2002) state, the record of this diatom species may be related to the increase of water level by precipitation instead of having been a permanent deep basin. Besides, *S. niagarae* is a diatom that inhabits fresh and clear water. These two features would be controlling the presence of this algae in the paleolake.

The changes in ostracode assemblage along the profile evidences a lake with variable conditions, which is reflected in the turn over from fresh to saline water ostracodes. The most ubiquitous species in the record, *E. patzcuaro*, is a species that grows and hatches under a wide range of temperatures; therefore, its populations would have been less affected by the variation of water temperature. Instead, salinity and water turbidity are the main features controlling the presence of *E. patzcuaro*.

The two *Limnocythere* species recorded inhabited contrasting environmental conditions: *L. bradburyi* lived in warm turbid waters, whereas *L. platyforma* preferred cold and clear waters. Palacios-Fest *et al.* (2002) also recorded the coexistence of *L. bradburyi* and *L. platyforma* for the same basin. Their occurrences are interpreted here

as indicative of an active lake during summer and winter seasons.

While the age control of Las Vacas profile is poor, it can be used in comparison with other records from the same basin. Using the ^{14}C ages, the Las Vacas profile is compared to the Zone II (Late Pleistocene-Holocene) of the reported profiles (Cano Magallanes, El Diablo and Don Beto) by Palacios-Fest *et al.* (2002). The faunal record at El Diablo ends near 4000 years B.P.; for Don Beto around 1300 years B.P.; and Cano Magallanes near 3500 years B.P. The profile from Las Vacas records the last assemblage near 2900 years B.P. As the water body shrank, the profiles located at the edge of the basin (Las Vacas, Cano M. and El Diablo) were exposed, primarily affecting the ostracode populations. Since the Don Beto profile was deposited at the depocenter, its record is extended. Chávez-Lara *et al.* (2012) reported a sequence from the eastern Babicora Basin with a time span of the *ca.* 72 ky. The authors described the presence of an ostracode association that ends at the 12 ky years B.P., record that otherwise is interpreted as the result of the desiccation of the lake at this zone.

The composition of the ostracode faunas within the lake shows differences between localities. As was early stated, the fauna that has been reported in the basin is composed of seven species, including two species not recorded in the present work: *Limnocythere sappaensis* and *L. ceriotuberosa*. According to the results of Palacios-Fest *et al.* (2002), Chávez-Lara *et al.* (2012) and the present study, the seven species show differential geographical distribution, which could be related to the establishment of microenvironments within the basin. This is reflected in the distinct faunas recorded in the several profiles from the east, central and western zones of the Babicora Basin.

Comparison between the values and trend of the Mg/Ca ratios measured, and the temperatures calculated herein with those of Zone II (Late Pleistocene- Holocene) in Palacios-Fest *et al.* (2002) show a similar behavior, therefore suggesting that all these traces are reflecting congruent and real climatic conditions for this interval of time.

Around 11000 to 10000 yrs B.P. the record shows relatively constant temperatures at El Cano ($\sim 6.5^\circ$) and El Diablo ($\sim 7.0^\circ$), in which this last profile remained low ($6.6 - 7.6^\circ\text{C}$) until 4346 ± 105 yrs B.P., which is in agreement with Las Vacas' inferred temperature (7.3 to 11.9°C). However, in Don Beto, Mg/Ca ratios increase from ≈ 9000 to 4000 yrs B.P., indicating higher temperatures (8.2 to 21.3°C). The high temperatures during this time interval for Don Beto remain controversial compared to data obtained from El Diablo and Las Vacas profiles.

We attribute the different temperature ranges between profiles to several features. Environmental conditions are influenced by the hydric balance (precipitation regime) and the pressure that input and output of lake water could exert on the temperature of these locations. Also, the compared samples in each profile do not correspond exactly to the same age; therefore ostracode calcification was done under

different time and conditions, which is reflected in the differential Mg/Ca mol values from the sites.

The presence of both *L. bradburyi* and *L. platyforma* species at Las Vacas from warm and cold seasons, respectively, also recorded at Don Beto and El Diablo profiles, was interpreted as a characteristic transitional environment between saline and freshwater lake with occasional saline incursions, more than with a temporal mixing from summer and winter assemblage. In addition, it is important to recall that data used here was calculated based on the trace element content from three different species of genus *Limnocythere*. We could be obviating vital factors inherent to each species and their consequences in the calcification process. In spite of these temperature differences between both profiles, we observe a similar pattern in temperature variation. Nevertheless, calculated temperatures from the profiles range between present day measured temperatures nearly: 3.5 °C to 20 °C (Ortega-Ramírez *et al.*, 1998).

Early Holocene corresponds to Zone I: the first unit (LV1; 9250 years B.P.) displayed the greatest ostracode abundance with a dominance of freshwater species (*L. platyforma*), probably representing the largest water inlet. The temperature has the highest record, similar to the El Diablo profile, where the temperature reached 6.6 – 7.6 °C. The second unit for Las Vacas (~8457 years B.P.) showed a decrease of ~1 °C, which is contemporaneous to a salinity increase supported by the gradual diminishing of clear and freshwater ostracodes. Instead, ostracodes with higher salinity tolerance (*L. bradburyi* and *E. patzcuaro*) have an increase in abundance. However, water conditions remain favorable for the development of *L. platyforma*. Early Holocene, as stated by Metcalfe *et al.* (2002), is characterized for being wetter than present Northern Mexico. Palacios-Fest *et al.*, (2002) interpreted the Early Holocene as a wet period, which is consistent with Las Vacas data. Our record suggests the presence of a water column suitable for development of the ostracode population, which we relate to humid conditions brought by summer's enhanced precipitation.

