Late Pleistocene (OIS 3) paleoenvironmental reconstruction for the Térapa vertebrate site, northcentral Sonora, Mexico, based on stable isotopes and autecology of ostracodes

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ABSTRACT

The Térapa fossil vertebrate site, northcentral Sonora, Mexico, provides a rare opportunity to study the paleoenvironmental conditions present in northwestern Mexico during mid-Oxygen Isotope Stage (OIS) 3. Ostracode faunal assemblages and stable oxygen ($\delta^{18}O$) and stable carbon ($\delta^{13}C$) isotope values from ostracode calcite were used to reconstruct the seasonality of precipitation and vegetation cover at Térapa at 40–43 ka. The ostracode fauna was a non-analogue mix of temperate and tropical ostracode species composed of 13 species from 12 genera. The nearctic ostracodes *Fabaeformiscandona caudata*, *Physocypria pustulosa*, *Cypridopsis vidua* and the cosmopolitan ostracode *Darwinula stevensoni* dominate the assemblage. Two tropical ostracode genera, *Chlamydotheca arcuata* and *Stenocypris* sp., were present throughout the deposit and indicate that mean monthly summer temperatures were probably no more than 4°C to 6°C cooler than at present, based on available ecological information. Winter precipitation dominated the hydrologic cycle as evidenced by low ostracode $\delta^{18}O$ values (-6‰ to -8‰ VPDB). Low ostracode $\delta^{13}C$ values (-7‰ to -8‰ VPDB) suggest that local vegetation was dominated by C_3 plants. A previous tooth enamel-based paleoenvironmental reconstruction at the same site favored a summer-dominated or evaporative hydrology and abundant C_4 vegetation. The Térapa megafauna site exemplifies the need for multi-indicator paleoclimate reconstructions in desert environments where marked differences in the seasonality of precipitation and vegetation cover may occur.

Key words: Sonora; OIS 3; paleoenvironment; ostracode; stable isotopes.

RESUMEN

El sitio de vertebrados fósiles Térapa, en el norte central de Sonora, México, ofrece una rara oportunidad de estudiar las condiciones paleoambientales presentes en el noroeste de México durante la etapa isotópica de oxígeno (OIS) 3. Ensambles de fauna de ostrácodos y valores isotópicos de oxígeno estable ($\delta^{18}O$) y valores isotópicos de carbono estable ($\delta^{13}C$) de calcita en ostrácodos fueron utilizados para reconstruir la estacionalidad de la precipitación y cobertura vegetal en Térapa a los 40–43 ka. La fauna de ostrácodos fue una mezcla de diferentes especies templadas y tropicales de ostrácodos compuestas de 13 especies de 12 géneros. Los ostrácodos neárticos Fabaeformiscandona caudata, Physocypria pustulosa, Cypridopsis vidua y la ostrácoda cosmopolita Darwinula stevensoni dominan el ensamble. Dos géneros de ostrácodos tropicales, Chlamydotheca arcuata y Stenocypris sp., estuvieron presentes durante el depósito indicando que las temperaturas promedio mensuales en verano probablemente no eran menores de 4°C a 6°C que en la actualidad, con base en información ecológica disponible. Las precipitaciones de invierno dominaron el ciclo hidrológico como lo demuestran los valores $\delta^{18}O$ bajos (-6‰ to -8‰ VPDB) en ostrácodos. Los valores $\delta^{13}C$ bajos (-7‰ to -8‰ VPDB) en ostrácodos sugieren que la vegetación local estaba dominada por plantas C_3. Una reconstrucción paleoambiental previa basada en esmalte de dientes en el mismo sitio favoreció una hidrología verano-dominada o de caracter evaporatorio y una abundante vegetación C_4. El sitio de megafauna Térapa ejemplifica la necesidad de reconstruccionesa partir de varios indicadores paleoclimáticos en ambientes desérticos donde pueden ocurrir diferencias marcadas en las temporadas de precipitación y cobertura vegetal.

Palabras clave: Sonora; OIS 3; paleoambiente; ostrácodo; isótopos estables.

INTRODUCTION

Absolutely dated vertebrate fossils sites that provide late Pleistocene paleoenvironmental information for northern Mexico are rare, and their distribution is highly fragmentary (Metcalfe *et al.*, 2000; Arroyo-Cabrales *et al.*, 2010; Ferrusquía-Villafranca *et al.*, 2010). The majority of such sites are located in the central and southern parts of the country and the resulting paleoenvironmental information displays a similar geographic bias (Ferrusquía-Villafranca *et al.*, 2010). Late Pleistocene fossil sites from Sonora only comprise about 2% of all known Mexican localities (Arroyo-Cabrales *et al.*, 2002; Ferrusquía-Villafranca *et al.*, 2010). The Térapa fossil vertebrate site, located in northcentral Sonora, Mexico, near the towns of San Clemente de Térapa and El Llano (hereafter Térapa; Figure 1), contains an exceptional and extensive array of Late Pleistocene aquatic and terrestrial faunal remains (Mead *et al.*, 2006, 2007; Hodnett *et al.*, 2009; Steadman and Mead, 2010; Oswald

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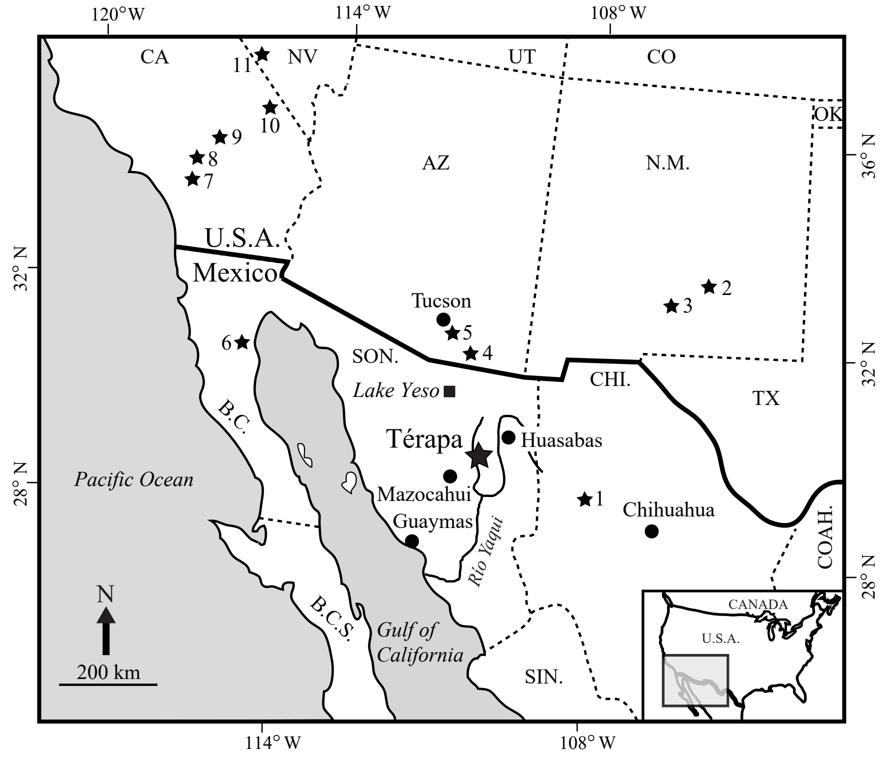

