# Ostracode and C/N based paleoecological record from Santiaguillo basin of subtropical Mexico over last 27 cal kyr BP

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## ABSTRACT

Changes in ostracode species assemblage suggest presence of oligohaline and mesohaline waters in the Santiaguillo basin of subtropical Mexico over the last *ca.*27 cal kyr BP. Paleoecological reconstruction is based on the distribution of *Limnocythere bradburyi* Forester, *Eucandona cf. patzcuaro* Tressler, *Cypridopsis vidua* Brady and *Limnocythere ceriotuberosa* Delorme. Source of organic productivity is inferred from C/N ratios. The basin hosted shallow and oligohaline water during the late glacial (*ca.*27–19 cal kyr BP) and lacustrine phytoplankton contributed to the organic productivity. However, the water body of Last Glacial Maximum (LGM) was relatively warmer (>13°C) and more diluted compared to the pre-LGM. Increased salinity and reduced lacustrine productivity at *ca.*19 cal kyr BP marked a shift in the paleoecological conditions. Water body was mesohaline during *ca.*9.5–4 cal kyr BP and periodic desiccation of the basin possibly caused the absence of ostracode valves in sediments of the last *ca.*3.5 cal kyr BP. Comparison with other proxy-records from the region indicates that the hydrological variations in different parts of subtropical north and northwestern Mexico were not synchronous during the late Pleistocene and Holocene.

Keywords: lacustrine ostracodes; C/N ratio; Paleoecology; Late Quaternary; Santiaguillo basin; Mexico.

## RESUMEN

*Los cambios en el conjunto de especies de ostrácodos sugieren presencia de oligohalina y mesohalina aguas en la cuenca de Santiaguillo ubicado en la parte subtropical de México durante los últimos ca.27 ka cal AP. La reconstrucción paleoecológica se realizó con base en la distribución de Limnocythere bradburyi Forester, Eucandona patzcuaro Tressler, Cypridopsis vidua Brady y Limnocythere ceriotuberosa Delorme. La fuente de la productividad orgánica se infiere a partir de la relación C/N. La cuenca albergó agua somera y oligohalina durante el pasado último glacial (ca. 27–19 ka cal AP) y el fitoplancton lacustre contribuyó a la productividad orgánica. Sin embargo, el cuerpo de agua durante el Último Máximo Glacial (UMG) fue relativamente cálido y más diluido comparado con el pre-UMG. Un incremento en la salinidad y la reducción de productividad lacustre a los ca.19 ka cal AP marcaron un cambio en las condiciones paleoecológicas. El cuerpo de agua fue mesohalino durante ca.9.5–4 ka cal AP y sequías periódicas de la cuenca causaron posiblemente la ausencia de valvas de ostrácodos en los sedimentos de los últimos ca.3.5 ka cal AP. Comparaciones con otros registros de la región indican que las variaciones hidrológicas en diferentes partes de la zona subtropical del norte y noroeste de México no fueron sincrónicas durante el Pleistoceno tardío y Holoceno.*

*Palabras clave: ostrácodos lacustre; relación de C/N; Paleoecología; Cuaternario tardío; cuenca de Santiaguillo; México.*

## INTRODUCTION

In the last two decades, the reconstruction of late Quaternary paleoecological and paleoclimatic conditions of the subtropical northern Mexico has received a significant increase in the scientific attention (Urrutia-Fucugauchi *et al.*, 1997; Metcalfe *et al.*, 1997, 2002; Murillo de Nava *et al.*, 1999; Ortega-Guerrero *et al.*, 1999; Palacios-Fest *et al.*, 2002; Lozano-García *et al.*, 2002; Holmgren *et al.*, 2003, 2007; Davis, 2003; Caballero *et al.*, 2005; Castiglia and Fawcett, 2006; Ortega-Rosas *et al.*, 2008; Roy *et al.*, 2010, 2012a, 2012b, 2013a, 2013b, 2014a, 2014b). The initial proxy registers and climate models reported humid conditions during the late last glacial and associated them to more winter precipitation. The subtropical high pressure zone in the eastern Pacific displaced southward and increased the frequency of westerly winter storms (COHMAP members, 1988; Manabe and Broccoli, 1985; Kutzbach and Wright, 1985; Kutzbach *et al.*, 1998). Most of the paleoclimatic records suggested the possible absence of summer precipitation in the region (*e.g.* Thompson and Anderson, 2000).

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The perception about the late Quaternary climate changed after Holmgren *et al.* (2006) and Kirby *et al.* (2006) reported that the influence of summer precipitation was reaching the USA-Mexico borderlands and coastal southwestern USA during different intervals in the last glacial period. Recently, Roy *et al.* (2013a) reconstructed paleohydrological conditions of the northern part of subtropical Mexico over the last *ca.* 80 cal kyr BP and hypothesized that the major influence of the winter storms remained in the region located to the north of 29°N latitude. The hydrology of northern Mexico was dominantly controlled by the summer precipitation and the intervals of increased summer precipitation were contemporary to warm interstadials (Roy *et al.*, 2013a). Summer precipitation was less during the Last Glacial Maximum (LGM) and it increased over the deglaciation (Roy *et al.*, 2010; Roy *et al.*, 2012b). During the Pleistocene-Holocene transition, increased summer precipitation led to wetter conditions in the region (Roy *et al.*, 2014a). However, the synthesis of Barron *et al.* (2012) suggested that the influence of summer precipitation reached different regions during different intervals over the Holocene.

Compared to the northern part of subtropical Mexico, the paleoecological and paleohydrological information are scarce from the central and southern parts (Figure 1a). Similarly, most of the proxy-records are based on the geochemical and magnetic properties of lacustrine sediments and the use of ostracodes as a paleoenvironment indicator has not been sufficiently explored. Ostracodes are micro-crustaceans with low-Mg calcite valves (Turpen and Angell, 1971) and are sensible to the environmental and climatic changes. Their abundance and diversity in lacustrine sediments provide important information about the past ecology and physicochemical conditions of the water column (*e.g.* water chemistry, salinity, conductivity and temperature) (Forester, 1986; Pérez *et al.*, 2013). The results obtained from previous studies of ostracode paleoecology from the region (i.e. Babicora and Bahia Kino) are promising (Caballero *et al.*, 2005; Palacios-Fest *et al.*, 2002; Chávez-Lara *et al.*, 2012). In this work, we infer the paleoecology of the central-southern part of the subtropical Mexico over the last *ca.* 27 cal kyr BP by studying the distributions and abundances of fossil ostracode valves in two different sediment profiles from the western margin of Santiaguillo basin (Figure 1b). Productivity is inferred from the concentrations of total organic carbon and the source of productivity is distinguished by the C/N ratio.

