Stable isotope values ($\delta^{18}O$ & $\delta^{13}C$) of multiple ostracode species in a large Neotropical lake as indicators of past changes in hydrology

Liseth Pérez a,f,*, Jason Curtis b, Mark Brenner b, David Hodell c, Jaime Escobar d,e, Socorro Lozano a, Antje Schwalb f

a Instituto de Geología, Universidad Nacional Autónoma de México (UNAM), Ciudad Universitaria, 04510 Distrito Federal, Mexico
b Department of Geological Sciences and Land Use and Environmental Change Institute, University of Florida, Gainesville 32611, Florida, USA
c Godwin Laboratory for Palaeoclimatic Research, Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK
d Departamento de Ingeniería Civil y Ambiental, Universidad del Norte, Colombia
e Center for Tropical Paleoclimatology and Archaeology, Smithsonian Tropical Research Institute, Panama
f Institut für Geosysteme und Bioindikation, Technische Universität Braunschweig, Langer Kamp 19c, 38106 Braunschweig, Germany

ARTICLE INFO

Article history:
Received 22 June 2012
Received in revised form 13 October 2012
Accepted 17 October 2012
Available online xxx

Keywords:
Stable isotopes
Auteology
Ostracoda
Neotropics
Late Pleistocene–early Holocene
Environmental change
Lake hydrodynamics
Lake level change

A B S T R A C T

Modern lake hydrodynamics, ostracode species autecology, stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) of multiple ostracode species, ostracode taphonomy and sediment geochemistry were studied to improve interpretation of the late Pleistocene–early Holocene (~24–10 ka) stable isotope record of ostracodes in sediment core PI-6 from Lago Petén Itzá, northern Guatemala. Oxygen and carbon stable isotopes in modern and fossil species assemblages of Lago Petén Itzá were used as indicators of changes in the balance between evaporation and precipitation, past lake level and carbon source. Ostracode taphonomy was used to detect past periods of strong currents, high-energy environments, and possible partial or full mixing of the lake. The modern lake water isotopic composition displays clear seasonal differences that are independent of lake level fluctuations. Modern benthic species displayed lower $\delta^{18}O$ and $\delta^{13}C$ values than nektobenthic species, with differences of 3.0‰ and 5.3‰, respectively. Valves of nektobenthic species display higher values of $\delta^{13}C$ because these ostracodes live in shallower environments among abundant algae and aquatic plants, where productivity is high. The benthic species *Limnocythere opesta* Brehm, 1939 displayed the smallest average offset from $\delta^{18}O$ water (+0.3‰) and the largest offset from $\delta^{13}C_{DIC}$ values (−4.1‰) among studied ostracode species. Nektobenthic species *Heterocypris punctata* Keyser, 1975 displayed the smallest difference relative to the $\delta^{13}C_{DIC}$ values (−0.1‰).

Late Pleistocene–early Holocene climate conditions and water levels in Lago Petén Itzá can be summarized as follows: 1) high lake levels and cold conditions (Last Glacial Maximum [LGM], ~24–19 ka), 2) fluctuating lake levels and cold conditions (Heinrich Stadial 1 [HS1], ~19–15 ka), 3) high lake levels and warm and wetter conditions (Bølling-Allered [BA], ~15–13 ka), 4) low lake levels and dry conditions (Younger Dryas [YD], ~13–11.5 ka) and 5) high lake levels and warm and wetter conditions (early Holocene, ~11.5–10.0 ka). Average lake level fluctuation in Lago Petén Itzá during the late Pleistocene–early Holocene was as much as ~25 m. Ostracode analyses suggest that the LGM was characterized by relatively low $\delta^{18}O$ (+4.7 to +6.0‰), and $\delta^{13}C$ values (~7.1 to −6.4‰) in ostracode valves, high inferred water depths and high percentages of broken adult and juvenile valves (>66%), suggesting a high-energy environment, strong currents, partial to full mixing, downwarp transport, colder water temperatures and wetter conditions. An increase in the relative abundance of the benthic species *L. opesta* and higher numbers of broken valves suggest heavy precipitation events during the LGM (~23.7, 21.7, 20.8 and 20.1 ka). HS1 was predominantly dry, but we identified times when lake levels were slightly higher, at the onset of the deglacial and a brief period (~17–16 ka) between HS1b and HS1a. All studied climate proxies indicate wetter and warmer conditions and lake system stability during the BA. Lake levels dropped during the YD and gradually increased during the Preboreal and early Holocene. We demonstrate that modern and fossil
1. Introduction

Stable isotope analysis of lacustrine ostracode shells is used routinely in paleoenvironmental studies (Lister, 1988; Hodell et al., 1991; von Grafenstein et al., 1992; Holmes, 1996; Schwalb, 2003). There are remote regions, however, where even the modern ostracode fauna remains largely unstudied. For instance, the first detailed taxonomic investigation of the ostracode fauna from 63 aquatic ecosystems on the Yucatán Peninsula (Guatemala, Belize and Mexico) was undertaken in 2005 (Pérez et al., 2011). Nevertheless, previous paleolimnological studies in some waterbodies from the region used the oxygen isotopic signature of ostracode valves to infer past shifts in the ratio of evaporation to precipitation (E/P) (Hodell et al., 1995; Curtis et al., 1996, 1998; Escobar et al., 2012). A firm understanding of the ecology of the local ostracode fauna is necessary for interpreting stratigraphies generated from stable isotope analyses of the calcite valves.

The first studies to use isotopic measurements on lacustrine shell material from the Yucatán Peninsula were carried out by Covich and Stuiver (1974) at Lake Chichancanab, Mexico. They measured δ18O in gastropod shells. Among the records reported from the Yucatan Peninsula were those of Hodell et al. (1995), Curtis et al. (1996, 1998) and Rosenmeier et al. (2002). Hodell et al. (1995) illustrated the great potential of ostracodes as indicators of Holocene climate change, using oxygen isotope signatures in Cyprina vallisalina (Jurine, 1820) and Cyprinotus cf. salinus (Brady, 1868) in sediment cores from Lake Chichancanab.

Recent advances in lake drilling technologies (Dean, 2010) enabled recovery in 2006 of high-quality, long sediment cores from the deepest (∼160 m) and possibly the oldest (∼200 ka, Mueller et al., 2010) lake in the northern lowland Neotropics, Lago Petén Itzá, Guatemala. This sediment record is probably unique in the region. Initial paleoenvironmental inferences used sedimentology (Mueller et al., 2010), geochemistry (Hodell et al., 2008), relative abundances of ostracode taxa with known ecological preferences, ostracode-based water depth and conductivity transfer functions (Pérez et al., 2011), and the stable isotope signature of shells from the ostracode Limnothene opes (Escobar et al., 2012). The latter study focused on the paleoclimate of northern Guatemala rather than past lake hydrology per se. Few studies in the Neotropics have used modern lake hydrodynamics and related environmental variables, i.e. calibration, to interpret fossil stable isotope records. Escobar et al. (2012) interpreted the δ18O record as a response to fluctuating E/P and temperature. Interpretation of shifts in carbon isotope values is more complicated. The authors used fluctuations in the δ13C of ostracode shells as an indicator of the position of the thermocline, and speculated that such variations are controlled by the nature of organic carbon delivered to the sediment. Elsewhere, investigators have used carbon stable isotopes in ostracode shells to infer past catchment vegetation, modes of organic decay, origin of CO2 and lake productivity (Schwalb, 2003; Bright et al., 2006). δ13C of ostracode shells in Lago Petén Itzá might serve as an indicator of productivity and/or sources of carbon in the sediment. There is great potential for using other, unstudied proxies for paleoenvironmental conditions in this lake, such as chironomids and diatoms. Other ostracode attributes (taphonomy), used in conjunction with stable isotopes, can provide more information for better interpretation of the isotopic record in carbonate fossils. For instance, ostracode taphonomy and valve preservation shed light on the energy of the environment and sediment conditions, and can be used to reconstruct past lake levels or determine past water-column circulation patterns (Park et al., 2003: Park and Cohen, 2011).