Figure 1. Illustration showing the location of Térapa, Sonora, Mexico (large black star) in relation to Lake Yeso (black square), to the southwestern U.S., and to northwestern Mexico. Small black stars are locations of climate records that extend to OIS 3. 1- Laguna Babicora; 2- Fort Stanton; 3- Lake Otero; 4- Murray Springs; 5- Cave of the Bells; 6- San Felipe; 7- Diamond Valley; 8- Baldwin Lake; 9- Harper Lake and Lake Manix, 10- Valley Wells; 11- Devils Hole. Figure modified from Bright *et al.* (2010).

and Steadman, 2011; Czaplewski *et al.*, 2015) preserved in an 11 m thick deposit of marsh and fluvial sediments that has been absolutely dated to 40–43 ka, or to mid Oxygen Isotope Stage (OIS) 3 (Bright *et al.*, 2010). Notably, the Térapa vertebrate fauna is a non-analogue fauna; several of the fossil vertebrates are from more temperate animals (*e.g.*, mammoth, bison) while others are extinct or have tropical affinities and are no longer found in the area today (*e.g.*, crocodile, capybara, glyptodont; Mead *et al.*, 2006; Ceballos *et al.*, 2010).

A preliminary ostracode faunal assemblage for Térapa was reported in Mead *et al.* (2006). This study expands on those results by reporting several additional ostracode species, and reconstructs in greater detail the paleoenvironment at Térapa through the use of the ostracode assemblage and stable isotope ($\delta^{18}O$ and $\delta^{13}C$) analysis of ostracode valve calcite. The ostracode $\delta^{18}O$ values provide insight into the seasonality of peak surface discharge, assuming that the water temperature at the time of calcification can be reasonably estimated. The ostracode $\delta^{13}C$ values can provide insight into the vegetation community growing around the site because respired CO_2 from plant roots contributed to the dissolved inorganic pool of the streams and wetland that deposited the Térapa sediments. In 2010, Nunez *et al.* published a paleoenvironmental interpretation for Térapa that was based on $\delta^{18}O$ and $\delta^{13}C$ values from herbivore teeth recovered from throughout the same deposit. The enamel $\delta^{18}O$ values were very high and the enamel $\delta^{13}C$ values suggested that a strong C_4 plant community was present. Our ostracode $\delta^{18}O$ and $\delta^{13}C$ data provide an excellent opportunity to compare paleoenvironmental interpretations for a single deposit that are derived from two very different and commonly used archives – aquatic ostracode calcite and terrestrial tooth enamel. To our knowledge, this is the first time such a comparison has been attempted. We demonstrate that seasonality of precipitation and ecologic variables must be considered when reconstructing paleohydrology from different stable isotopic archives, especially in environments that experience marked differences in the seasonality of precipitation and vegetation cover. Our results provide an important, albeit brief, absolutely dated record of paleoenvironmental conditions in northeastern Sonora at a time when biotic communities and their associated environmental gradients were considerably different than today.

SITE DESCRIPTION AND BACKGROUND

The town of Térapa (29°41’ N; 109°39’ W; Figure 1) is located in the Moctezuma River valley, in the northwestern portion of the Sierra Madre Occidental, at an elevation of 605 meters above sea level (m a.s.l.). The vegetation community at Térapa is classified as foothills thorn-scrub (Van Devender *et al.*, 1997; Martin *et al.*, 1998). Oak and oak-pine woodlands dominate at higher elevations (> 1,400 m a.s.l.) and the vegetation below about 600 m a.s.l. is classified as Sonoran Desert (Búrquez *et al.*, 1992; Orvis, 1998).

The Moctezuma Valley is located between the Oposura Mountains (max. elevation ~ 1,800) to the west and the Sierra La Madera (max. elevation ~ 2,300 m a.s.l.) and another lower (max. elevation ~ 1,800 m a.s.l.) unnamed range to the east (Figure 2). The local geology consists of Lower Cretaceous fossiliferous limestone, granites, Eocene to Miocene-aged ignimbrites, Miocene and Pliocene-aged basin fill, and Quaternary-aged basalts of the Moctezuma Volcanic Field (Paz-Moreno *et al.*, 2003).

The mean annual temperature (MAT) and mean annual precipitation (MAP) at Térapa are approximately 22°C and 58 $cm \cdot yr^{-1}$, respectively (Figure 3). Average minimum monthly temperatures do not fall below 4°C and average maximum monthly temperatures approach 40°C in the summer (Figure 3). Monsoon rainfall during just two months (July-August) accounts for nearly 50% of the total annual precipitation (Figure 3). Winter precipitation is derived from Pacific storms that pass over the area as the polar jet stream and the associated storm track shift southward during the winter (Magaña *et al.*, 2003; Nicholas and Battisti, 2008).

The δ^{18}O value (VSMOW) of precipitation at Térapa is not monitored, but modeled values range from about -12‰ in the winter to -6‰ in the summer, with an average annual value of -7 ± 2‰ (Bowen, 2014; Figure 3). In contrast to modeled values, limited seasonal precipitation collections (2003-2004) at two stations within 50 km of Térapa (Figure 1) produced average δ^{18}O values for winter (November-May) and summer (June-October) precipitation that were -7 ± 1‰ and -3 ± 2‰, respectively (n = 4; Figure 3; C. Eastoe, unpublished data). The winter precipitation δ^{18}O value falls near the modeled value, but the summer precipitation δ^{18}O value is much higher. The δ^{18}O value of summer and winter precipitation in the southwestern U.S. varies by several per mille from year to year (Wright *et al.*, 2001; Eastoe and Dettman, 2016). This variability likely explains the discrepancy between the modeled δ^{18}O value for summer precipitation and the limited seasonal measurements near Térapa (Figure 3).

The fossiliferous sedimentary sequence at Térapa was deposited in a roughly 1 km × 2 km-wide basin along the eastern edge of the Tonibabi lava flow (Figure 2). The basin was created when the Tonibabi lava flow spilled southward from its vent and down the Río Moctezuma Valley (Figure 2). The Tonibabi lava flow blocked and altered the course of the Río Moctezuma and many small tributaries. The blocking of these tributaries caused water and sediments to be impounded along the edges of the flow (Mead *et al.*, 2006).

The source of the water and sediments that inundated the Térapa basin has not been conclusively identified (Mead *et al.*, 2006). Given the overall fine grain size of the sediments and the orientation of the modern stream network, the water and sediments were most likely derived from several small washes that are sourced from small catchments in the eastern highlands (Figure 2; Mead *et al.*, 2006). The basin at Térapa was two orders of magnitude smaller than its upstream source area, making it sensitive to changes in effective moisture in the eastern mountains.