## REGIONAL SETTING

Subtropical Mexico hosts large parts of Sonora and Chihuahua Deserts. The Santiaguillo basin (24º39'–24º58' N, 104º39'–104º57' W and ~1960 m asl) is located in a NW-SE oriented tectonic basin in the central part of the Chihuahua Desert of Mexico and forms part of the “Basin and Range” sub-province of Sierra Madre Occidental Mountains (Figure 1b). The geology and tectonic evolution of the basin is described by Nieto-Samaniego *et al.* (2012). The semi-graben was formed between *ca.*39 and 32 Ma and igneous rocks (rhyolite, ignimbrite and basalt) comprise the geology of the basin. Minor exposures of lacustrine and alluvium deposits and conglomerates are also present in the basin surroundings. The lacustrine basin covers an area of ~2000 km$^2$ and is surrounded in the east and west by ~2500 to 3000 m high hills.

The meteorological station at Guatimape (western part of the basin) registered an average annual precipitation of ~430 mm between AD 1951 an 2010 (Servicio Meteorológico Nacional, México). More than 80% of this annual precipitation occurred during the summer months of June to September as a result of monsoonal circulation and

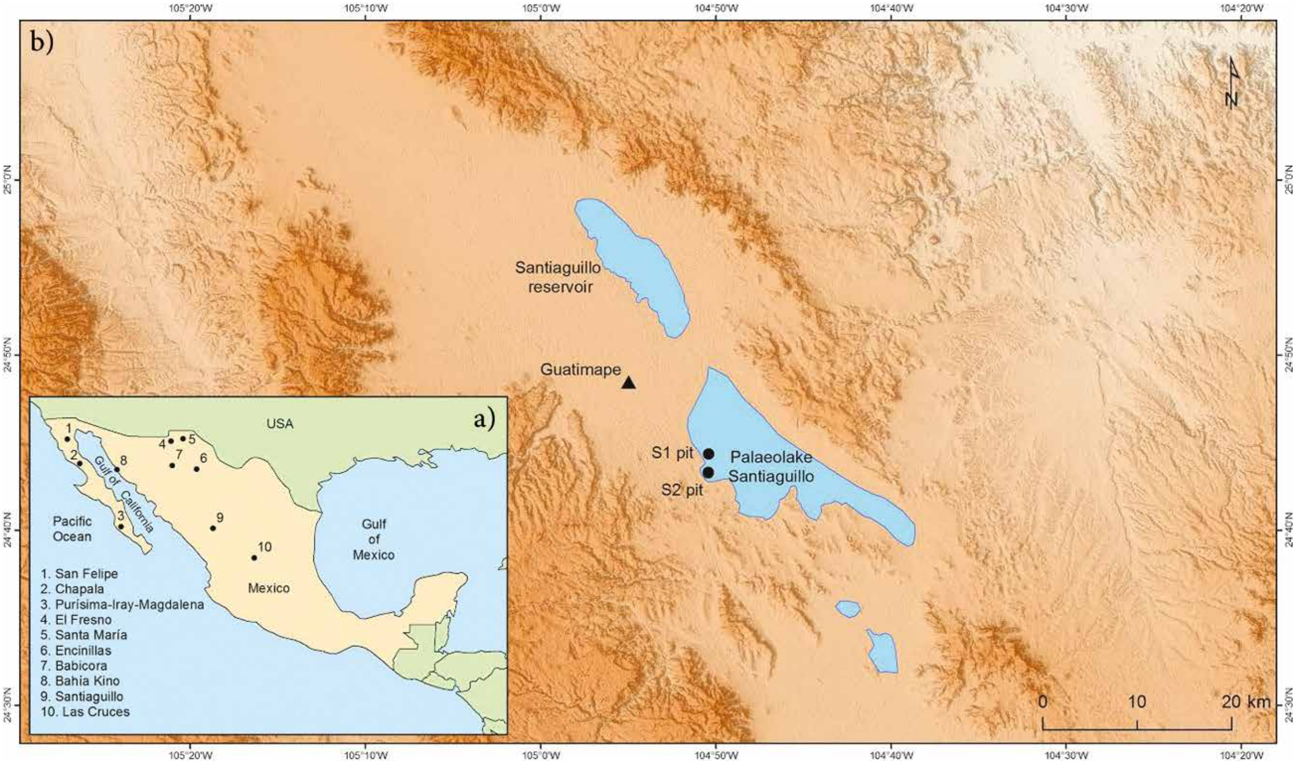

Figure 1. (a) Location of sites with proxy paleoclimatic and paleoecological records from the region and (b) the Santiaguillo basin. Santiaguillo basin is located in a semi-graben in the sub-tropical northern Mexico and is surrounded by ~2500 to 3000 m high volcanic hills. Ostracode and C/N analysis were performed in sediments collected from two different pits (S1 and S2) located at the western margin of the basin.

tropical cyclones, whereas the precipitation during winter months of November to March represented less than 10% of the annual rainfall (Figure 2). The registered maximum average temperature was ~34°C during June, and minimum temperature reached sub-zero during December-January. According to the classification of Köppen, the region represents semi-arid climate with precipitation during the summer (BSk) (García, 1973).

## MATERIAL AND METHODS

Sediment samples were collected from two different pits (S1 and S2) at the western margin of the basin (Figure 1b). S1 and S2 pits have depths of 300 cm and 200 cm, respectively (Figure 3). Chronology of the sediment sequence from S1 pit is based on 4 different Accelerator Mass Spectrometry radiocarbon(AMS $^{14}$C) dates on organic carbon present in the bulk sediments. Similarly, the sediment profile of S2 pit is chronologically constrained by 2 different AMS $^{14}$C dates on sediment organic carbon (Figure 3). The $^{14}$C dates were calibrated in Calib 6.0 program using the IntCal09 calibration curve of Reimer *et al.* (2009) and the values of maximum probability within the 2σ range were considered for the reconstruction of age models.

A total of 61 samples at an interval of ~5 cm from the S1 pit and 20 different samples at an interval of ~10 cm from S2 pit were processed for the ostracode analysis. Each sample (~10 g) was oven dried and disintegrated by soaking in water for 2–3 days. The samples were washed through two sieves of 74 µm and 177 µm. The sieve residues were oven dried and examined under a Leica stereomicroscope to identify the different species and determine their abundance based on the descriptions provided by Morkhoven (1963), Delorme (1971a, 1971b, 1971c), Forester (1985) and Carreño (1990). Total ostracode abundance in each sample was calculated by adding the number of adult and juvenile valves of all the observed species and is reported as the number of valves in 1 g of dry sediment (valves/g). Adult valves of each species were counted in the dry sediment and presented as relative abundance (in %). The adult valves were extracted and stored in Plummer type microfossil slides. Images of the ostracode valves were taken using a Jeol JSM-5600LV LCM scanning electron microscope.