Paleolimnological studies carried out in the northern Neotropics generally measured stable isotopes in a single ostracode taxon to avoid vital effects. When this was not possible, several species from different sediment depths, and in some cases parallel cores, were used to obtain a continuous record. Vital effects should be evaluated by comparing isotope values from multiple species collected at the same sediment depth (this study). Recent studies highlighted the influence of species autecology and environmental factors on ostracode stable isotope values (von Grafenstein et al., 1999; Decoury et al., 2011; Van der Meer et al., 2011). Such information from remote areas is often missing. Pérez et al. (2010a, 2010b) provided the first autecological information for modern ostracode species of Lago Petén Itzá, the lowlands and highlands of Guatemala (2012) and the Yucatán Peninsula and surrounding areas (2011). Modern stable isotope analyses of ostracodes are important for calibrating paleoclimatic and paleolimnological reconstructions, however, such analyses were still lacking prior to this study.

In summary, few studies have used modern lake hydrodynamics and ostracode species autecology and stable isotopes in paleoenvironmental and paleoclimate reconstructions. This study aims to improve the knowledge of ostracode species autecology, the isotopic composition of modern and fossil ostracodes and present- and late Pleistocene—early Holocene lake hydrodynamics of Lago Petén Itzá. Here we used 1) autecological information for eight extant ostracode species in Lago Petén Itzá, 2) oxygen and carbon isotope values for modern ostracode species collected across a N–S water depth transect (0–160 m), 3) isotope composition of fossil waters and related environmental variables determined during summer and winter, 4) isotope values in fossil ostracode assemblages (Last Glacial Maximum [LGM]—early Holocene) of Lago Petén Itzá, 5) complementary ostracode information (taphonomy, inferred water depth), as well as geochemical analysis, to improve previous paleoenvironmental reconstructions and to infer past lake hydrodynamics during the late Pleistocene to early Holocene.

2. Study area

Lago Petén Itzá is located in the Central Petén Lake District, northern Guatemala, on the southern Yucatán Peninsula (Fig. 1). Nearby waterbodies include Lakes Salpetén, Quexil, Sacnab, Yaxhá and Perdida, among others (Brenner et al., 2002). It is the deepest (Zmax > 160 m) and one of the largest lakes (~112 km2) in the karst lowland Neotropics (~110 m asl). The lake is oligo-mesotrophic and population growth around the lake is changing its trophic state, at least in some locations (Rosenmeier et al., 2004; Pérez et al., 2010c). Surface waters of the large north basin, however, display a total phosphorus concentration of only 9 μg L−1 and transparency is relatively high (Secchi disk ~ 7.5 m). Lago Petén Itzá waters are dominated by calcium, magnesium, bicarbonate and sulfate (Pérez et al., 2010b).

The thermocline is located between 20 and 40 m during the warm period of the year, but appears to nearly break down during the colder winter months. Average monthly air temperature ranges...
from 23.8 to 27.7 °C and the annual average relative humidity is 67.3% (Pérez et al., 2010b). Average annual precipitation in Petén is ~1665 mm. Two main seasons characterize northern Guatemala, a rainy season from June to October and a dry season from January to May. Modest rainfall occurs during November and December. Rainfall in the region is mainly controlled by the Azores-Bermuda high-pressure system and the seasonal migration of the Intertropical Convergence Zone (ITCZ). The ITCZ is found farthest northward in the summer rainy season and farthest southward during the dry season, when the Azores-Bermuda high in the Gulf of Mexico and the Caribbean dominate (Hastenrath, 1991).

Lago Petén Itzá is an appropriate water body for study of lake hydrodynamics because it lacks surface inflows or outflows, making it sensitive to changes in the ratio of evaporation to precipitation. Such closed-basin lakes respond faster to changes in the ratio of evaporation to precipitation than do open systems. In years 1938, the early 1990s and 2008 precipitation. Such closed-basin lakes respond faster to changes in the ratio of evaporation to precipitation, making it sensitive to changes in the ratio of evaporation to precipitation (Holmes and Chivas, 2002). All ostracode valves for isotope analysis were soaked in 15% H₂O₂ for 15 min to remove organic material, 2) rinsed with distilled water and then with methanol and 3) dried in an oven at 60 °C overnight. If valves were not completely clean after the procedure, fine brushes were used to remove remaining sediments or other impurities. The number of valves used for each measurement depended on the species. Average adult valve weights were as

3. Materials and methods

3.1. Field methods

Surface sediment samples (n = 27) for ostracode analysis (species assemblages and stable isotopes) were collected along a N–S transect in Lago Petén Itzá in November 2005, and February and March 2008, extending from the littoral zone to a maximum water depth of ~160 m (Fig. 1). Environmental variables temperature, pH, conductivity, dissolved oxygen and alkalinity as well as the water chemical (SO₄, Cl, Ca, Mg, Na, K) and isotopic composition (δ¹⁸O, δ¹³C) were determined throughout the water column above the lake’s deepest point. Further information on field methods is found in Pérez et al. (2010b, 2011). Long core PI-6, taken in ~71 m of water (Fig. 1), was retrieved in 2006 by the Petén Itzá Scientific Drilling Project (PISDP). For further information regarding core recovery, see Mueller et al. (2010) and Pérez et al. (2011).

3.2. Laboratory methods

3.2.1. Modern ostracodes

Ostracodes were extracted from 50-ml, wet surface sediment samples by sieving samples with a 63-μm mesh and using a Leica MZ 7.5 stereo microscope and fine brushes. At least 100 ostracode valves were removed from each sample, including adults and juveniles as well as ostracodes with well preserved soft parts (living) and specimens without soft parts (dead). Ostracode carapaces with soft parts were used for identification to species level. If valves of living ostracodes were found in sediment, only such valves were used for isotope analysis. If such valves were scarce, but present, valves of both living and dead ostracodes were analyzed. Ostracode identification followed Furtos (1933, 1936a, 1936b), Brehm (1939), Ferguson et al. (1964), Keysor (1976, 1977) and Pérez et al. (2010a, 2012). Autecological information for ostracode species in Lago Petén Itzá was taken from Pérez et al. (2010a, 2010b).

3.2.2. Fossil ostracodes (LGM—early Holocene)

Samples of 1-cm thickness were taken for fossil ostracode analysis primarily at 20-cm intervals from LGM—early Holocene sediments in long sediment core PI-6. LGM sediments contained lower numbers of ostracode valves and counts had to be made on 5 g dry sediment aliquots. Long-core sediment samples were wet-sieved using a 63-μm mesh. Ostracodes were extracted, identified and enumerated with respect to numbers per g dry sediment. Adult and juvenile intact and broken valves were differentiated. Broken valves were counted if >50% was encountered and when identification was still possible. Details of fossil ostracode analysis can be found in Pérez et al. (2011).

3.2.3. Measurement of stable isotopes in lake waters

Water samples for stable isotope analysis were preserved in the field with CuSO₄ (500 mg L⁻¹) and analyzed in the Department of Geological Sciences, University of Florida. Samples were analyzed using a VG/Micromass PRISM Series II isotope ratio mass spectrometer with a multi-prep preparation device (oxygen isotopes of water) and a Finningan-MAT DeltaPlus XL isotope ratio mass spectrometer with a GasBench II universal on-line gas preparation device (carbon isotopes of DIC).

3.2.4. Measurement of stable isotopes in ostracode carbonates

Only modern and fossil ostracode valves without evidence of alteration, i.e. dissolution or development of calcite overgrowth, were selected for oxygen and carbon isotope analysis. This was done to avoid diagenetic effects on measured values (Holmes and Chivas, 2002). All ostracode valves for isotope analysis were 1) soaked in 15% H₂O₂ for 15 min to remove organic material, 2) rinsed with distilled water and then with methanol and 3) dried in an oven at 50 °C overnight. If valves were not completely clean after the procedure, fine brushes were used to remove remaining sediments or other impurities. The number of valves used for each measurement depended on the species. Average adult valve weights were as
A weak late fall—winter thermocline (November—February) was determined at the lake's deepest point. During late spring—summer (May—August), however, the position of the thermocline at the shallower San Andrés station varied, with the top of the metalimnion as shallow as 5 m and the bottom of the metalimnion as deep as 30 m. Lake thermal stratification is more stable during summer months than during November—February. In November 2005, water at 20 m depth was slightly warmer than overlying waters, perhaps reflecting loss of heat from surface waters and the onset of thermocline breakdown.