The sedimentology and age of the Térapa fossil deposit is covered in detail in Mead *et al.* (2006) and Bright *et al.* (2010). Briefly, the entire sediment package is about 11 m thick (Figure 4). The basal 0.5 m of sediment (units A_{s1} and A_{s2}) is comprised of coarse-grained sands that are deposited directly on the Tonibabi lava. Unit A_{s2} is overlain by about 1.5 m of silty clay (Unit A_c). A well-sorted wedge of sand (Unit A_{s3}) occurs within Unit A_c. The basal A-series sediments are overlain by roughly 1.5–2 m of blocky fossiliferous clays (Unit B_{p1}), which are in turn overlain by about 4 m of faintly bedded sandy silt (Unit B_c). A fairly prominent oxidized sorted sand occurs near the top of Unit B_c, which here is denoted $B_{c\text{-}s}$ ("s" for sand). Unit B_c is overlain by another blocky fossiliferous unit that is about 1.5 m thick (Unit B_{p2}). Coarse pebble-armored stream channel deposits are formed into Unit B_{p2} (Figure 4). Abruptly on top of both Unit B_{p2} and the Tonibabi basalt are 2 to 4 m of coarse cobbles and sands of Unit C. Unit C likely represents coarse alluvial valley fill that spread across the valley floor after the Térapa basin was completely filled in with sediment. The Térapa locality has been dated, using multiple geochronological techniques, to about 40–43 ka, or to mid-marine Oxygen Isotope Stage (OIS) 3 (Bright *et al.*, 2010).

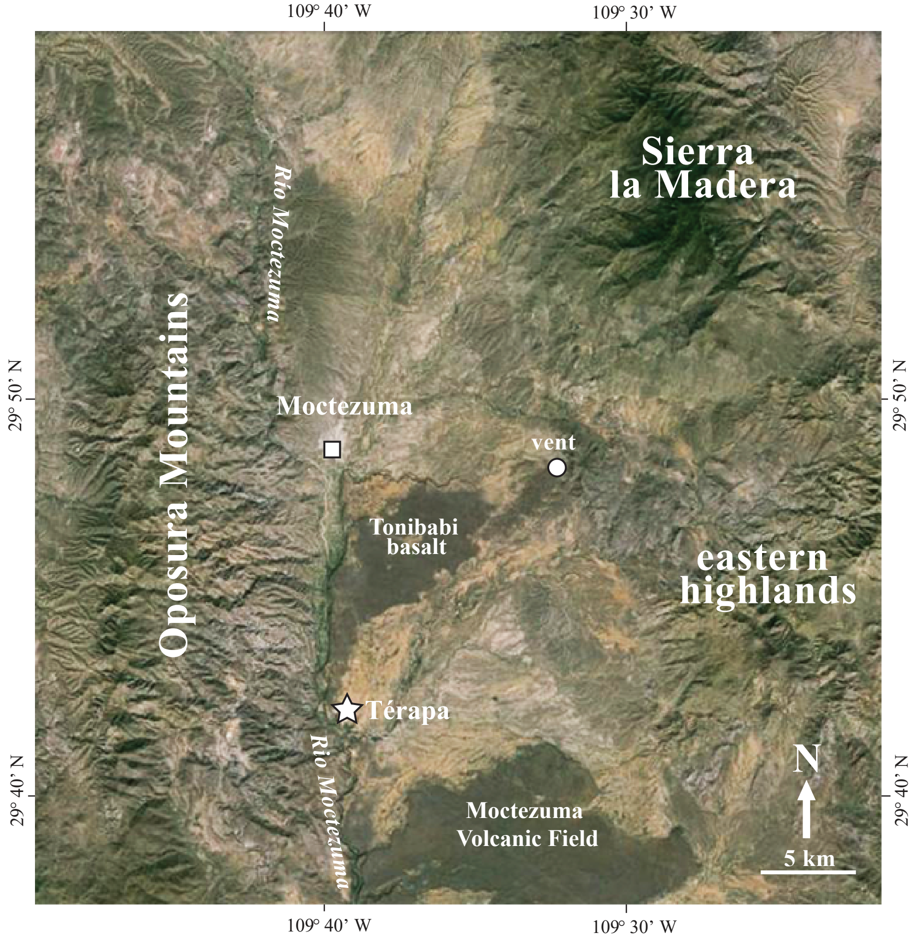

Figure 2. Satellite image of Térapa, Sonora, Mexico (white star) and its location in relation to the town of Moctezuma (white square), the Río Moctezuma, the Tonibabi lava flow and its vent (white circle), the Moctezuma Volcanic Field, and the surrounding highlands. Image modified from Google Earth.

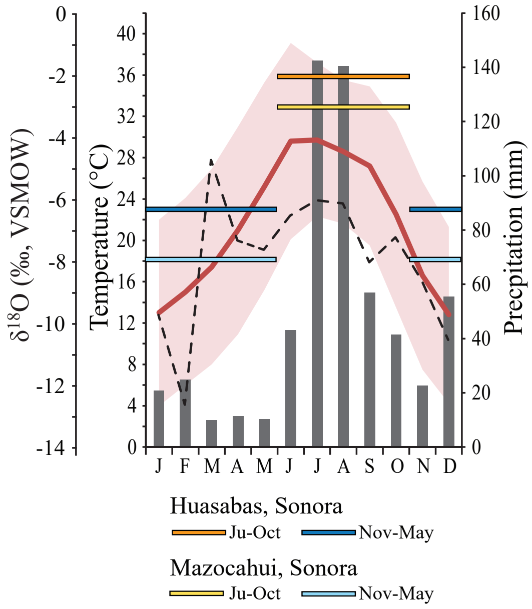

Figure 3. Climate data for Térapa, Sonora, Mexico. Average monthly precipitation totals in mm (gray columns); average monthly air temperatures (°C) (red line); average minimum and average maximum monthly air temperatures (°C) (red shading); and δ^{18}O values of summer (June-October, warm colored horizontal lines) and winter (November-May, cool colored horizontal lines) precipitation collected at the towns of Huasabas and Mazocahui (see Figure 1) from 2002-2004. Dashed black line shows model-predicted δ^{18}O values in Térapa precipitation from http://www.waterisotopes.org. Temperature and precipitation data are from http://smn.conagua.gob.mx/climatologia/normales/estacion/son/NORMAL26251 at the time of writing. Period of record, 1971-2000.