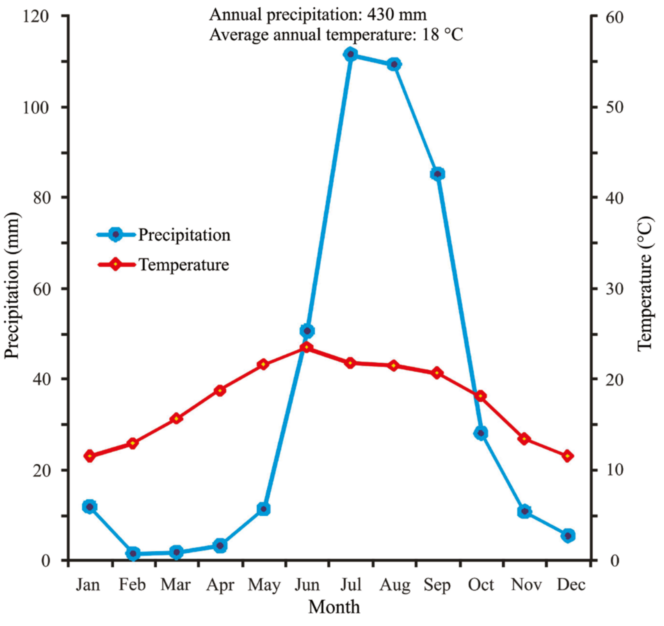

Figure 2. Average monthly precipitation and temperature (AD 1951-2010) recorded at Guatimape meteorological station. The basin received an average annual precipitation ~430 mm and the average annual temperature in the region is ~18°C. (Source: Servicio Meteorológico Nacional, México).

Concentration of total organic carbon (TOC) in the bulk sediments was analyzed in all the samples in a Thermo Scientific HiperTOC solid analyzer after oven drying (50 °C) and powdering the sediments in an agate pestle. Concentration of total carbon (TC) was measured by heating the sample to 980°C and the amount of inorganic carbon (TIC) was measured by acidifying the sediment with 10% $H_3PO_4$. Total organic carbon (TOC) content was estimated by subtracting the inorganic carbon (TIC) from total carbon (TC). Concentration of total nitrogen (TN) was measured in 51 samples (31 samples from S1 pit and 20 samples from S2 pit) in a CHNS/O 2400 series II Perkin Elmer elemental analyzer.

## RESULTS

### Sediment and Chronology

Figure 3 shows the sediment profiles of S1 and S2 pits. Sediments of S1 pit comprise clay and calcareous silt intercalations from 300 to 278 cm depth and massive calcareous silt and silty-sand from 278 to 75 cm depth. Silty-clay and silt intercalations are deposited between 75 and 50 cm. Massive silty-sand with abundant root remnants are present between 50 and 0 cm. Almost 65 cm long vertical desiccation fissures are present at 75 cm depth. In the S2 pit, the sediments are calcareous silt and silty-sand between 200 and 100 cm depth. Almost 10 cm long desiccation fissures were observed at depths of 140 cm and 100 cm. Intercalations of massive silt and silty-clay are present at 100–50 cm and massive silty-sand with abundant root remnants represents the sediments of 50–0 cm depth.

Table 1 presents the $^{14}$C dates and calibrated values in the 2σ range. The maximum probability within the 2σ range of calibrated age *vs.* depth plot (Figure 4) provides the age models for both profiles. Age model of S1 pit is reconstructed from 4 different radiocarbon dates. The rate of sedimentation varies between 10.1 cm/kyr and 12.1 cm/kyr for sediments deposited during *ca.* 24.9–3.9 cal kyr BP (279–49 cm). The base of the sequence is assigned an age of *ca.*27 cal kyr BP by extrapolating the rate of sedimentation (10.5 cm/kyr) calculated between 205 and 279 cm. Sediments between 49 and 205 cm depth are assigned ages by interpolating the sedimentation rates calculated between consecutive $^{14}$C dates. We estimate sedimentation of 12.5 cm/kyr for the upper 49 cm of the sequence by assuming that the surface sediments represent present day. It is similar to the higher side of sedimentation rates calculated for S1 pit. Desiccation fissures at 75 cm depth indicate absence of any water body and dry conditions at the site of S1 pit at *ca.* 6.5 cal kyr BP.

The age model of S2 pit includes 2 different calibrated $^{14}$C dates and assigns *ca.*19 cal kyr BP to the base. Assuming the surface sediments to represent the present day, a sedimentation rate of 26.7 cm/kyr was estimated for the upper 99 cm of the sequence. Estimated sedimentation rate for upper part of the sediment profile is very different from the sedimentation rate calculated between 199 and 99 cm depths (6.7 cm/kyr). The vertical fissures at 140 cm and 100 cm depths indicate that the site of S2 pit experienced multiple events of desiccation between *ca.*18.6 and 3.7 cal kyr BP. Lower sedimentation calculated between 199 and 99 cm could be due to the aeolian activity eroding the earlier deposited sediments during the dry intervals and lake desiccation. Due to limitations associated with both the age models, we did not undertake detailed paleoecological reconstruction occurred over last *ca.*3.9 cal kyr BP in S1 pit and last *ca.*3.7 cal kyr BP in S2 pit.