4.2. Environmental variables and isotopic composition of lake waters

Fig. 3 displays variables in a water column profile from Lago Petén Itzá, including dissolved oxygen concentration, dissolved inorganic carbon (DIC), chlorophyll a and total phosphorus plotted with the stable oxygen and carbon isotopes. Dissolved oxygen profiles from November 2005 and February 2008 overlie one another. Values were near saturation in surface waters, declined through the thermocline and displayed hypoxia in the lower half of the water column, $^{18}$O$_{SMOW}$ in waters were slightly more positive in February 2008 than in August 2002, but overall there was little vertical or inter-annual variation, with all values between +2.7 and +3.4. $^{13}$C$_{DIC}$ values in February 2008 were between −5.1 and −0.1‰, and the hypolimnion displayed more negative values. DIC values in February 2008 ranged from 1.3 to 8.7 mg L$^{-1}$. Chlorophyll a concentrations in summer were consistently low throughout the vertical profile ($<0.25$ µg L$^{-1}$), but displayed a small peak (1.17 µg L$^{-1}$) at ~42.8 m water depth, just below the base of the thermocline. The top 20 m displayed concentrations ranging from only 0.11 to 0.25 µg L$^{-1}$. Total phosphorus ranged from 6 to 21 µg L$^{-1}$. The highest concentration in the epilimnion was 11 µg L$^{-1}$, whereas the highest value in the hypolimnion was 21 µg L$^{-1}$. In February 2008, $^{18}$O and $^{13}$C were positively correlated with oxygen concentration, temperature, pH and chlorophyll a (r values > 0.5) and the two isotopes were highly correlated with one another (r = 0.98, Table 1). Temperature, pH and dissolved oxygen displayed high correlations with one another as well (r ≥ 0.88).

4.3. Ostracode autecology

Table 2 contains a list of the ostracode taxa that have inhabited Lago Petén Itzá since the late Pleistocene, along with autecological information for each taxon. Candonocypris serratamarginata (Furtos, 1936), Cypretta sp. and Stenocypris major (Baird, 1859) were excluded because we lacked sufficient material for stable isotope analyses. Eight species were collected in modern surface sediments of Lago Petén Itzá, five of which were also found in sediments deposited during the LGM and seven of which were also found in deposits of the deglacial to early Holocene.

4.4. Stable isotope values in modern ostracodes from the N–S water-depth transect

Ostracodes found in Lago Petén Itzá from 0 to 60 m water depth displayed $^{18}$O values from +0.1 to +3.5‰, during winter (Figs. 4 and 5). Highest values were determined in shells of bentic Pseudocandona sp. (+1.3 to +3.5‰), the nektobenthic species C. okeechobei Furtos, 1936 (+1.2 to +3.0‰) and in shells of benthic D. stenvoni Brady & Robertson, 1870 (+1.6 to +1.9‰). Limnothamnocypris punctata, a bentic species, displayed the lowest $^{18}$O values at all sampled water depths, except 15 m. Oxygen isotope values of L. opesta varied from +0.1 to +1.7‰. Similar to L. opesta, C. illosayi Daday, 1905 displayed lower values than other ostracode species, but we only used measurements in valves collected from each species water-depth range (tolerance) for interpretation. Water depth ranges of species were taken from Pérez et al. (2010b) and ranged from 0 to 60 m. We used the equation of Kim and O’Neil (1997) to determine the oxygen isotopic composition of calcite precipitated under equilibrium conditions in lake waters.
with $^{18}$O values ranging from $+0.4$ to $+1.5\%_{\text{avr}}$. The $\delta^{18}$O values of the nektobenthic species $P. globula$ Furtos, 1933 were slightly more positive and varied from $+1.1$ to $+1.9\%_{\text{avr}}$. Heterocypris punctata, a littoral ostracode species, displayed a value of $+1.4\%_{\text{avr}}$. Of all ostracode taxa, $L. opesta$ displayed $\delta^{18}$O values closest to the equilibrium $\delta^{18}$Ocalcite value, with an offset ranging from $+0.03$ to $+1.1\%_{\text{avr}}$ across the water depth transect. Pseudocandona sp. displayed the largest offset, ranging from $+1.0$ to $+2.9\%_{\text{avr}}$. Offsets for the other ostracode species were as follows: $C. ilosvayi$ ($+0.1$ to $+1.0\%_{\text{avr}}$), $P. globula$ ($+0.7$ to $+1.0\%_{\text{avr}}$), Strandesia intrepidia Furtos, 1936 ($+0.6$ to $+1.7\%_{\text{avr}}$), $C. okeechobei$ ($+0.9$ to $+2.4\%_{\text{avr}}$), $H. punctata$ ($+1.0\%_{\text{avr}}$), and $D. stevensoni$ ($+1.2$ to $+1.4\%_{\text{avr}}$).

Ostracode $\delta^{13}$C values across the N–S water depth transect ranged from $-6.3$ to $-1.0\%_{\text{avr}}$, a broader range than found for $\delta^{18}$O values (Fig. 4). Nektobenthic species $C. okeechobei$, $H. punctata$ and $S. intrepidia$ generally displayed the highest $\delta^{13}$C values. Values in shells of $C. okeechobei$ and $S. intrepidia$ ranged from $-3.4$ to $-1.0\%_{\text{avr}}$ and from $-1.7$ to $-1.4\%_{\text{avr}}$, respectively. Heterocypris punctata displayed $\delta^{13}$C values of $-1.4\%_{\text{avr}}$ at a water depth of 0.1 m. Physocypria globula, another nektobenthic species, but one that prefers deeper waters, displayed more negative values ($-5.4$ to $-2.5\%_{\text{avr}}$). Benthic species displayed more negative values than nektobenthic species. Carbon isotopic composition of $C. ilosvayi$ ranged from $-5.2$ to $-2.1\%_{\text{avr}}$ and those of $D. stevensoni$ ranged from $-4.6$ to $-3.4\%_{\text{avr}}$. Benthic species $L. opesta$ and Pseudocandona sp. displayed the most negative values among all species, with values ranging from $-6.3$ to $-2.9\%_{\text{avr}}$ and from $-6.1$ to $-2.2\%_{\text{avr}}$, respectively.
Ostracode δ¹³C values were compared with the δ¹³CDIC of lake waters (Fig. 4). Nektobenthic species displayed smaller differences than did benthic species (C. okeechobei [−3.3 to −0.02‰], S. intrepida [−1.5 to −0.1‰], H. punctata [−0.1‰], except for P. globula, which displayed offsets similar to those of benthic species (−5.3 to −1.2‰). Benthic species L. opesta displayed the largest difference (−6.2 to −2.7‰), followed by Pseudocandona sp. (−6.1 to −10.0‰), D. stevensoni (−5.4 to −2.1‰) and C. ilosvayi (−5.0 to −1.7‰).

Fig. 5 shows a cross plot of the oxygen and carbon isotope values of ostracode valves collected across the N–S water depth transect in Lago Petén Itzá. Nektobenthic species are easily distinguished from those of benthic species (−5.3 to −12.2‰). Benthic species L. opesta displayed the lowest δ¹³O and δ¹³C values among all ostracode species, whereas C. okeechobei displayed the highest values.

4.5. Fossil ostracode assemblages in sediment core PI-6

Cytheridella ilosvayi was the only species analyzed for stable isotopes that was absent in late Pleistocene sediments (Table 2).

![Graph of environmental variables](image)

**Fig. 3.** Main environmental variables of ostracode host waters determined during August 2002, November 2005 and February 2008 at Lago Petén Itzá’s deepest point. Dashed lines indicate previously published data. August data (green) are from Hillesheim et al. (2005), and November 2005 (light blue) and February 2008 (dark blue) data are from Pérez et al. (2010b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Unit III in core PI-6 (LGM, 24–19 ka) was characterized by the presence of benthic species D. stevensoni, L. opesta and Pseudocandona sp., and nektobenthic species P. globula and C. okeechobei (Fig. 6). Nektobenthic species were more common during Unit II (deglacial–early Holocene, ~19–10 ka). They included C. okeechobei, H. punctata, P. globula and S. intrepida. Three benthic ostracode species, D. stevensoni, L. opesta and Pseudocandona sp., were found in these sediments. Limnocythere opesta and P. globula dominated late Pleistocene species assemblages. Few or no valves of P. globula were found from ~13 to 11 cal ka BP (subunit I, Younger Dryas [YD]), whereas this species was very abundant (up to 6114 valves g⁻¹) from ~15 to 13 cal ka BP (subunit II, Bolling-Allerød [BA]).