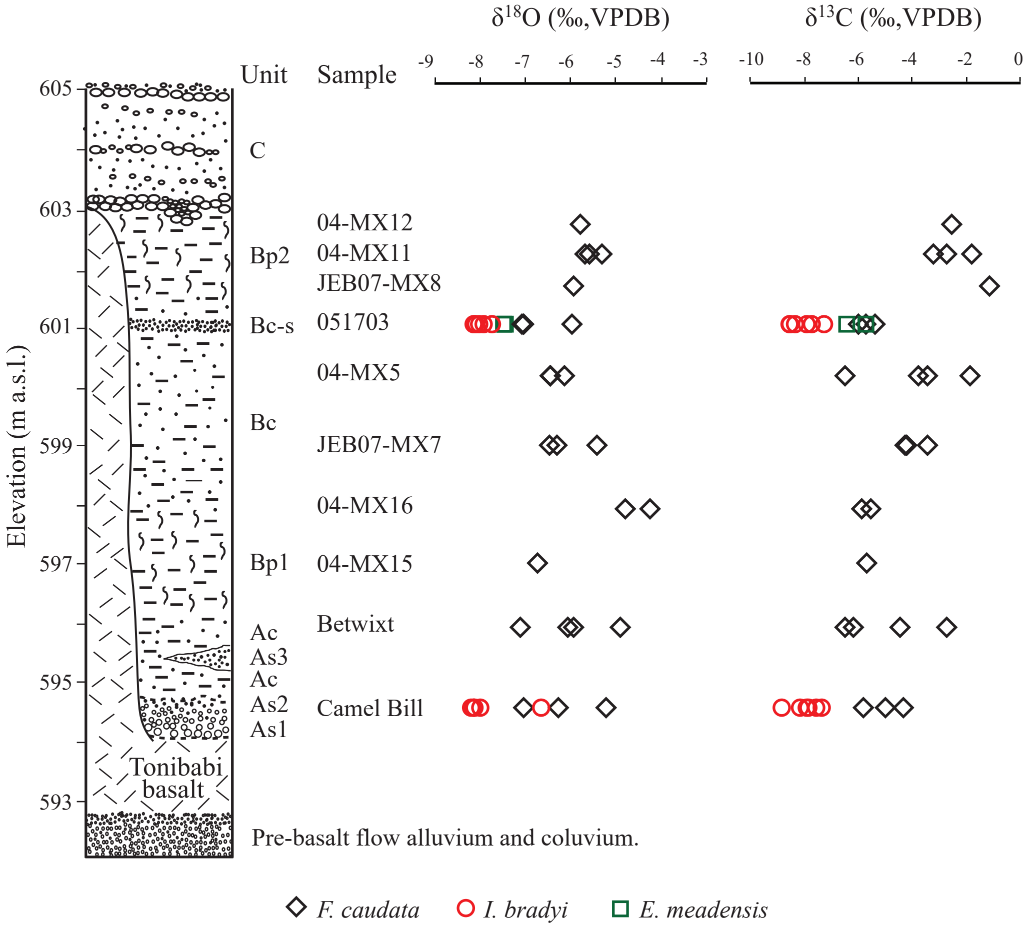

Figure 4. Stylized composite stratigraphic column for the Térapa deposit (modified from Mead *et al.* (2006)). Uncorrected ostracode calcite δ^{18}O and δ^{13}C values (‰, VPDB) are displayed in stratigraphic context. Black diamonds - *Fabaeformiscandona caudata*; red circles - *Ilyocypris bradyi*; green squares - *Eucypris meadensis*. Unit designations and sample names are the same as in Table 2 and Figure 6.

METHODS

Ostracode faunal analysis

Thirty four sediment samples from Térapa were analyzed for their ostracode faunas. Each sediment sample was placed in relative position within the master stratigraphic column of Mead *et al.* (2006). The majority of the sediment samples (n = 26) were processed at Northern Arizona University's Amino Acid Geochronology Laboratory using a modified version of Forester (1988). Sediments were disaggregated in a weak (3 gm·L^{-1}) solution of sodium hexametaphosphate and sodium bicarbonate instead of Calgon®. The sediment solutions were washed over 150 μm sieves using hot deionized water. All residues were rinsed with deionized water and then air-dried. Northern Arizona University's Laboratory of Paleontology provided eight samples of hand-picked ostracode valves that were collected during their screen washing process (> 300 μm). The larger screen size means these samples were biased towards larger ostracode valves and species. Ostracode species were tabulated as presence-absence data, rather than individual valve counts. While individual valve counts and percent data are preferred for paleoenvironmental reconstructions, presence-absence data have been shown to be equally reliable (Muller *et al.*, 2002) and will suffice for the purpose of this paper. Ostracode species were identified to genus, and where possible, species level based on drawings and images in Gutentag and Benson (1962), Meisch (2000), Delorme (1970a, b, c, d; 1971), Smith and Delorme (2010), and Ferguson (1967). The genus *Stenocypris* was identified by R. Forester (USGS, deceased).

δ^{18}O and δ^{13}C analysis of ostracode valve calcite

Whole, adult valves from fossil *Fabaeformiscandona caudata*, *Ilyocypris bradyi*, and *Eucypris meadensis* were manually picked from residues where they were most abundant and best preserved. These three species were selected because of their affinity for flowing water (*e.g.*, Curry, 1999; Quade *et al.*, 2003), which minimizes the effect of evaporation. The valves were cleaned by manual brushing with a fine paintbrush followed by gentle sonication and thorough rinsing using distilled water. The *F. caudata* and *I. bradyi* valves were sub-sampled into aliquots containing up to 4 valves (n = 37). The *E. meadensis* valves were large enough to be analyzed individually (n = 2). The δ^{18}O and δ^{13}C values of the ostracode valves were measured using an automated KIEL-III carbonate preparation device coupled to a Finnigan MAT 252 gas-ratio mass spectrometer. The samples were reacted with dehydrated phosphoric acid under vacuum at 70°C. The isotope ratio measurement is calibrated based on repeated measurements of NBS-18 and NBS-19 standards. The stable isotope results are reported in standard delta (δ) notation where: $\delta‰ = [(R_{sample}/R_{std})-1] \times 10^3$; and R = ratio of $^{18}O/^{16}O$ or $^{13}C/^{12}C$. R_{std} refers to the standard Vienna Peedee belemnite (VPDB). Precision for δ^{18}O and δ^{13}C measurements are ±0.1‰ and ±0.08‰, respectively.

RESULTS

Ostracode fauna

The fossil ostracode fauna at Térapa currently consists of 13 species from 12 genera (Table 1). The nearctic ostracodes *Fabaeformiscandona caudata*, *Physocypria pustulosa*, *Cypridopsis vidua*, and the cosmopolitan ostracode *Darwinula stevensoni* (Figure 5) were encountered most frequently (Table 1). *Pelocypris* cf. *tuberculatum*, *Cypridopsis okeechobei*, *Chlamydotheca arcuata*, *Limnocythere paraornata*, and *Heterocypris incongruens* (Figure 5) are species not previously reported in Mead *et al.* (2006). The ostracode fauna is generally similar and consistent throughout the deposit (Table 1).