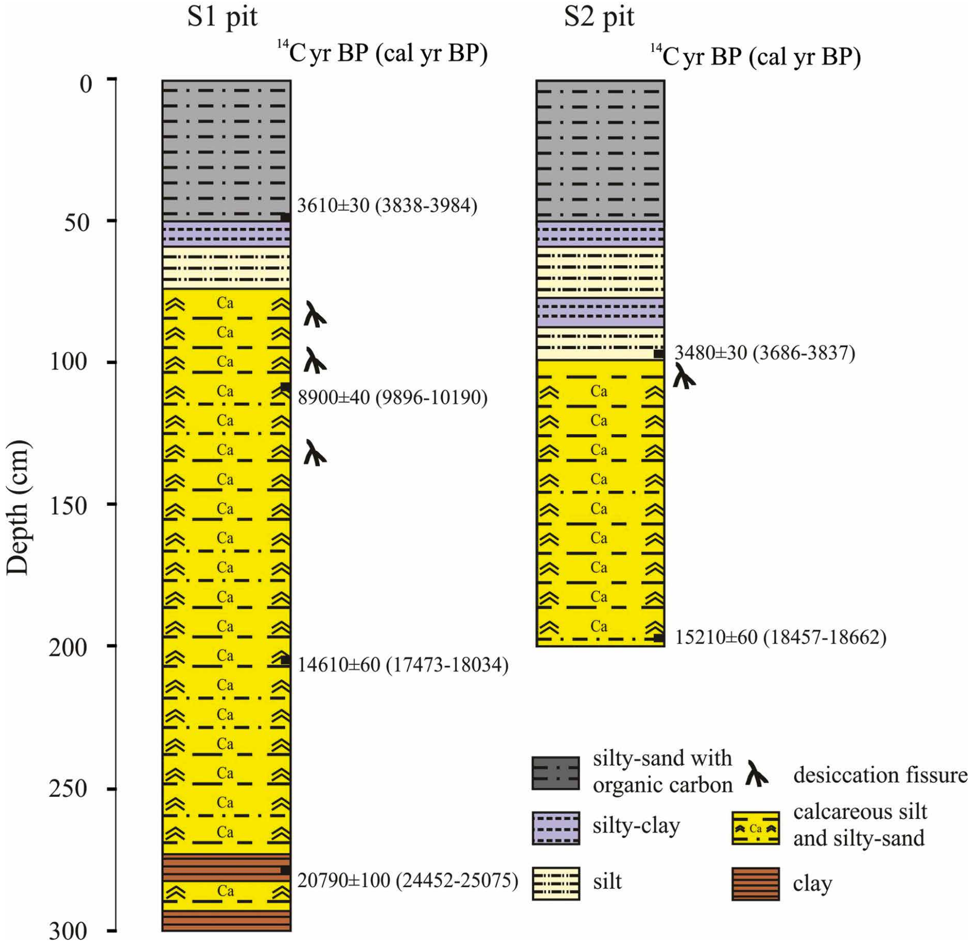

Figure 3. Sediment profiles of S1 and S2 pits and AMS $^{14}$C dates of bulk sediment.

**Ostracode species assemblages**

The ostracode assemblages comprise 5 species (Figure 5). Except for one, the species were present as adults and juveniles. Low abundance and presence of only juvenile instars of one species precluded an accurate taxonomic identification. The paleoecological inferences are strictly based on the adult counts as the last ostracode moult takes place during the optimal environmental conditions (De Deckker, 2002). Two of the species belong to the genus *Limnocythere* (*L. bradburyi* Forester, 1985 and *L. ceriotuberosa* Delorme, 1967) and the other two are *Eucandona cf. patzcuaro* Tressler (1954) and *Cypridopsis vidua* Brady (1868). Most of the shells are well preserved and almost all are covered with authigenically precipitated carbonate minerals. Figures 6 and 7 summarize the total ostracode abundance (valves/g) and the relative abundance of each species (%) in both pits. Based on the variation in total ostracode abundance and relative abundances, S1 profile is divided into 5 different zones and S2 profile is divided into 3 different zones. The zones in both pits have comparable temporal distributions.

In the sediments of S1 pit, the total ostracode abundance varies between 0 and 125 valves/g (Figure 6). The juvenile shells are more frequent (up to 102 valves/g) than the adult shells (up to 57 valves/g). *L. bradburyi* (0–50 valves/g) is the most abundant species and it is followed by *E. patzcuaro* (0–9 valves/g). Both *C. vidua* (0–1 valves/g) and *L. ceriotuberosa* (0–1 valves/g) are the least abundant species. The zones are characterized by different total ostracode abundances and associations.

Sediments of zone 5 (300–265 cm, *ca.* 27–23.5 cal kyr BP) display a total ostracode abundance between 4 and 24 valves/g, and most of them are juveniles (up to 18 valves/g). This zone is characterized by highest species richness (4 species). *L. bradburyi* and *E. patzcuaro* constitute 69–100% and up to 31% of the adult ostracodes. Adult shells of *L. ceriotuberosa* are observed at depths of 299 and 281 cm. Similarly, one adult shell of *C. vidua* was observed at a depth of 299 cm. Sediments of zone 4 (265–220 cm, *ca.*23.5–19 cal kyr BP) shows the highest and variable ostracode abundance (8–125 valves/g) and most of them are

Table 1. Radiocarbon analysis and calibrated values of bulk sediments collected at different depths from two different pits in the western margin of Santiagullo basin.

| | Lab. code | Depth (cm) | AMS $^{14}$C age (yr BP) | 2-sigma range (cal yr BP) | $\delta^{13}$C (‰) |
|---|---|---|---|---|---|
| **S1 pit** | Beta-299072 | 49 | 3,610 ± 30 | 3,838 – 4,058 | -18.0 |
| | Beta-321663 | 111 | 8,900 ± 40 | 9,896 – 10,190 | -20.2 |
| | Beta-299075 | 205 | 14,610 ± 60 | 17,473 – 18,034 | -20.7 |
| | Beta-299076 | 279 | 20,790 ± 100 | 24,452 – 25,075 | -20.9 |
| **S2 pit** | Beta-299077 | 99 | 3,480 ± 30 | 6,715 – 6,950 | -18.5 |
| | Beta-299078 | 199 | 15,210 ± 60 | 18,457 – 18,662 | -20.9 |

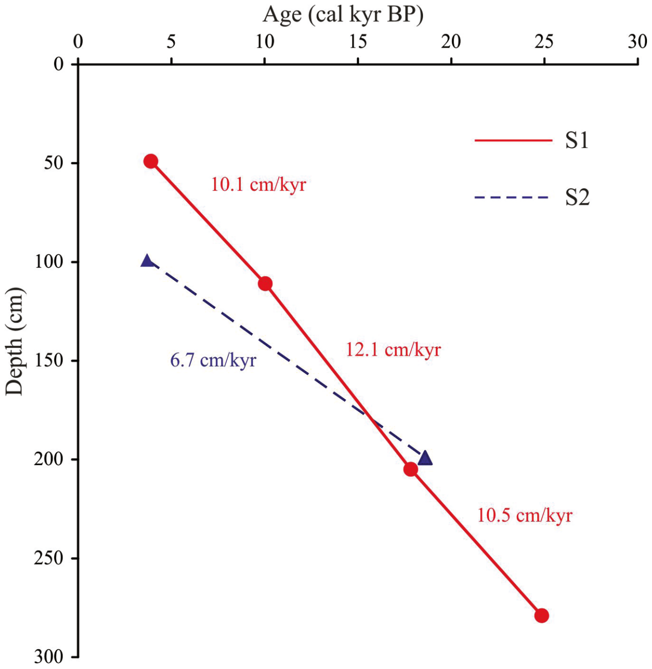

Figure 4. Age model constructed for both pits from the calibrated ages *vs*. depth and the calculated sedimentation rates.