Total numbers of adult valves were lower during Unit III (~396 g⁻¹) than during Unit II (~6479 g⁻¹). Juveniles of P. globula exceeded the number of adults, whereas the number of adult L. opesta was sometimes much greater than the number of juveniles. A high number of broken adult and juvenile valves characterized Unit III. Higher numbers of valves were found in gypsum-rich deposits (subunits V, Heinrich Stadial b [HS1b], III Heinrich Stadial a [HS1a] and I, YD, Fig. 6) and during subunit II (BA). The highest numbers of broken adult (~2646 valves g⁻¹) and juvenile (~7409 valves g⁻¹) valves during the deglacial were encountered at 14.6, 13.6–13.4 and at 10.4–10.7 cal ka BP. For all ostracode species, numbers of juvenile valves exceeded adult valves. This was generally the case for all sediment samples, except those marked with an asterisk in Fig. 6.

4.6. Geochemical proxies and ostracode taphonomy

![Graph of geochemical proxies](image)

**Fig. 7.** shows the relative abundance of L. opesta, magnetic susceptibility, total sulfur (i.e. gypsum), C/N ratio and percent broken adult and juvenile ostracode valves. Fluctuations in relative abundance of L. opesta are inversely related to shifts in magnetic susceptibility. Relatively greater magnetic susceptibility (<80 SI*E⁻⁶) was
measured in unit III, subunit IV and II. Greater concentrations of total sulfur (TS < 20%) and C/N ratios (< 40) characterize subunits V, III and I. Percentages of broken adult and juvenile valves were high (> 66% and > 39%, respectively) in unit III but low during subunit II and at the end of unit II (< 41% and < 33%). Highest percentages of broken adult and juvenile valves were typical of subunits V, III and I. High percentages of broken ostracode valves characterized the beginning of subunit V and end of subunit III.

Table 2
Overview and ecology of the ostracode fauna of Lago Petén Itzá, Guatemala since the late Pleistocene.

<table>
<thead>
<tr>
<th>Species</th>
<th>SEM</th>
<th>Modern lake&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Deglacial–early Holocene</th>
<th>LGM Life style</th>
<th>Depth range (m)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Autecology&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cypridopsis okeechobei</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>NB</td>
<td>≤ 40</td>
<td>Prefers littoral zones with rich vegetation.</td>
</tr>
<tr>
<td>Cytheridella ilosvayi</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>B</td>
<td>≤ 40</td>
<td>Prefers warm shallow waters (&gt; 20 °C), tolerates high conductivities (up to 5960 µS cm&lt;sup&gt;−1&lt;/sup&gt;) and sulfate concentrations (2300 mg L&lt;sup&gt;−1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>Darwinula stevensoni</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>B</td>
<td>≤ 15</td>
<td>Prefers shallow waters, slow currents, can tolerate high salinities (13.5&lt;sub&gt;‰&lt;/sub&gt;).</td>
</tr>
<tr>
<td>Heterocypris punctata</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>NB</td>
<td>≤ 1</td>
<td>Prefers littoral zones with abundant macrophytes, calm water and tolerates salinities of up to 10&lt;sub&gt;‰&lt;/sub&gt;.</td>
</tr>
<tr>
<td>Limnocythere opesta</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>B</td>
<td>&lt; 40</td>
<td>Marks the thermocline, abundant in littoral zones with abundant macrophytes. Tolerates high conductivities and sulfate concentrations.</td>
</tr>
<tr>
<td>Physocypria globula</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>NB</td>
<td>&lt; 50–60</td>
<td>Displays high tolerance, prefers deep waters, can tolerate water with low dissolved oxygen (~ 3 mg L&lt;sup&gt;−1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>Pseudocandona sp.</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>B</td>
<td>&lt; 40</td>
<td>Prefers shallow water (&lt; 15 m), prefers sediments with high organic content.</td>
</tr>
<tr>
<td>Strandesia intrepidá</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>NB</td>
<td>&lt; 15</td>
<td>Prefers shallow, well-oxygenated warm waters.</td>
</tr>
</tbody>
</table>

Abbreviations: Nektobenthic (NB), Benthic (B).
* Information from Pérez et al. (2010b, 2010c).
4.7. Water depth transfer function

Fig. 7 displays the inferred past water depth in Lago Petén Itzá. Here we show the average water depths. The water depth reconstruction suggests that lake stage at the core site during unit III averaged 26 m, and during subunits V, IV, III, II, I of Unit II, lake level averaged 24, 31, 10, 40, 4 and 58 m, respectively. Highest lake levels were inferred for subunits II and I, and lowest lake levels occurred in subunits V, III and I (Fig. 7). The improved transfer function, using the WA-PLS model, has an $r^2$ of 0.74 and a RMSE of only 9 m after excluding ostracode samples from waters deeper than 60 m, where ostracodes are scarce or absent.

4.8. Late Pleistocene ostracode stable isotope record

Fig. 8 displays the late Pleistocene--early Holocene oxygen and carbon isotope records developed using multiple ostracode taxa. Oxygen and carbon isotope values uncorrected for vital effect fluctuated between $+3.1$ and $+7.3\permil$, and from $-8.1$ to $+3.7\permil$ respectively. Highest $\delta^{18}O$ and $\delta^{13}C$ values were determined in valves of $H. punctata$. Nektobenthic species $H. punctata$ and $C. okeechobei$ ($+2.6\permil$) displayed higher $\delta^{13}C$ values than other species. Generally, $L. opesta$ and $P. globula$ showed more positive $\delta^{18}O$ values ($\leq -7.2\permil$ and $+6.9\permil$ respectively) than other ostracode species. In deposits corresponding to the LGM, we found sufficient ostracode valves for measurement in only two sediment samples. The $\delta^{18}O$ values ranged from $+5.12$ to $+5.3\permil$, and $\delta^{13}C$ values from $-7.1$ to $-6.4\permil$. $\delta^{18}O$ values display variability between $-19$ and $15$ ka BP. HS1b and HS1a are characterized by high $\delta^{18}O$ values, up to $+6.9\permil$ ($P. globula$) and $+7.3\permil$ ($H. punctata$), respectively. Between HS1b and HS1a, values decrease to $+4.9\permil$ ($P. globula$), however slightly higher $\delta^{18}O$ values of $+6.4\permil$ ($L. opesta$) were determined at $\sim 16.6$ cal ka BP. $\delta^{13}C$ from early HS1b to late HS1a shows an upward trend, from $-8.1$ to $+3.7\permil$. Highest $\delta^{13}C$ values in HS1b and HS1a were reported for $H. punctata$. The BA is characterized by lower $\delta^{18}O$ and $\delta^{13}C$ values in $L. opesta$ ($+3.8\permil$ and $+5.9\permil$) and $P. globula$ ($+3.8\permil$ and $-5.7\permil$). Stable isotope values increase after the BA and $\delta^{18}O$ values in $L. opesta$ range from $+5.2$ to $+5.7\permil$ and $\delta^{13}C$ from $-1.9$ to $-0.2\permil$ during the YD. At $\sim 11.7$ cal ka BP values start to decrease.

Fig. 9 displays $\delta^{18}O$ and $\delta^{13}C$ values for valves of multiple ostracode species in long core PI-6. Isotope values for periods of high and low lake level, as well as for periods of wetter and drier conditions during the late Pleistocene--early Holocene are displayed. The LGM, early deglacial and early Holocene were characterized by $\delta^{13}C$ values between $-8.0$ and $-6.3\permil$, and $\delta^{18}O$ values between $+3.1$ and $+6.1\permil$. Relatively high $\delta^{18}O$ values, from $+5.1$ to $+5.3\permil$, are typical of valves from the LGM, whereas
18O values from +3.10 to +3.6‰ characterized valves deposited in the early Holocene. Valves from the BA displayed less negative 13C values (−5.9 to −3.4‰) than those from the LGM, early deglacial and early Holocene. In general, greater δ18O (≥+5.0‰) and δ13C (≥−3.0‰) values were measured when lake levels were low.