δ^{18}O and δ^{13}C values from ostracode valve calcite

The $\delta^{18}O_{OST}$ and $\delta^{13}C_{OST}$ values (VPDB) range from about -4‰ to -8‰ and from about-1‰ to -9‰, respectively (Figures 4 and 6; Table 2). With the exception of 2 outliers, *Ilyocypris bradyi* valves have the lowest δ^{18}O and δ^{13}C values (Figures 4 and 6; Table 2). The average δ^{18}O and δ^{13}C values from *I. bradyi* valves are -8 ± 0‰ and -8 ± 1‰, respectively (n = 12). The average δ^{18}O and δ^{13}C values from *F. caudata* valves are -6 ± 1‰ and -4 ± 2‰, respectively (n = 25). The two *E. meadensis* valves produced δ^{18}O and δ^{13}C values of about -8‰ and -6‰, respectively (Figures 4 and 6; Table 2). The $\delta^{18}O_{OST}$ and $\delta^{13}C_{OST}$ values are positively correlated (r = 0.74), although the low δ^{18}O and δ^{13}C values from *I. bradyi* control much of the correlation (Figure 6a). Excluding the *I. bradyi* values reduces the correlation considerably (r = 0.37).

DISCUSSION

Paleohydrology reconstruction

Ostracodes indicative of flowing-water settings (*I. bradyi*, *E. meadensis*) are sometimes found intermixed with ostracodes indicative of vegetated, more wetland-like conditions (*H. incongruens*, *C. vidua*, *C. arcuata*). The mixing of flowing- and stagnant-water ostracodes suggests environmental heterogeneity or possibly post-mortem reworking of the valves. Infrequent occurrences of *C. okeechobei* and *E. meadensis* may be indicative of spring discharge. The presence of *C. arcuata* and an unidentified *Stenocypris* species (Figure 5) is notable. Both *Chlamydotheca* and *Stenocypris* have circumtropical distributions (Tressler, 1949). At Térapa, these two tropical ostracode species are frequently found in association with *F. caudata*, an ostracode with a range that is currently restricted to the continental United States and Canada (Forester *et al.*, 2005).

The fossil ostracode fauna at Térapa is indicative of a persistent fresh-water setting. The majority of the fossil ostracode species have upper total dissolved solids (TDS) limits generally < 1,000 mg·L^{-1}, and both *F. caudata* and *L. paraornata* commonly inhabit water with TDS values between about 200 and 600 mg·L^{-1} (Forester *et al.*, 2005). To date, no ostracode species indicative of chemically evolved water, such as *Limnocythere staplini* or *Limnocythere sappaensis,* has been recovered at Térapa even though they were common in Late Pleistocene-aged closed-basin lakes from the southwestern U.S. and northern Mexico (*e.g.*, Palacios-Fest *et al.*, 2002; Wells *et al.*, 2003; Allen *et al.*, 2009; Chávez-Lara *et al.*, 2012). The persistent low-TDS ostracode fauna suggests that the Térapa impoundment was through-flowing. Over-spilling or leakage through the Tonibabi basalt are also reasonable mechanisms that would have suppressed evaporative chemical enrichment and maintained a freshwater environment.

The presence of *P. pustulosa*, *C. arcuata*, and the unidentified *Stenocypris* species are key warm-water indicators at Térapa. *Physocypria pustulosa* requires at least 2 consecutive months with water temperatures above 20°C to complete its lifecycle (Forester *et al.*, 1987). *Chlamydotheca* and *Stenocypris* are both considered circumtropical genera (Tressler, 1949). *Chlamydotheca* and *Stenocypris* have both been reported in the continental United States, but reports are typically from southern and Gulf-coast states or from warm (geothermal) spring settings (Furtos, 1933; Hoff, 1944; Ferguson, 1962, 1964, 1966; Bowen, 1976; Davis, 1980; Forester, 1991, 1999; Ourso and Horing, 2000; Curry and Baker, 2000). Being tropical genera, *Chlamydotheca* and *Stenocypris* are probably unable to survive cold winter temperatures (*e.g.*, Addo-Bediako *et al.*, 2000; Sunday *et al.*, 2011). Uncontrolled experiments have shown that water temperatures below about 20°C are lethal to *C. arcuata* (Forester, 1991). Both of the tropical ostraco-

Table 1. Fossil ostracode species presence (P) or absence (-) listed by sample and stratum, Térapa, Sonora, Mexico.

Sample	Unit (Figure 4)	Fc	Pp	Cyp	Ds	Ib	Pot	Em	Stn	Cha	Hi	Lp	Pt
JEB06-MX04	Bp2 (top)	P	P	P	P	-	P	-	-	-		-	-
04MX-12	Bp2 (top)	P[b]	P	P	-	-	-	-	-	-	P	-	-
Code104-2	Bp2 (top)	-	P	P	P	-	-	-	-	-	P	-	-
Organ Pipe [a]	Bp2 (middle)	P	-	-	-	-	-	P	-	P	-	-	-
Baez[a]	Bp2 (middle)	P	-	-	-	-	-	P	-	-	-	-	-
Code104-4	Bp2 (middle)	-	P	P	P	-	P	P	P	-	-	-	-
Code 104-11	Bp2 (middle)	P	P	P	P	-	P	-	P	-	-	-	-
051703-2	Bp2 (middle)	P[b]	P	P	P	P[b]	P	P[b]	P	-	-	-	-
04MX-11	Bp2 (middle)	P[b]	P	-	-	-	-	-	-	-	-	-	-
04MX-10	Bp2 (middle)	P	P	P	P	P	P	-	-	-	-	-	-
JEB07-MX3	Bp2 (base)	P	P	P	P	-	-	-	-	-	-	-	-
JEB07-MX8	Bp2 (base)	P[b]	P	P	P	P	-	-	-	P	-	-	-
JEB07-MX2	Bp2 (base)	P	P	P	P	-	-	-	-	-	-	-	-
04MX-4	Bp2 (base)	P	P	P	P	P	-	-	-	-	-	-	-
Carnivore 03-2004[a]	Bp2 (base)	P	-	-	-	-	-	P	-	P	-	-	-
Code104-3	Bp2 (base)	P	P	P	-	-	-	-	-	-	-	-	-
04MX-5	Bc (top)	P[b]	P	P	P	P	P	-	-	-	-	-	-
JEB07-MX9	Bc (middle)	-	P	P	-	-	-	-	-	-	-	-	-
JEB07-MX7	Bc (middle)	P[b]	P	P	P	-	-	-	-	P	-	-	-
04MX-16	Bc (middle)	P[b]	P	P	P	P	P	P	P	-	-	-	-
04MX-6	Bc (base)	-	P	P	-	-	-	-	-	-	-	-	-
04MX-15	Bp1 (top)	P[b]	-	P	P	-	-	-	-	-	-	-	-
Code104-9	Bp1	P	P	-	P	P	P	-	-	-	-	-	-
05MX-5A	Bp1	P	P	-	P	P	-	-	-	-	-	P	-
05MX-5B	Bp1	P	P	-	P	P	-	-	-	-	-	-	-
JEB06-MX13B	Bp1	P	P	P	-	-	-	-	P	-	P	P	P
Swift Turtle[a]	Bp1	P	-	-	-	-	-	P	-	P	-	-	P
Imhoff 2001[a]	Bp1	P	-	-	-	-	-	-	-	-	P	-	-
Betwixt 2003[a]	Ac-Bp1	P[b]	-	P	-	-	-	-	-	-	P	-	-
Imhoff-Ramon[a]	Ac-Bp1	P	-	-	-	-	-	-	-	-	-	-	-
Armadillo[a]	Ac-Bp1	P	-	-	-	-	-	-	-	-	-	-	-
05MX-6	Ac	-	-	P[c]	P	-	-	-	-	-	-	P	-
Code104-8	Ac	P	P	P	-	-	-	-	-	-	-	-	-
Camel Bill	As2-Ac	P[b]	P	P	P	P[b]	P	P	P	-	-	-	-
	Occurrence	29	24	24	19	10	9	8	6	5	5	3	2