juveniles (up to 102 valves/g). *L. bradburyi* and *C. patzcuaro* constitute 52–92% and up to 47% of the adult ostracodes. *C. vidua* is present in sediments at depths of 265–225cm. Zone 3 (220–105 cm, *ca.*19–9.5 cal kyr BP) displays total ostracode abundance between 2 and 113 valves/g. Both adults and juveniles are present in almost equal proportions. *L. bradburyi* represents 67–100% of the adult shells and *E. patzcuaro* constitutes up to 33% of the adult ostracodes. Sediments at depths of 185, 165–160 and 125–111 cm contain *C. vidua*. The depth interval 105–50 cm (*ca.*9.5–4 cal kyr BP) represents zone 2 and have a total ostracode abundance of 1–15 valves/g. This is monospecific and contains only *L. bradburyi* (100%). Zone 1 comprises the sediments at depths of 50–0 cm (last *ca.*4 cal kyr BP) and does not contain ostracodes.

The ostracode abundance is lower in the sediments of S2 pit compared to S1. Total ostracode abundance varies between 0 and 38 valves/g (Figure 7). Abundance of adult (up to 17 valves/g) and juvenile shells (up to 19 valves/g) are similar. Sediments of this pit do not contain *L. ceriotuberosa*, while *L. bradburyi* (0–17 valves/g) is the most abundant species. The abundances of *E. patzcuaro* (0–3 valves/g) and *C. vidua* (0–1 valve/g) are similar.

Sediments of zone 3 (200–135 cm, *ca.*19–9 cal kyr BP) have ostracode abundance of 3–38 valves/g. This zone is characterized by the presence of *L. bradburyi*, *E. patzcuaro* and *C. vidua*. *L. bradburyi* and *E. patzcuaro* display relative abundances of 83–100% and of 0–15%, respectively. Adult shells of *C. vidua* were observed at depths of 200–195 cm and 175–165 cm. Zone 2 (135–85 cm, *ca.*9–3.5 cal kyr BP) has an ostracode abundance of 3–12 valves/g and is characterized by the absence of *C. vidua*. *L. bradburyi* represents 80–100% of the adult shells and *E. patzcuaro* was observed at depths of 125 cm and 115 cm. Zone 1 comprises sediments deposited at depths of 85–0 cm (last *ca.*3.5 cal kyr BP) and lacks ostracode valves.

### Total organic carbon (TOC) and organic carbon/nitrogen (C/N)

Concentrations of TOC and C/N in bulk sediments from both pits are presented in Figures 6 and 7. Sediments of S1 pit have TOC of 0.2–1.2%, total nitrogen (TN) of 0.02–0.10% and C/N values between 3.5 and 34 (Figure 6). Sediments rich in TOC generally contained lower number of ostracodes (i.e., 300–255 cm and 50–0 cm). Zones 5 and 4 (*ca.*27–19 cal kyr BP) have lower and uniform values of C/N (3.5–7). Sediments from zone 3 (*ca.*19–9.5 cal kyr BP) and zone 2 (*ca.*9.5–4 cal kyr BP) have higher and variable C/N (7–34). Zone 1 (last *ca.*4 cal kyr BP) have intermediate C/N values (8–16).

Sediments of S2 pit have TOC concentrations of 0–1.0%, total nitrogen contents of 0.09–0.16% and C/N values of 0–10 (Figure 7). TOC abundance is inversely related to total ostracode abundance. Sediments of all the 3 zones have similar values of C/N. Zone 3 (*ca.*19–9 cal kyr BP) has C/N values between 0 and 10 and zone 2 sediments (*ca.* 9–3.5 cal kyr BP) are characterized by C/N values of 2–10. Zone 1 sediments (last *ca.*3.5 cal kyr BP) have C/N values of 1–10.

## DISCUSSION

### Paleoecological reconstruction

Ostracodes preserved in the sediments of Santiaguillo basin tolerate almost similar ranges of temperature (5–32°C) and pH (8–10) (Delorme, 1989; Palacios-Fest, 2007, 2010). It was not possible to reconstruct the water column temperature in the absence of trace element geochemistry of ostracode valves and modern training sets in the area. However, the changing ostracode species assemblages suggest that the water column salinity varied between oligohaline and mesohaline over the last *ca.* 27 cal kyr BP. The salinity reconstruction is based on the classification proposed by Meisch (2000). Accordingly, the oligohaline waters are characterized by salinity range of 500–5,000 ppm and the mesohaline waters have 5,000–18,000 ppm of salinity. Except for the last *ca.* 3.5 cal kyr BP, the sediments preserve 4 different ostracode species and *L. bradburyi* is the most abundant. Forester (1985) identified *L. bradburyi* in different shallow oligohaline to euhaline lakes from central Mexico. We relate the highest abundance of *L. bradburyi* to the presence of shallow water bodies at the western margin of Santiaguillo between *ca.* 27 and 3.5 cal kyr BP. Palacios-Fest (2010) relates the occurrence of *E. patzcuaro* to intervals of fresh to oligohaline water as a result of increased fresh water inflow into the basin. Similarly, the presence of *C. vidua* was observed in warm (>13°C) and fresh to oligohaline lakes in southwestern USA (Palacios-Fest, 2010). *L. ceriotuberosa* tolerates oligohaline to mesohaline conditions in USA and Canada (Delorme, 1971a, 1971b, 1971c; Palacios-Fest, 2007). In the interior plains of Canada, Smith and Delorme (2010) observed that *L. ceriotuberosa* was present in waters with low dissolved oxygen content (3 mg/L).

The paleoecological conditions of Santiaguillo are divided into pre-LGM, LGM and post-LGM. The interpretations are supported by TOC and C/N data. TOC content in bulk sediment reflects the amount of primary productivity (Cohen, 2003) and C/N ratio reflects the contribution of terrestrial vegetation and lacustrine algae on the deposited organic matter (Meyers and Ishiwatari, 1995). Lacustrine algae and terrestrial plants have different contents of nitrogen and the increasing contribution of one of them to the organic matter is reflected by the C/N ratio. Sediment with higher C/N (>10) represents dominant contribution from terrestrial plants and lower C/N (<10) indicates that the organic matter originated from aquatic plants (Talbot and Johannessen, 1992; Meyers and Ishiwatari, 1995; Cohen, 2003).