Low-temperature conditions extend to lower Middle Holocene (~7310 years B.P.), Zone II. These features are interpreted as a period with less humidity and cold conditions. Ostracode assemblage, represented by Zone II, reflects the dominance of *E. patzcuaro* and *L. bradburyi*. These two are species that inhabit turbid water and, for *E. patzcuaro*, salinity is under 5000 ppm. This is interpreted as a period with less humidity which affected water salinity and turned it into turbid conditions. Ortega-Ramírez *et al.* (2000) interpreted boggy conditions in the paleolake during Mid-Holocene. This was related to the decrease in moisture conditions for this time, inferring that this condition was related to decreasing precipitation.

In the interval between ~6340~5370 years B.P. (Zone II), the record of ostracode Mg/Ca ratios shows temperatures with an increase of 1 °C. During this period, ostracode valves

abundance is high, which implies favorable conditions for ostracode reproduction and growth, dominated by *E. patzcuaro* and with a major presence of *L. bradburyi* over *L. platyforma*. This change in the assemblage structure may be related to the establishment of saline waters, where *L. platyforma* did not find optimum conditions. Palacios-Fest *et al.* (2002) found low temperatures and dry conditions during Mid-Holocene in the El Diablo profile, which is consistent with our trend. For this period, two regimes of precipitation have been identified for northern Mexico and the southern United States. The first was a period of precipitation with high temperatures (Van Devender, 1990a, b; Waters and Haynes, 2001; Metcalfe *et al.*, 1997 and 2000), whereas in the second, Antevs (1948) proposed an Altithermal period characterized by low precipitation and decreasing moisture (Ortega-Ramírez *et al.*, 2000; Clement *et al.*, 2000; Menking and Anderson, 2003; Castiglia and Fawcett, 2006). Based on the environmental characteristics of the Las Vacas profile for this time interval, an Altithermal precipitation regime could explain such features.

Around 6000 years B.P. the Northern Hemisphere, including North America, warmed as a result of increasing solar radiation and the heightening of monsoon activity (Harrison *et al.*, 2003; Schmidt *et al.*, 2004), allowing the formation of precipitation regimes that affected southwestern U.S. (moister) and the adjacent regions (drier).

During the end of the Middle Holocene (~4929 years B.P., last part of Zone II) the Mg/Ca ratio records a decrease of ~3 °C temperature with a marked fall in the number of valves. The environmental conditions continued to be the same along the Zone II, interpreted by the association dominated by *E. patzcuaro*.

The last part with ostracode presence (Zone III) records a drastic turnover in assemblage composition. It is characterized by a low number of valves with an incipient presence of *E. patzcuaro* and dominated by both *Limnocythere* species, suggesting that the lake was active during warm and cold seasons, which may be implying that modern conditions were thus established: warm summers and cold winters (Chávez-Lara *et al.*, 2012). Conditions during this time were not as optimal as previous zones since we could not obtain valves for the Mg/Ca ratio analyses. However, according to the Don Beto record, the temperature shows a decline for the late Holocene (~1300 years B.P.). According to Metcalfe (2006), current climatic conditions were established in the region around 4000 years B.P., characterized by hot and dry conditions. Ortega (1990) and Metcalfe *et al.* (1997) concluded that for the late Holocene (3000 – 2000 years B.P.), the environmental conditions within the same basin were much drier. These conditions could have been reflected in the disappearance of the ostracode populations (Zone IV), driven by shrinkage of the water body, consequently salinizing the water. Finally we want to acknowledge two anonymous reviewers provided valuable comments on the manuscript.

5. Conclusions

The climate and environmental history of northern Mexico has been reconstructed with a compound of several records. Our results add to the reconstruction of paleoenvironmental and paleoclimate history of Holocene Babícora Basin, a period with previous scarce fossil evidence.

The fossil ostracode fauna evidenced fluctuating conditions within the basin with a permanent body of water at the western edge of the basin from ~9250 to ~3400 years B. P., an age when the ostracode associations disappeared from the sedimentary record. Environmental conditions were variable, with an early Holocene dominated by *L. platyforma*, indicating low salinity conditions. For the Middle Holocene, salinity, water turbidity and temperature increased as indicated by the domination of *E. patzcuaro*. The onset of the Late Holocene is marked by a slight increase in population preceding the total decline and absence of the ostracode population, implying the disappearance of the water at this locality. According to this, we infer that the main factors driving the ostracode populations seem to be changes in water temperature and salinity, features controlled mainly by summer and winter precipitation.

Temperatures were estimated applying a geochemical approach. The values fell within the range of instrumental measured temperatures for the region, which we interpreted as veracious temperatures. Moreover, the observed temperature trend is congruent with a previous report from the basin. However, we observed a difference in the ranges of temperature between the compared records. We attributed these differences to several factors related to the hydrological and sedimentological features as well as the biological processes inherent to the different species employed.

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