Fc – *Fabaeformiscandona caudata*; Pp – *Physocypria pustulosa*; Cyp – *Cypridopsis vidua*; Ds – *Darwinula stevensoni*; Ib – *Ilyocypris bradyi*;. Pot – *Potamocypris* sp.; Em – *Eucypris meadensis*; Stn – *Stenocypris* sp.; Cha – *Chlamydotheca arcuata*; Hi – *Heterocypris incongruens*; Lp – *Limnocythere paraornata*; Pt – *Pelocypris* cf. *P. tuberculatum*. [a] Samples processed by N.A.U. Laboratory of Paleoecology and screen washed at 300 µm. [b] Species used for stable isotope analysis. [c] Includes several valves of *Cypridopsis okeechobei*.

des at Térapa undoubtedly required optimal water temperatures that were much warmer than 20°C. For example, Bowen (1976) reported that *Stenocypris* sp. would only appear in a pond in South Carolina when the minimum water temperature exceeded 28°C, and Forester (1991) recovered *Chlamydotheca* from several springs in the western U.S. and northern Mexico where water temperatures were between 25°C and 32°C.

The water temperature requirements of the tropical ostracode species at Térapa provide insight into summer temperatures in northeastern Mexico at 40–43 ka. A modern shallow lake in north-central Sonora (Lake El Yeso; Figure 1) has mean monthly lake water temperatures that are, on average, about 3°C cooler than the mean monthly air temperatures (Palacios-Fest and Dettman, 2001). Using the water and air temperature relationship at Lake El Yeso as an analog, the mean summer air temperature at Térapa during OIS 3 could not have been more than 5°C cooler than today (Figure 4) in order to support the tropical ostracode taxa. This estimate seems reasonable based on temperature reconstructions for the last glacial period from southern California, southern Arizona, and southern Texas that collectively suggest a reduction in annual temperatures of about 4°C to 6°C, with associated errors of ± 0.5°C to ±1.1°C depending on the study (Stute *et al.*, 1992; Anderson *et al.*, 2002; Holmgren *et al.*, 2006; Kulongoski *et al.*, 2009).

To our knowledge, the Térapa locality is only the third reported fossil occurrence of *F. caudata* in northern Mexico, with the other two being from Late Pleistocene sediments deposited in Laguna Babicora, Chihuahua (Figure 1; Palacios-Fest *et al.*, 2002), and juvenile valves that have been reported from extensive but undated sediments at Comarca Lagunera (Paleolake Irritia) of Durango and Coahuila (Czaja *et al.*, 2014). The modern distribution of *F. caudata* is confined to Canada and the continental United States (Forester *et al.*, 2005) where it lives in water with optimal and maximum temperatures of about 6°C to