Pre-LGM (*ca.*27–23.5 cal kyr BP): Sediments of S1 pit (zone 5, 300–265 cm) documented the paleoecological conditions that occurred prior to the last glacial maximum (pre-LGM). The ostracode assemblage suggested presence of shallow water column and oligohaline conditions. Presence of a permanent water body in the western margin of the basin is indicated by lacustrine phytoplankton (C/N<10)

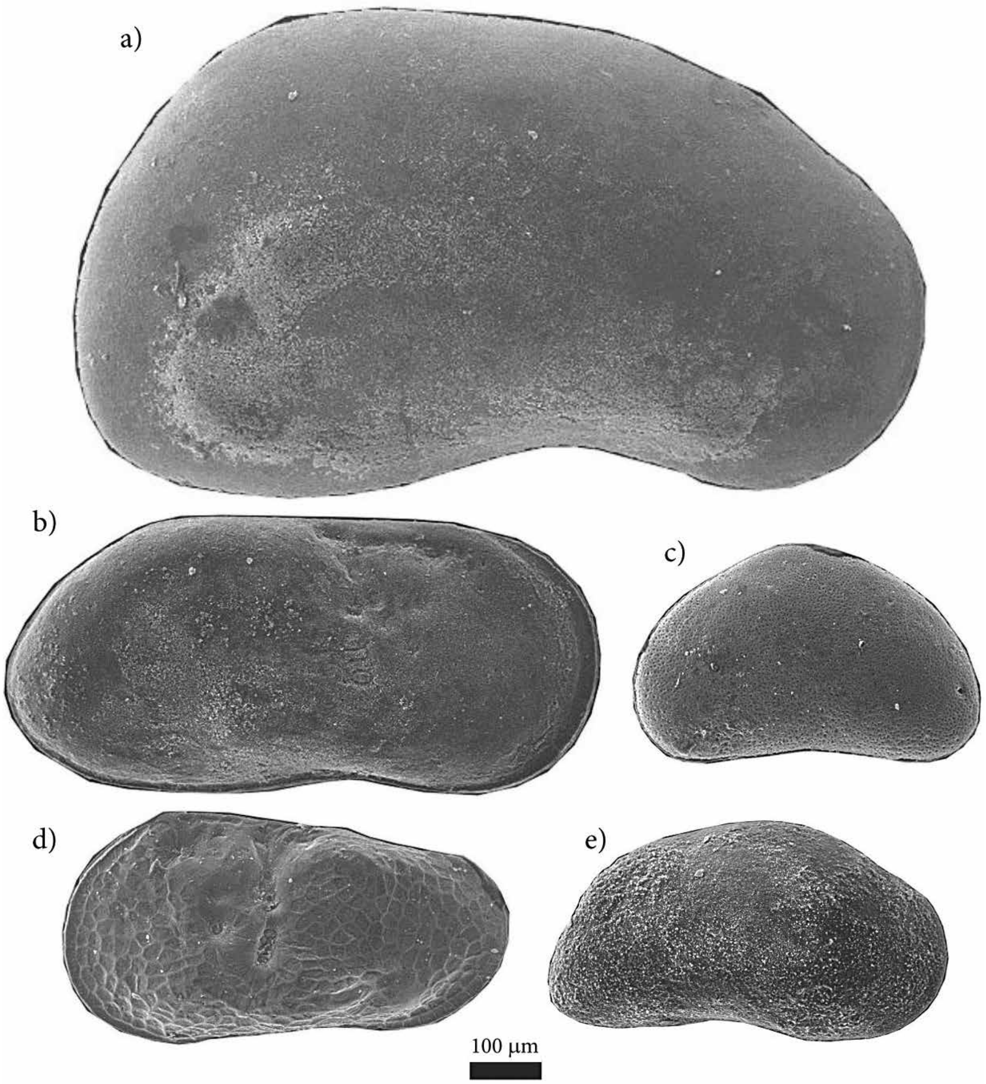

Figure 5. SEM photographs showing external views of lacustrine fossil ostracodes from the Santiaguillo basin. (a) *Eucandona cf. patzcuaro*, male, right valve, (b) *Limnocythere bradburyi*, male, right valve, (c) *Cypridopsis vidua*, asexual, left valve, (d) *Limnocythere ceriotuberosa*, female, left valve, and (e) unidentified species (juvenile), right valve.

dominantly contributing to the organic productivity, as well as the continuous increase in ostracode productivity. Occurrence of both *C. vidua* and *L. ceriotuberosa* indicated relatively low salinity at *ca.*27 cal kyr BP. The absence of *C. vidua* during rest of the interval suggested a slight increase in salinity in the oligohaline range. *L. ceriotuberosa* at 299 cm and 281 cm depths represented the intervals of less oxygenated water column (*e.g.* Smith and Delorme, 2010).

LGM (*ca.*23.5–19 cal kyr BP): Paleoecological condition of the last glacial maximum (LGM) was recorded by the lower part of S1 pit (zone 4, 265–220 cm). Existence of the shallow and permanent water body continued during this interval and the organic productivity was contributed by the lacustrine phytoplankton (i.e. C/N≤10). The ostracode assemblage of *L. bradburyi*, *E. patzcuaro* and *C. vidua* suggested the presence of a warm (>13°C) and more diluted oligohaline water body. Total ostracode abundance was higher at *ca.*20–19 cal kyr BP (60–125 valves/g) compared to *ca.*23.5–20 cal kyr BP (8–35 valves/g). The inverse relationship between total ostracode abundance and TOC could be due to the result of ostracode dissolution in an acidic environment formed by the organic carbon decomposition.

Post-LGM (last *ca.*19 cal kyr): Sediments of zone 3 (220–105 cm) and zone 2 (105–50 cm) of S1 pit documented the paleoecological conditions that occurred post the last glacial maximum (post-LGM). This interval was also represented by sediments of zones 3 and 2 (200–85 cm) of S2 pit. Ostracodes of S1 pit represented *ca.*19–4 cal kyr BP and ostracodes of S2 pit indicated the paleo-hydrochemical characteristics occurred during *ca.*19–3.5 cal kyr BP. The ostracode assemblages suggested presence of oligohaline to mesohaline water bodies in the western margin.