Fig. 5. Cross plot of δ18O and δ13C values in modern ostracode valves from eight nektobenthic and benthic ostracodes species living in Lago Petén Itzá. Nektobenthic species, except for Physocypria globula, generally displayed higher stable isotope values (oxygen and carbon) than benthic species.

δ18O values from +3.10 to +3.6‰ characterized valves deposited in the early Holocene. Valves from the BA displayed less negative δ13C values (−5.9 to −3.4‰) than those from the LGM, early deglacial and early Holocene. In general, greater δ18O (≥+5.0‰) and δ13C (≥−3.0‰) values were measured when lake levels were low.

5. Discussion

5.1. Modern lake hydrodynamics

Paleolimnological reconstructions are more robust when modern lake dynamics are well understood. Here we present limnological variables in Lago Petén Itzá, which provide information about the position of the thermocline during the rainy (summer) and dry (winter) seasons, and report data on dissolved oxygen, δ18O, δ13C, dissolved inorganic carbon, chlorophyll a and total phosphorus, which can be used as indicators of lake productivity and the balance between precipitation and evaporation.

Lake surface waters reach a maximum temperature (32 °C) in May, but temperatures begin to decrease with the onset of summer rains (Fig. 2). Coldest surface water temperature (27.7 °C) was reported in August 1980. Lake water temperatures, however, can differ year-to-year, because of changes in solar radiation (e.g. cloud cover), duration of the rainy season, and climate change (Cohen, 2003). For instance, surface temperature in August 2002 was 30 °C.

Temperature measurements in summer 2002 (August) indicated the thermocline was between 20 and 40 m. Thermal data collected in 1980 from a station near the town of San Andrés indicate the summer thermocline position was shallower, between 5 and ~30 m water depth. Temperature profiles in summer months, especially August, show a well-defined epilimnion and hypolimnion. Whereas the change in temperature across the thermocline in August 2002 was not great (<5 °C), the density difference at such high temperatures is evidently sufficient to impart stable thermal stratification. The winter profile, on the other hand, shows only about 2 °C difference between surface and deep waters. This small temperature difference, coupled with strong nortes, strong cold northeasterly winds along the Gulf of Mexico, can lead to winter mixing. This probably explains the lower temperatures from 10 to 20 m in the November vertical profile (Fig. 2). With the onset of winter, surface waters begin to cool, particularly at night, and because they possess greater density than...
the underlying strata, they begin to stream downward. On the day we sampled, there had probably been some warming and wind mixing of the uppermost water column, but the profile certainly reflects the breakdown of thermal stratification.

In November 2005, oxygen concentrations remained constant throughout the top 10 m (8.9 mg L\(^{-1}\)), and reflect slight supersaturation, despite low chlorophyll \(a\) concentrations. \(^{13}\)C\textsubscript{DIC} values in the epilimnion were slightly more positive than in the hypolimnion in February 2008. Basterrechea (1988) defined the circulation pattern of Lago Petén Itzá as warm monomictic, and indicated that weak mixing takes place during winter. High-temporal-resolution sampling of the Lago Petén Itzará water column should be carried out over several years to determine if circulation is complete and exactly when it occurs.

### Fig. 7.
Ostracode-inferred water depth and modern lake level (vertical line) at core site, relative abundance of Limnocythere opesta (LOP rel Ab.), geochemical proxies and ostracode taphonomic proxies (adult broken valves (ABV), and juvenile broken valves (JBV)) during the late Pleistocene—early Holocene in Lago Petén Itzá, Guatemala. Lithological units are in Mueller et al. (2010). Magnetic susceptibility reflects lithologic changes in long core PI-6 during the LGM and deglacial—early Holocene. High total sulfur (TS) and C/N ratios indicate low lake levels and dry climate conditions. White bars indicate sections where no ostracodes were found. Cold conditions are indicated with blue and warmer conditions with red. The dashed lines indicate previously published data. Magnetic susceptibility data are from Mueller et al. (2010) and the abundance of \(L.\) opesta, TS concentrations and C/N ratios are from Pérez et al. (2010b). Abbreviations: Last Glacial Maximum (LGM), Heinrich Stadial 1 (HS1), Bølling-Allerød (BA), Younger Dryas (YD). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

<table>
<thead>
<tr>
<th>Water depth (m)</th>
<th>LOP rel. Ab. (%)</th>
<th>Mag. Susceptibility (SI\textsuperscript{1E-08})</th>
<th>TS (%)</th>
<th>C/N ratio</th>
<th>% ABV</th>
<th>% JBV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Fig. 8.
Late Pleistocene—early Holocene stable isotope record of multiple ostracode species. Lines with symbols show the \(^{18}\)O and \(^{13}\)C values of Limnocythere opesta, Physocypria globula, Cypridopsis okeechobei, Heterocypris punctata. Lower values characterized periods with high lake levels such as the LGM, BA and the early Holocene. The HS1 and YD were drier, lake levels were lower in Lago Petén Itzá, and \(^{18}\)O and \(^{13}\)C were higher. Cold conditions are indicated with blue and warmer conditions with red. Blue dashed line shows stable isotopes determined at a higher resolution by Escobar et al. (2012). Abbreviations: Last Glacial Maximum (LGM), Heinrich Stadial 1 (HS1), Bølling-Allerød (BA), Younger Dryas (YD). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article in press as: Pérez, L., et al., Stable isotope values (\(^{18}\)O & \(^{13}\)C) of multiple ostracode species in a large Neotropical lake as indicators of past changes in hydrology, Quaternary Science Reviews (2012), http://dx.doi.org/10.1016/j.quascirev.2012.10.044
We only have measurements of lake water $\delta^{13}$C for February 2008, but we suspect that the difference between values in winter and summer are much larger than for $\delta^{18}$O values (\(\sim -0.4\%_\text{w} \)), which should be taken into account when interpreting the fossil ostracode isotope record. It should be easy to identify fluctuations in the fossil $\delta^{13}$C profile of ostracodes. $\delta^{18}$O values mainly indicate wet and dry periods (high and low lake levels), whereas $\delta^{13}$C values provide information on primary productivity and carbon sources to the sediment. Low total phosphorus concentration in Lago Petén Itzá suggests low productivity in the lake. Higher TP values in deeper waters probably reflect the presence of seston descending through the water column, but might also reflect presence of zooplankton or non-photosynthetic bacteria at greater depths. Chlorophyll a was measured only in August 2002. Concentrations are low in the epilimnion, near zero in the metalimnetic boundary, at \(\sim 43 \text{ m} \). It was necessary to understand how environmental variables correlate with oxygen and carbon stable isotopes in modern lake waters of Lago Petén Itzá to infer paleohydrology and lake level changes from stable isotope signatures recorded in multiple ostracode species in the lake (Table 1). This was done to discern which limnological variables should be taken into account when interpreting the oxygen and carbon stable isotopes in fossil ostracode shells. February 2008 data suggest that $\delta^{18}$O and $\delta^{13}$C in the water column are positively correlated with dissolved oxygen, temperature and pH. Variations in the $\delta^{18}$O values in the epilimnion might be explained by changes in E/P. Higher evaporation could explain more positive $\delta^{18}$O values measured in February 2008. The weighted mean oxygen isotopic composition of precipitation in the region is \(-4.0\%_\text{w} \) (Hillesheim et al., 2005), which could explain lower $\delta^{18}$O values in lake surface water during the rainy season. The fact that $\delta^{13}$C values are positively correlated with dissolved oxygen and pH in February probably reflects several processes: 1) oxygen concentration is higher in the epilimnion as a consequence of primary production, but declines in deeper waters of the tropholytic zone, 2) pH is higher in upper waters as a consequence of CO2 withdrawal for photosynthesis, but is greater in bottom waters, where intense respiration prevails, and 3) DIC of bottom waters is dominated by light carbon from microbial breakdown of organic matter with relatively negative $\delta^{13}$C values. $\delta^{13}$C values, concentration of dissolved oxygen and pH in upper waters of Lago Petén Itzá were slightly higher than in hypolimnetic waters, reflecting productivity in the epilimnion.