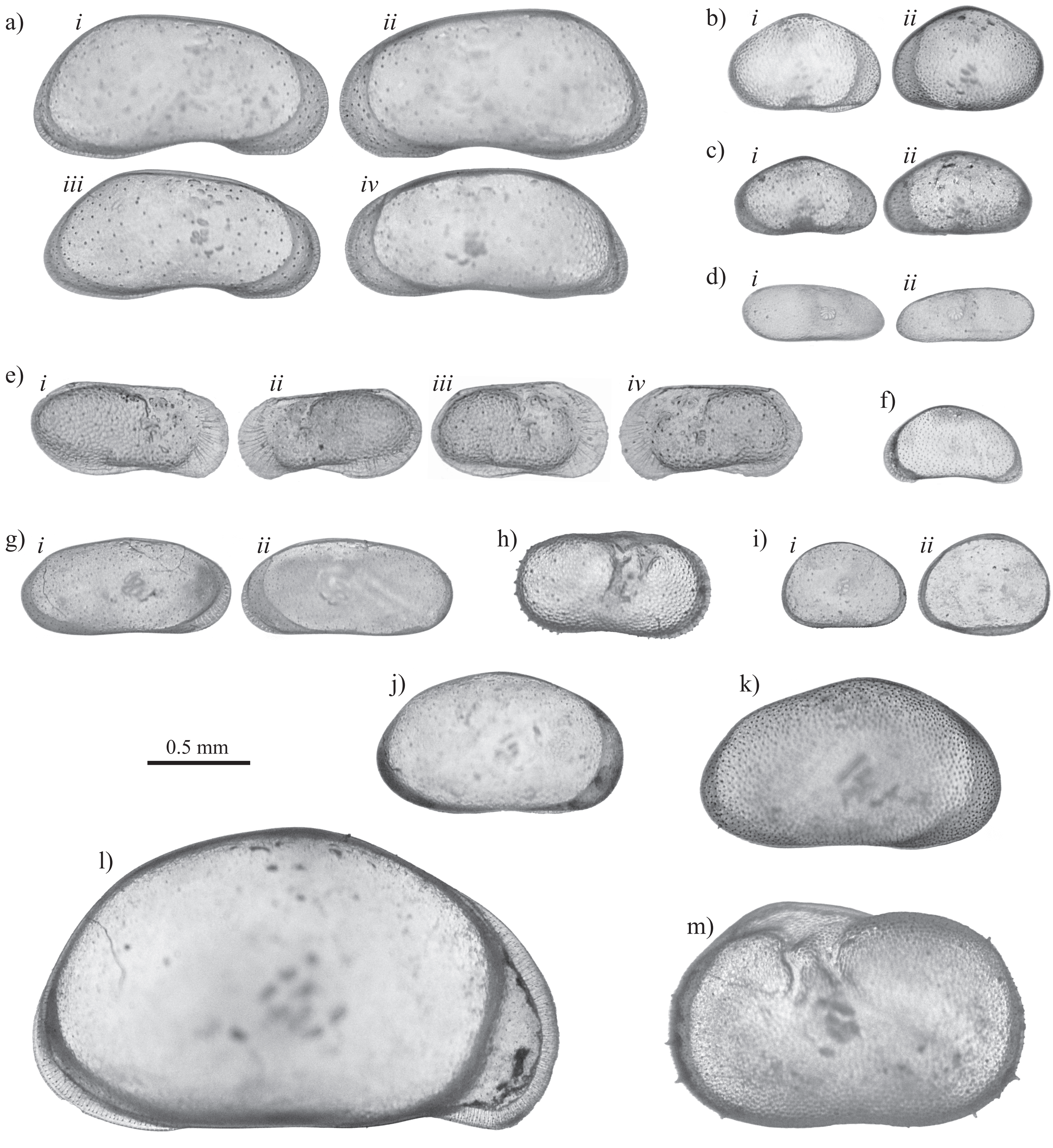

Figure 5. Digital images of the fossil ostracode fauna at Térapa, Sonora, Mexico. Group a) *Fabaeformiscandona caudata* ; *i*- male right valve, *ii*- male left valve, *iii*- female right valve, *iv* - female left valve. Group b) *Cypridopsis vidua*; *i*- right valve, *ii*- left valve. Group c) *Cypridopsis okeechoebi*; *i*- right valve, *ii*- left valve. Group d) *Darwinula stevensoni*; *i*- right valve, *ii*- left valve. Group e) *Limnocythere paraornata*; *i*- male right valve, *ii*- male left valve, *iii*- female right valve, *iv*- female left valve. f) *Potamocypris* sp., left valve. Group g) *Stenocypris* sp.; *i*- right valve, *ii*- left valve. Group h) *Ilyocypris bradyi*, right valve; Group i) *Physocypria pustulosa*; *i*- right valve, *ii*-left valve. j) *Heterocypris incongruens*; right valve. k) *Eucypris meadensis*; right valve. l) *Chlamydotheca arcuata*; right valve. m) *Pelocypris* cf. *P. tuburculatum*; left valve. All images are external lateral views taken under transmitted light using an Olympus SXZ-12 binocular microscope fitted with an Olympus DP71 digital camera. Images were modified in Photoshop CS3 for contrast and clarity.

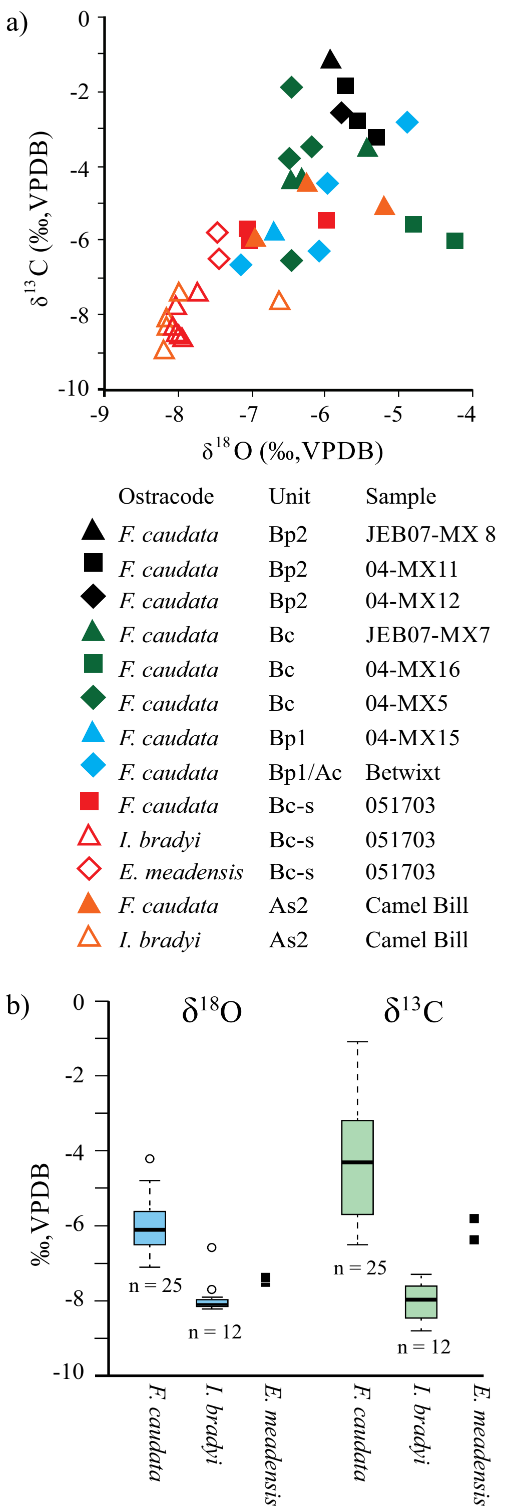

Figure 6. Uncorrected $\delta^{18}O$ and $\delta^{13}C$ values (‰, VPDB) from ostracode calcite preserved at Térapa, Sonora, Mexico. a) Cross-plot of individual $\delta^{18}O$ and $\delta^{13}C$ values are grouped by ostracode taxon and sedimentary unit. Sedimentary unit and sample names are as in Figure 4. b) Box-and-whisker plots of uncorrected $\delta^{18}O$ values (blue boxes) and $\delta^{13}C$ values (green boxes) from *Fabaeformiscandona caudata* and *Ilyocypris bradyi* valves. Thick black line – median value, colored box – 1st to 3rd quartile values, dashed lines and whiskers – maximum and minimum as 1.5×interquartile range, open circles – outliers. Individual $\delta^{18}O$ and $\delta^{13}C$ values from two *Eucypris meadensis* valves are plotted as small black boxes.

12°C and 18°C, respectively (Curry, 1999). Although *F. caudata* can tolerate water temperatures above 20°C, it does not live in areas where such temperatures persist annually (Forester, 1991). The southward expansion of *F. caudata* into northern Mexico during the last glacial interval is most likely attributed to the southward expansion of polar air masses (*e.g.*, Kutzbach and Wright, 1985; Kutzbach, 1987; Ortega-Ramírez *et al.*, 1998), which was probably accompanied by a reduction in summer temperatures. Although *F. caudata* and *C. arcuata* are found together at Térapa, the optimal water temperatures reported for *F. caudata* are several degrees cooler than the lower survival limit of *C. arcuata* (Forester, 1991). The most likely explanation is that the life cycles of these two ostracodes were seasonally offset, with *F. caudata* completing its life cycle during the cooler spring or fall months and *C. arcuata* completing its life cycle during the warmer summer months (*e.g.*, Bowen, 1976; Pieri *et al.*, 2007).

Surface water $\delta^{18}O$ reconstruction and seasonality of precipitation

Correcting ostracode $\delta^{18}O$ values for vital effects

Ostracodes molt eight or nine times over the course of their life cycle and calcify their new valves within a few hours to at most a few days after molting (Turpen and Angel, 1971; Chivas *et al.*, 1983). Rather than providing a continuous isotopic record over weeks to years like mollusk shell or tooth enamel, the calcite in ostracode valves provides a "snapshot" of the $\delta^{18}O$ composition of the host water at the time the ostracode molted.