Post *ca.*19 cal kyr BP, the decreasing abundance of *E. patzcuaro* and increasing C/N values reflected a shift in the paleoecological conditions. Higher C/N values (>10) indicated that the terrestrial vegetation contributed more to the organic matter as the lacustrine productivity decreased. Gradual reduction in the amount of pluvial discharge into the basin was reflected by the decreasing abundance of *E. patzcuaro*. More salinity (Na and $HCO_3$-Cl enriched water body) was reflected by an increase in the abundance of *L. bradburyi* (*e.g.* Forester, 1985). Absence of both *E. patzcuaro* and *C. vidua* in the sediments of *ca.*13–11.5 cal kyr BP indicated less fresh water inflow into

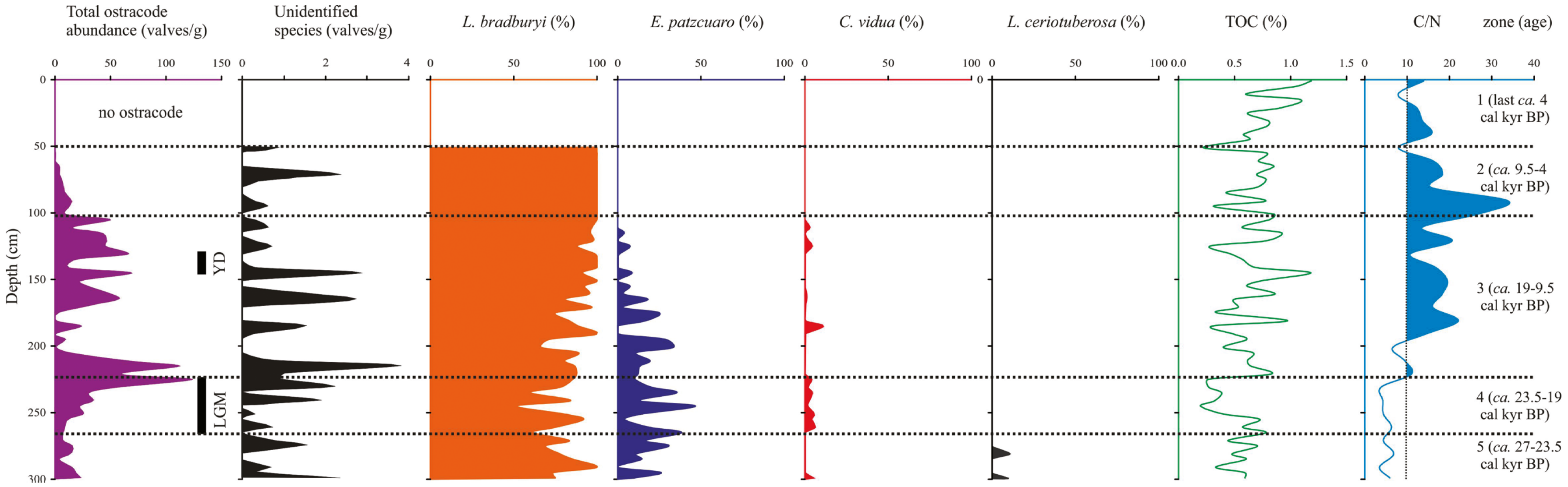

Figure 6 Total ostracode abundance (valves/g), distribution of the unidentified species, relative abundance of 4 different species (%), concentrations of total organic (TOC, %) and C/N relations in sediments of S1 pit.

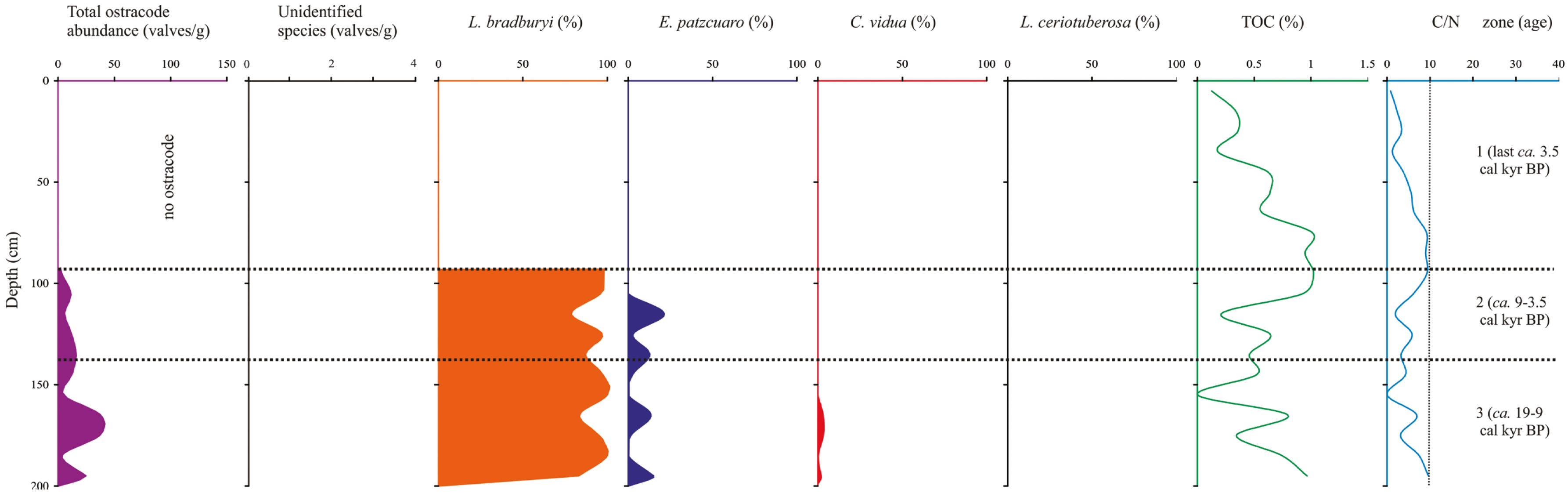

Figure 7 Total ostracode abundance (valves/g), distribution of the unidentified species, relative abundance of 4 different species (%), concentrations of total organic (TOC, %) and C/N relations in sediments of S2 pit.

the basin and more salinity (mesohaline) during the Younger Dryas (YD). However, the reappearance of both the species in sediments of the Pleistocene-Holocene transition suggested presence of relatively diluted oligohaline water column. Based on the concentrations of Ti and K in bulk sediments from another core in Santiaguillo, Roy *et al.* (2014) also identified a humid interval during the Pleistocene-Holocene transition and related it to enhanced summer precipitation in the region. During *ca.*9.5–4 cal kyr BP, the water body was ephemeral and was possibly present only during the summer months. Ostracode abundance gradually decreased, while the concentration of TOC increased. The occurrence of only *L. bradburyi* at 111–50 cm depths in S1 pit suggests presence of mesohaline water body in the western margin of the basin. Arid conditions caused enhanced aeolian activity in the surroundings of Santiaguillo during *ca.* 9.3–4.3 cal kyr BP (Roy *et al.*, 2014a). Similarly, the desiccation fissures at 75 cm depth indicate that the location of S1 pit remained dry for a longer duration at *ca.*6.5 cal kyr BP.