5.2. Modern isotopic composition and autecology of ostracode species

Clear differences between the oxygen and carbon isotopic composition of the studied ostracode species in Lago Petén Itzá can be seen in Fig. 5. Stable isotopes were determined mainly in valves of living ostracodes, e.g. ostracodes with well-preserved soft parts. Such isotopic values reflect the isotopic composition of the lake water when they were living. Nektobenthic species display more positive $\delta^{13}$C values and lower $\delta^{18}$O values than do benthic species, at least during winter. The benthic species L. opesta displayed the most negative $\delta^{18}$O values and the lowest offset from expected equilibrium values among ostracode species. This might be expected for a benthic species that
lives on the bottom of the lake, unaffected by evaporation and
temperature shifts in the epilimnion. We could not compare our
Limnothryre data with data from other waterbodies in the northern
Neotropics because such information is lacking, analyses were run
on ostracode valves of other species, or multiple species were
not analyzed in other studies. von Grafenstein et al. (1999) studied
the stable isotopic values of multiple ostracode species in Lakes
Ammersee and Sarnberger See, southern Germany. They found that
Limnothryre inopinata and D. stevensoni were the ostracode species
with the smallest offset (−0.8‰) from equilibrium δ18Ocal, whereas
species of the Candonia group displayed higher offsets
(≤2‰). L. oesta was the ostracode species in our study with the
largest offset relative to δ13Cdic. The average δ13C offset was,
however, much larger (−4.0‰) than that for δ18O (+0.3‰).

Similar to L. oesta, C. ilosvayi is a benthic species and displays
only slightly more positive δ18O values, reflecting the fact that both
species live at similar water depths (<40 m) and temperatures, δ13C
values of L. oesta, however, are much more negative than those of
C. ilosvayi. This might suggest that L. oesta is an infaunal species
that builds its shell from relatively negative DIC from the interstitial
waters. The more positive values of C. ilosvayi and D. stevensoni
suggest they may live above the sediment surface (epifaunal). In
addition, the influence that the microhabitat has on δ18O values of
ostracode valves, vital effects (metabolic differences) may play an
important role as well.

Physocypris globula was the only species found living down to
a water depth of 60 m. δ18O values of P. globula fluctuate little along
the N–S water depth transect (1.1 to 1.9‰), whereas δ13C varied
from −5.4 to −2.5‰, probably suggesting that this species mollusks
in a specific water depth or water depth range. The vertical
δ18Ocal,δ18Osw,δ13C profile at the deepest point of Lago Petén Itzá varied
little compared to the δ13Cdic profile. Physocypris globula is a nekto-
benthic species that lives in the littoral zone and in the water column.
Previous studies revealed that this species prefers deeper waters,
~50–60 m (Pérez et al., 2011), because it tolerates waters
with low concentrations of dissolved oxygen (Curry and Filippelli,
2010). Its broad tolerance with respect to a combination of envi-
ronmental variables explains why it displays more positive δ13C
values in shallower water where productivity is high and lake waters
are 13C-enriched, and why it displays more negative values in
deepers waters, where there is decay of organic matter.

The nektobenthic species H. punctata was found only in waters
<1 m deep. This suggests that it is restricted to littoral zones. It
might therefore be expected to display more positive δ18O because
shallow waters are more affected by evaporation. However, this
littoral nektobenthic species displayed δ18O values slightly lower
(+1.4‰) than the benthic species Pseudocandona sp. (+1.5‰). These
results are similar to those of Bridgwater et al. (1999) for Lake
Pátzcuaro, central México. That study reported lower δ18O values
for H. punctata than for the benthic species Candona patzcuaro.
Bridgwater et al. explained this difference as a consequence of the
species occupying different micro-habitats. They suggested that
reduced mixing of the water column restricted transport of fresh-
water with low δ18O ratio, into the bottom waters. Warming of the
shallow littoral zone down to the surface sediments and the fact
that species belonging to Candoniidae generally prefer the phyal
zone (Meisch, 2000) might account for the small difference between
δ18O values of H. punctata and Candona sp. Cypridopsis okeechobei,
S. intrepidu and Pseudocandona sp. displayed the highest δ18O values
among ostracode species (<3.5‰) in Lago Petén Itzá. Cypridopsis okeechobei and S. intrepidu are nektobenthic species
that prefer littoral zones with abundant macrophytes where
productivity is high, temperatures are warm and evapora-
tion is high (Pérez et al., 2010b), and this could well explain their
very positive δ18O values, similar to H. punctata.

5.3. Late Pleistocene–early Holocene hydrodynamics and climatic
conditions

Lago Petén Itzá displayed dramatic fluctuations in water level,
hydrodynamics and climate conditions during the late
Pleistocene–early Holocene. Such environmental and climatic
fluctuations can be summarized as follows:

5.3.1. High lake levels (~26 m) and cold conditions (LGM,~24–19 ka)

The LGM was characterized by low numbers of adult specimens
(<396 valves g⁻¹) and by dominance of benthic species over nek-
tobenthic species (Fig. 6). This suggests that species such as D.
stevensoni, L. oesta, Pseudocandona sp. and P. globula, tolerated
slightly lower water temperatures. Using pollen, Bush et al. (2009)
suggested a cooling of 3–5°C relative to present. Because the
temperature difference between the dry (winter) and wet
(summer) season in the northern Neotropics is small, lake water temperatures for Petén Itzá during the LGM have not been inferred.
Distributions of ostracodes and other bioindicators (cladocers,
diatoms and chironomids) of the Yucatan Peninsula are determined
by conductivity and HCO3 rather than temperature, one reason why
transfer functions for temperature have yet to be developed (Pérez
et al., in press). Limnothryre oesta and P. globula and C. okeechobei
however, seem to prefer warmer temperatures, in contrast to
Pseudocandona sp. and D. stevensoni, which were rare during
the deglacial–early Holocene, when temperatures increased.
This would suggest that these latter taxa could be winter species, i.e.
reaching adulthood during wet winter months. We found few adult
specimens of these species, suggesting minimal winter rains during
the sampling months.

The water depth reconstruction based on ostracodes is consis-
tent with geochemical proxies and lithology. It is important to
compare this water depth reconstruction with inferences from
other proxies because ostracode distribution is not directly affected
by water depth. It is, instead, the combination of factors at a given
water depth that affect ostracode distribution. Those factors
include: macrophyte distribution, suspended load of streams, dust
influx, nutrients, water transparency, waves, among others. Our
inferred water depth suggests that during the LGM lake level
averaged ~26 m (Fig. 7). Ostracode taphonomic analysis also
suggests that there were strong currents and lake mixing during
the LGM, which accounted for high numbers of broken adult
and juvenile valves and times when adult ostracode valves exceeded
juvenile valves (Figs 6 and 7). In the absence of transport, juvenile
valves should exceed adult valves, because each individual mollusks
about eight times to reach adulthood (Meisch, 2000). Colder
temperatures and a smaller difference between surface and lake
bottom water temperatures, might have led to an unstratified or
weakly stratified lake, and lake circulation. There are, however,
other factors that might have accounted for the high number of
broken valves, such as sediment redeposition, shifting wave base,
an oscillating thermocline level, periods of flash floods or down-
slope transport of shells during storm events. LGM sediments are
characterized by the presence of clay with interbedded turbidites,
suggesting individual heavy rain events (Mueller et al., 2010) and
down-slope transport. White bars in Fig. 7 indicate times when
adult ostracodes were absent and times when few or no juveniles
were present. All ostracode species that lived during the LGM
display sporadic increases in the number of adult valves. These
results indicate movement by currents and down-slope transport.
δ18O values were relatively low (<5.1‰ to <5.3‰), but not as low as
during the BA and early Holocene (>3.4‰). Escobar et al. (2012),
evertheless, determined stable isotopes at a higher resolution and
reported δ18O values from +4.7 to +6.0‰ and δ13C values from −8.5...
to \(-4.6^{\circ}\) (Fig. 8). This suggests colder temperatures during the LGM and lower precipitation than during the BA and early Holocene, when lake level averaged \(\sim 40\) m. \(^{13}C\) values were more negative (\(-7.1^{\circ}\) to \(-6.4^{\circ}\)) than values during the BA and early Holocene. The low values during the LGM and BA and early Holocene indicate high lake levels. The slightly more positive \(^{13}C\) values during the BA and early Holocene suggest higher temperatures and therefore more productivity. For instance, Hodell et al. (2012) inferred a water temperature of \(<24\) °C and \(<26\) °C, respectively.