Although both the pits are located in the western margin of the basin, the sediments collected from them have different characteristics. Compared to sediments of S1 pit, the sediments of S2 pit are characterized by lower total ostracode abundance (up to 38 valves/g), C/N relation (<10) and rate of sedimentation (6.7 cm/kyr). Total ostracode abundance (up to 70 valves/g), C/N relation (>10) and sedimentation rate (10.1–12.1 cm/kyr) are higher in sediments of S1 pit. The desiccation fissures at 140 cm and 100 cm depths and lower sedimentation rate suggest that the site of S2 pit experienced multiple events of desiccation and erosion of previously deposited sediments during *ca.*18.6–3.7 cal kyr BP. The arid intervals might have caused oxidation of organic matter and poor preservation of ostracode valves in S2 pit.

Sediments representing the last *ca.* 4 cal kyr BP in S1 pit and last *ca.*3.5 cal kyr BP in S2 pit do not contain ostracodes. Sediments of this interval are relatively coarser (i.e. fine sand) compared to the lower parts (i.e. clay, silt, silty-sand and silty-clay). Over the last *ca.* 3.5 cal kyr BP, the amount of sediments deposited at the location of S2 pit (99 cm) is almost twice of the sediment deposited at S1 site (<50 cm). This was possibly due to the higher inflow into the site of S2 pit. The difference in the amount of inflow into two different sites in the western margin is also reflected by the C/N values indicating a terrestrial source for the organic matter deposited at S1 pit and lacustrine source for the organic matter deposited at S2 pit.

### Comparison with regional records

Comparison of the paleoecological information from Santiaguillo with other paleoclimatic records from northern and northwestern Mexico (see Figure 1a for locations) suggests that the region experienced different climatic and hydrological conditions over the last *ca.*27 cal kyr BP. Paleohydrological and paleoclimatic information are available from Babicora (Metcalfe *et al.*, 2002; Roy *et al.*, 2012b), El Fresno and Santa María (Castiglia and Fawcett, 2006) from Chihuahua, San Felipe (Lozano-García*et al.*, 2002; Roy *et al.*, 2010, 2012a) and Chapala (Davis, 2003) from Baja California, Purísima-Iray-Magdalena from Baja California Sur (Murillo de Nava *et al.*, 1999) and Las Cruces from San Luis Potosi (Roy *et al.*, 2013b). Between *ca.*27 and 19 cal kyr BP, the salinity of Santiaguillo basin was lower compared to the salinity of water column at Babicora. The ostracode species assemblage suggested presence of oligohaline water body at Santiaguillo and oligohaline to mesohaline water bodies at Babicora. Multielement geochemistry of the sediments indicated reduced runoff into Babicora and San Felipe basins (Roy *et al.*, 2010, 2012a, 2012b). During this interval, the vegetation in the surroundings of Babicora comprised *Pinus* and *Picea* (Metcalfe *et al.*, 2002) and vegetation in the surroundings of San Felipe basin were *Abies*, *Pinus* and *Eryngium* (Lozano-García *et al.*, 2002).

Over the last *ca.*19 cal kyr BP, the runoff into Santiaguillo gradually reduced and the water body became more saline. However, Babicora received more precipitation post *ca.*18 cal kyr BP (Roy *et al.*, 2013b) and the runoff into San Felipe increased after ca.13 cal kyr BP (Roy *et al.*, 2010). The formation of linear and mega-barchan dunes indicate hot and arid conditions at the Purísima-Iray-Magdalena basin during *ca.*14–8 kyr BP (Murillo de Nava *et al.*, 1999). During the early to middle Holocene, the Santiaguillo sediments indicated mesohaline conditions (*ca.*9.5–4 cal kyr BP), enhanced aeolian activity (*ca.*9.3–4.3 cal kyr BP) and multiple events of desiccation. In general, both Babicora and San Felipe received more runoff over the Holocene. However, Babicora experienced an event of desiccation at *ca.*3 cal kyr BP and San Felipe sediments documented more aeolian activity at *ca.*8 cal kyr BP. Laguna El Fresno and Laguna Santa María experienced wet conditions and higher lake stands at *ca.*9.4–9.3 cal kyr BP, *ca.*7.5–7.2 cal kyr BP and *ca.*4.9–4.2 cal kyr BP (Castiglia and Fawcett, 2006). The pluvial discharge into Las Cruces was more during *ca.*8.4–5 cal kyr BP compared to the last *ca.*5 cal kyr (Roy *et al.*, 2013b). A permanent lake was present in the Chapala basin till *ca.*8.4 cal kyr BP and dune formation commenced post 7.5 cal kyr BP (Davis, 2003). At Purísima-Iray-Magdalena, the dune activity was stabilized and the present lagoon system was developed at *ca.*6–5 kyr BP.

## CONCLUSIONS

Several multi-proxy studies have attempted to reconstruct the late Pleistocene-Holocene paleoecological and paleoclimatic conditions of subtropical Mexico. However, the information is less from the central and southern parts compared to the northern part. Similarly, ostracodes have received limited attention so far compared to the study of sediment geochemistry and palynology. In the present study, we intend to improve the paleoecological information of the central-southern part of subtropical Mexico by studying the abundances and species associations of 4 different ostracode species in combination with TOC and C/N data in sediments deposited over the last *ca.*27 cal kyr BP in the Santiaguillo basin. More specifically;

Ostracode assemblage consists of 4 species (*Limnocythere bradburyi*, *Eucandona cf. patzcuaro*, *Cypridopsis vidua* and *Limnocythere ceriotuberosa*) and the highest (125 valves/g) abundance occurred during the LGM.

During pre-LGM (*ca.*27–23.5 cal kyr BP), the western margin of the basin hosted shallow and oligohaline water body and experienced dominant lacustrine productivity. Changes in the abundances of *C. vidua* and *L. ceriotuberosa* indicated relatively lower salinity at *ca.*27 cal kyr BP compared to *ca.*27–23.5 cal kyr BP.

*L. bradburyi*, *E. patzcuaro* and *C. vidua* suggested presence of warm (>13°C) and more diluted oligohaline water body during the LGM (*ca.*23.5–19 cal kyr BP).

Lower abundance of *E. patzcuaro* and higher C/N ratio reflected a shift in the paleoecological conditions at *ca.*19 cal kyr BP. Both the pluvial discharge into the basin and lacustrine productivity decreased. Higher abundance of *L. bradburyi* suggested that the water column became more saline.

The water body was mesohaline during *ca.*9.5–4 cal kyr BP and the absence of ostracode shells in sediments of last 3.5 cal kyr BP was possibly caused by ephemeral conditions and periodic desiccation.

Comparison with other proxy-records from the region suggests that the paleohydrological and paleoclimatic changes occurred over the last *ca.*27 cal kyr BP in different parts of sub-tropical northern Mexico were not synchronous.

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