The temperature inference was made by measuring the oxygen stable isotopic composition in shells of \(L.\) opesta. Alternatively, the low carbon isotope values may reflect the fact that \(L.\) opesta lived in \(^{13}C\)-depleted sediments, suggesting that it might be an infaunal species. Foraminifera can be depleted or enriched owing to oxidation of sediment organic matter or methanogenesis. Escobar et al. (2012) indicated that methanogenesis in Lake Petén Itzá is prevented by abundant dissolved sulfate in the water column and porewaters.

The water depth transfer function derived using ostracodes suggests maximum late Pleistocene lake levels during the LGM, about 20.6 cal ka BP, when \(^{13}O\) and \(^{18}O\) values show a small decrease. Lower lake levels were inferred at 23.7, 21.7, 20.8 and 21.4 cal ka BP (Fig. 7). Oxygen, and especially carbon, stable isotope values measured in shells of \(L.\) opesta are slightly higher during these short periods (Fig. 8). This indicates that even during the LGM, lake level in Lago Petén Itzá fluctuated, but not as much as during the deglacial. Another possibility is that ostracode valves were transported to deeper waters by heavy precipitation events, suggested by the presence of several turbidities in LGM sediments. Because application of water depth transfer functions can be confounded by changes in lake productivity and water chemistry, we compared our inferences of past water depth with geochemical and taphonomic proxies and obtained consistent results. Fluctuations in the relative abundance of the ostracode \(L.\) opesta generally correlate with fluctuations in magnetic susceptibility (Fig. 7). Although the two analyses were carried out at different sampling resolutions, slightly lower values of magnetic susceptibility during the LGM coincide with peaks in the relative abundance of \(L.\) opesta. Such increases in the abundance of \(L.\) opesta might suggest that valves were transported from shallower to deeper waters.

Previous studies by Pérez et al. (2010b) indicate that \(L.\) opesta is an indicator of shallow waters, because higher numbers of living specimens were collected at water depths <20 m. Percentages of broken adult valves were greater during periods of high lake levels in the LGM. At several times, the number of broken adult and juvenile valves was almost as high as the total number of ostracode valves, indicating possible mixing of the lake (see arrows, Fig. 6) and down-slope transport, because of colder temperatures and higher precipitation typical of the LGM (Hodell et al., 2008). From \(\sim 23.0\) to 22.0 cal ka BP, the increase in \(P.\) globula, along with a decline in \(L.\) opesta, reflects a continuous increase in lake level. \(C/N\) ratios were low and stable, indicating that deposited organic matter came from autochthonous production. Ostracode analyses, combined with lithologic and magnetic susceptibility measurements (Mueller et al., 2010), and TS and \(C/N\) ratios, indicate that wetter and colder conditions characterized the LGM.

5.3.2. Fluctuating lake levels (\(\sim 10–31\) m) and cold conditions (HS1, \(\sim 19–15\) ka)

The HS1 is characterized by dominance of \(L.\) opesta and \(P.\) globula (Fig. 6) suggesting colder temperatures. Inferred past water depths, changes in the relative abundance of \(L.\) opesta, TS concentration, \(C/N\) ratios and percentage of adult and juvenile broken valves indicate lake level fluctuations, especially from \(\sim 19\) to \(\sim 16.7\) cal ka BP (Fig. 7). Both low and high lake levels characterized HS1b (subunit V), but lower lake levels, gypsum deposition and dry conditions were more common. Relative abundance of \(L.\) opesta during HS1 displays trends that correspond to \(C/N\) ratios and magnetic susceptibility. High \(L.\) opesta percentages are associated with high \(C/N\) ratios and low magnetic susceptibility, validating previous paleoclimatological studies (Pérez et al., 2010b) that found this species is more abundant in shallow waters that are rich in aquatic vegetation.

Hodell et al. (2012) described the HS1 in northern Guatemala as an arid period displaying hypolimnetic water temperatures as low as \(16–20\) °C, estimated from coupled measurements of oxygen isotopes in gypsum hydration water and ostracode shell carbonate. Although drier climate conditions prevailed, there were short wet periods during HS1. Our independent water depth reconstruction provides a more detailed picture and suggests higher lake levels during the early deglacial (\(\sim 19–18.5\) ka), at 17.5, 17 (subunit V), and from 16.5 to 16.0 ka (subunit IV, Fig. 7), coinciding with slightly lower \(^{13}C\) and \(^{18}O\) values in ostracode valves (Fig. 9). Similar to the LGM conditions, the low stable isotope values are attributed mainly to \(^{13}C\)-depleted deep waters, owing to decay of organic matter and \(^{18}O\)-depleted waters owing to higher precipitation and lower evaporation.

Benthic species \(P.\) pseudocandona sp. and \(D.\) stevensoni are still present during the early deglacial, but valve numbers begin to decrease \(\sim 18.0\) cal ka BP, indicating increasing aridity that characterize most of HS1. Both species were present during the LGM, because they prefer slightly colder temperatures and higher water depths, contrary to the climatic conditions during HS1. The maximum number of adult and juvenile valves during HS1, however, occurs at \(18.0\) cal ka BP (Fig. 6), when lake levels dropped after the LGM. \(C.\) okeechobei, a nektobenthic species that prefers littoral zones with abundant macrophytes and lives at a maximum water depth of 40 m, appears at the onset of the deglacial, when lake level starts to decrease (Fig. 7). The \(^{18}O\) values of \(C.\) okeechobei and \(P.\) globula, reflecting high photosynthetic productivity in their littoral habitat (Fig. 8). Vital effects, however, could have played an important role. The \(^{13}C\) values of \(C.\) okeechobei are generally slightly more negative than those of benthic \(L.\) opesta and nektobenthic \(P.\) globula, reflecting high photosynthetic productivity in their littoral habitat (Fig. 8). Vital effects, however, could have played an important role. The \(^{13}C\) values of \(C.\) okeechobei and \(P.\) globula, reflecting high photosynthetic productivity in their littoral habitat (Fig. 8). Vital effects, however, could have played an important role.
lake. Even if warm and/or wetter conditions dominated during the phase between HS1b and HS1a, slight increases in TS concentration, C/N ratio and a higher relative abundance of L. opesta suggest lower lake levels during most of HS1. The number of valves of C. okeechobei dramatically decreased at ~17.0 cal ka BP when lake level increased (subunit IV). This species and L. opesta recovered when gypsum deposition began again around 15.7 cal ka BP (Fig. 6), indicating lake level lowering.

Littoral zone indicators H. punctata and S. intrepidus appear sporadically during HS1, coinciding with gypsum deposition and indicating much lower lake levels (HS1a, b, Fig. 6). Nektobenthic H. punctata displayed highest δ18O values during HS1b and HS1a and highest δ13C values during HS1a (Fig. 8). Similar isotope values were seen in modern ostracodes restricted to shallow waters, indicating that this nektobenthic species can be used as an indicator of shallow waters.

During HS1a, arid conditions negatively affected species such as L. opesta, P. globula and C. okeechobei. This marked the first long period (15.5–15.3 cal ka BP) when P. globula was completely absent and suggests drier conditions persisted for a much longer time than previously. This was apparently a stable phase of HS1, characterized by low lake level, high TS concentration, generally high C/N ratios and high percentages of broken ostracode valves, attesting to high energy levels. Highest δ18O values during HS1 were determined during HS1a, as well as slightly higher δ13C values. Higher δ18O values during HS1a might be a result of greater and longer aridity and higher evaporation than during HS1b. Higher δ13C values during HS1a could suggest lower lake levels and higher productivity.

High-energy environments and lake mixing likely occurred during HS1b (subunit V) and HS1a (subunit III) when conditions were cold and lake levels low (Fig. 6). C/N ratios and the percent of broken adult and juvenile valves (Fig. 7) fluctuate strongly during times of gypsum deposition (subunits V and III), coinciding with times of valve transport. Colder temperatures and shallower water may have permitted greater lake mixing, which could explain the high percentage of broken valves.

5.3.3. High lake levels (~40 m), warmer and wetter conditions (BA, ~15–13 ka)

The BA is dominated by P. globula, followed by L. opesta. Other ostracode species are absent or scarce. Highest numbers of adult and juvenile ostracodes during the deglaciation were recorded for the BA and consist mostly of P. globula. Thus, the BA assemblage closely resembles the modern assemblage at the core site (71 m water depth). Physocypria globula is a species known to prefer deeper waters. The BA displayed relatively stable high lake level, low abundance of L. opesta, high magnetic susceptibility, low TS and C/N ratios, and low ostracode δ18O and δ13C values. The maximum inferred water depth at the core site was ~76 m, suggesting deeper water than today (71 m at core site). The applied transfer function, however, has a RMSE of 9 m and other paleo-proxy data display the lowest δ18O values of all identified lake occurrences.

Carbon isotope values were slightly higher during the BA than during the LGM, although inferred lake levels are higher than during the LGM. It might have been that water temperatures during the BA were much higher (20–24 °C, Hodell et al., 2012), which could have increased lake productivity. Similar δ13C values (~−6‰) were determined in modern ostracode shells of L. opesta collected at water depths >20 m, suggesting that the source of carbon and water temperature could be similar to those during the BA. δ18O values are lower than those measured during the LGM, indicating wetter and warmer conditions in the BA. The δ14C record of L. opesta and P. globula display similar values, whereas their δ13C values differ from one another. The δ18O values of P. globula during the BA are generally more negative than those for L. opesta, except at 14.1 cal ka BP (Fig. 8). We found similar δ13C values in both species in the deep, modern lake (Figs. 4 and 5). This was not the case for δ18O differences between the species. In our modern data set for winter months, benthic L. opesta display more negative δ18O values than nektobenthic P. globula. The BA may resemble the modern summer months, in that nektobenthic species display more negative δ18O values as a consequence of higher temperatures and summer precipitation (~4.0‰) (Hillesheim et al., 2005), leading to more negative δ18O values in lake waters.

Lower percentages of broken adult and juvenile valves in the BA, compared to the rest of the Late-glacial and little fluctuation in the stable isotope values, indicate a stable, thermally stratified lake with little mixing or water currents. At ~14.6 cal ka BP there is a peak in the relative abundance of L. opesta, and slightly lower lake levels and magnetic susceptibility, indicating a short, drier period.

5.3.4. Low lake levels (~4 m) and dry conditions (YD, ~13–11.5 ka)

The YD is characterized by the dominance of L. opesta, whereas P. globula is rare, similar to the situation during HS1a. Littoral zone indicator H. punctata is also present. Total numbers of adult and juvenile valves are much lower than during the BA, despite the fact that lake levels were lower and more nektobenthic and benthic species might be expected. The relative abundance of L. opesta was high, TS concentrations and C/N ratios remained high, and the percentage of broken valves was again high, similar to all previous periods of low lake level characterized by gypsum deposition. Stable isotope values of L. opesta fluctuated slightly, however a decrease is seen from ~12.8 to 12.5 cal ka BP. δ13C values of C. okeechobei at 12.5 ka are much higher than those of L. opesta, similar to our modern data. The oxygen and carbon stable isotope values first decrease and then increase, correlating with our water depth reconstruction. A slight increase in lake level (~35 m) occurred at the onset of the YD, followed by a later lake level drop (~10 m). Other sediment variables do not display major changes at that time, although the TS profile shows a decrease, and inferred lake levels did not drop between 12.8 and 12.5 cal ka BP (Fig. 7). This suggests that cold temperatures drove a decrease in lake productivity and a short wet period might explain the lower δ18O values.

5.3.5. High lake levels (~58 m), warm and wetter conditions (early Holocene, 11.5–10.0 ka)

The onset of the early Holocene is well defined by an increase in ostracodes (L. opesta and P. globula) and inferred lake level. Lower TS concentrations and C/N ratios, higher percentages of broken ostracode valves and declines in δ13C and δ18O values of ostracodes indicate wetter conditions, rising lake level and stronger currents.

6. Conclusions

Modern limnological information and species autecology are helpful for understanding stable isotope signatures of ostracode species that live in Lago Petén Itzá. Such information is essential for inferring past lake hydrodynamics from isotope measure in subfossil ostracode shells in lake sediment cores. Lake water temperatures, together with environmental variables dissolved oxygen, pH, and water depth, chemistry, substrate, macrophyte cover, habitat structure, and food availability determine the spatial distribution of ostracodes in Lago Petén Itzá. Generally, δ13C and δ18O values of littoral and shallow-water species were higher than those inhabiting deeper waters, i.e. ~20 m. δ13C values generally decline moving from the epilimnion to the deeper thermocline waters (~20–40 m). Limnodiastoma opesta displayed the lowest δ18O and δ13C values and the lowest δ18O offset from calcite equilibrium.
among modern ostracode species. Nektobenthic species C. okeechobei, H. punctata and S. intrepidu showed highest δ13C values, reflecting higher productivity. Low isotope values in L. ophthia suggest it might be an infantual species, whereas other benthic taxa, displaying higher δ13C values such as D. stevensoni and C. ilosiavai, might be epifaunal.

The late Pleistocene stable isotope record (δ13C and δ18O) of ostracodes in Lago Petén Itzá shows fluctuations that are explained mainly by changes in the balance between evaporation and precipitation, lake stage, and carbon source. We identified five periods in the late Pleistocene—early Holocene record from Lago Petén Itzá, with respect to lake level and evaporation/precipitation (E/P), using ostracode analysis in combination with lithology, magnetic susceptibility, TS and C/N ratios: 1) high lake levels and cold conditions (LGM), 2) fluctuating lake levels and cold conditions (HS1), 3) high lake levels and warm and wetter conditions (BA), 4) low lake levels and dry conditions (YD) 5) high lake levels and warm and wet conditions (early Holocene). The composition of fossil species assemblages changed at the LGM—early deglacial transition. Benthic species and P. globula characterized the LGM, and nektobenthic species and L. ophthia dominated during the deglacial. Deep-water species P. globula dominated during the early Holocene.

Future studies should carry out monthly sampling of limnological variables throughout the year over several years in this large Neotropical lake. The isotopic composition of multiple living ostracode species, as well as their life cycles, should be analyzed at high temporal resolution throughout the year as well. Interpretation of long stable isotope records might be improved if such information were acquired, along with monthly fluctuations in lake variables. Our study demonstrates that use of isotopic measurements from multiple ostracode species to generate reliable paleoenvironmental-inferences, requires a strong understanding of species ecological preferences and lake hydrodynamics.

Acknowledgments

We thank all who assisted us during field trips to Lago Petén Itzá and other regional waterbodies. We are grateful to the following people and agencies: Roberto Moreno, Margarita Palmieri, Margret Dix, Eleonor de Tott (Universidad del Valle de Guatemala), Consejo Nacional de Áreas Protegidas (CONAP), Asociación para el Manejo y Desarrollo Sostenible de la cuenca del Lago Petén Itzá (AMPI), Michael Hillesheim, Burkhard Scharf, Julia Lorenschat, Rita Manejo y Desarrollo Sostenible de la cuenca del Lago Petén Itzá, USA) for core curation and members of the Drilling, Observation and Sampling of the Earth’s Continental Crust (DOSECC) for their financial support during drilling operations in Lago Petén Itzá in 2006. The Deutsche Forschungsgemeinschaft (DFG, grant Schw 671-3), Technische Universität Braunschweig (TU-BS, Germany), National Science Foundation (NSF, USA), International Continental Scientific Drilling Program (ICDP), Swiss Federal Institute of Technology and Swiss National Science Foundation provided financial support for core recovery and analysis.

References

Dean, W., 2010. Recent advances in global lake coring hold promise for global change research in paleolimnology. J. Paleolimnol. 44, 741–743.
Jugantsoa, S., 2003. 1.5 ed. Newcastle University, Newcastle upon Tyne.

Please cite this article in press as: Pérez, L., et al., Stable isotope values (δ18O and δ13C) of multiple ostracode species in a large Neotropical lake as indicators of past changes in hydrology, Quaternary Science Reviews (2012), http://dx.doi.org/10.1016/j.quascirev.2012.10.044