Unlike inorganic calcite, the oxygen isotope value in ostracode calcite ($\delta^{18}O_{OST}$) does not appear to be in isotopic equilibrium with the surrounding water; for a given water temperature and $\delta^{18}O$ value, $\delta^{18}O_{OST}$ is usually more positive than the expected equilibrium value (*e.g.*, Pérez *et al.*, 2013), partially because of the presence of a poorly understood "vital effect" (*e.g.*, von Grafenstein *et al.*, 1999). The $\delta^{18}O$ vital effect in ostracodes is species specific, but is probably relatively similar within any given genus (von Grafenstein *et al.*, 1999). Numerous natural calibration studies on a variety of *Fabaeformiscandona* species report vital effects of about +2‰ to +3‰ (*e.g.*, von Grafenstein *et al.*, 1999; Keatings *et al.* 2002; Wetterich *et al.*, 2008; Belmecheri *et al.*, 2010). Xia *et al.* (1997) reported a slightly lower vital effect of about +1‰ from laboratory cultured *F. rawsoni*. However, the ostracode valves from this experiment were less massive than the valves of naturally occurring *F. rawsoni* and this vital effect may not be accurate. We favor correcting the *F. caudata* $\delta^{18}O$ values using vital effects of +2‰ and +3‰ because of the larger naturally calibrated data set.

Correcting the *I. bradyi* $\delta^{18}O$ results ($\delta^{18}O_{ILY}$) is more problematic because a vital effect for *Ilyocypris* has not been clearly established. Published vital effects for various species of *Ilyocypris* are as high as about +2‰ (Develle *et al.* 2010) and as low as about +0.2‰ (Schwalb *et al.* 2002; Belis and Ariztegui, 2004; Mischke *et al.*, 2008; Lawrence *et al.*, 2008). For the purposes of this paper we corrected the *I. bradyi* $\delta^{18}O$ values using vital effects of 0‰ and +2‰.

To our knowledge, there are no data on vital effects specifically for *E. meadensis* calcite. Li and Liu (2010) demonstrated that there is no vital effect in cultured *E. mareotica* at 10°C and a small negative vital effect at both 15°C and 19°C. Based on our optimal water temperature estimate (see below), the *E. meadensis* $\delta^{18}O$ values were not corrected for any vital effect.

The $\delta^{18}O$ value of ostracode calcite ($\delta^{18}O_{OST}$) is dictated by the water temperature and the $\delta^{18}O$ value of the water ($\delta^{18}O_{SW}$) in which the ostracode calcified its valves (von Grafenstein *et al.*, 1999). Our $\delta^{18}O_{OST}$ (VPDB) values were converted to surface water $\delta^{18}O$ values ($\delta^{18}O_{SW}$; VSMOW) using the calcite-water fractionation data of Friedman and

Table 2. Stable oxygen (δ^{18}O) and carbon (δ^{13}C) isotope values in ostracode calcite from Térapa, Sonora, Mexico.

Sample	**Lat** (°N)	**Long** (°W)	**Genus species**	**n**	**Unit** (Figure 4)	**δ^{18}O** (‰, VPDB)	**δ^{13}C** (‰, VPDB)
04MX-12	29.688561	109.653133	*Fabaeformiscandona caudata*	2	Bp2	-5.9	-1.1
04MX-11	29.688561	109.653133	*Fabaeformiscandona caudata*	2	Bp2	-5.7	-1.8
04MX-11	29.688561	109.653133	*Fabaeformiscandona caudata*	2	Bp2	-5.3	-3.2
04MX-11	29.688561	109.653133	*Fabaeformiscandona caudata*	2	Bp2	-5.6	-2.7
JEB07-MX8	29.689275	109.653192	*Fabaeformiscandona caudata*	2	Bp2	-5.8	-2.6
51703	29.688561	109.653133	*Ilyocypris bradyi*	4	Bc-s	-8.1	-7.7
51703	29.688561	109.653133	*Ilyocypris bradyi*	4	Bc-s	-8.1	-8.4
51703	29.688561	109.653133	*Ilyocypris bradyi*	3	Bc-s	-8.0	-8.5
51703	29.688561	109.653133	*Ilyocypris bradyi*	3	Bc-s	-7.7	-7.3
51703	29.688561	109.653133	*Ilyocypris bradyi*	3	Bc-s	-8.1	-7.9
51703	29.688561	109.653133	*Ilyocypris bradyi*	3	Bc-s	-7.9	-8.5
51703	29.688561	109.653133	*Fabaeformiscandona caudata*	2	Bc-s	-7.0	-6.0
51703	29.688561	109.653133	*Fabaeformiscandona caudata*	2	Bc-s	-7.1	-5.7
51703	29.688561	109.653133	*Fabaeformiscandona caudata*	2	Bc-s	-6.0	-5.4
51703	29.688561	109.653133	*Eucypris meadensis*	1	Bc-s	-7.5	-5.8
51703	29.688561	109.653133	*Eucypris meadensis*	1	Bc-s	-7.4	-6.4
04MX-5	29.689275	109.653192	*Fabaeformiscandona caudata*	2	Bc	-6.2	-3.5
04MX-5	29.689275	109.653192	*Fabaeformiscandona caudata*	2	Bc	-6.4	-6.5
04MX-5	29.689275	109.653192	*Fabaeformiscandona caudata*	1	Bc	-6.4	-3.8
04MX-5	29.689275	109.653192	*Fabaeformiscandona caudata*	1	Bc	-6.5	-1.8
JEB07-MX7	29.689275	109.653192	*Fabaeformiscandona caudata*	2	Bc	-5.4	-3.4
JEB07-MX7	29.689275	109.653192	*Fabaeformiscandona caudata*	2	Bc	-6.5	-4.3
JEB07-MX7	29.689275	109.653192	*Fabaeformiscandona caudata*	2	Bc	-6.3	-4.2
04MX-16	29.688561	109.653133	*Fabaeformiscandona caudata*	2	Bc	-4.2	-5.9
04MX-16	29.688561	109.653133	*Fabaeformiscandona caudata*	2	Bc	-4.8	-5.5
04MX-15	29.688561	109.653133	*Fabaeformiscandona caudata*	2	Bp1	-6.7	-5.7
Betwixt	29.685936	109.652986	*Fabaeformiscandona caudata*	2	Ac-Bp1	-5.9	-4.5
Betwixt	29.685936	109.652986	*Fabaeformiscandona caudata*	2	Ac-Bp1	-7.1	-6.5
Betwixt	29.685936	109.652986	*Fabaeformiscandona caudata*	1	Ac-Bp1	-6.1	-6.2
Betwixt	29.685936	109.652986	*Fabaeformiscandona caudata*	1	Ac-Bp1	-4.9	-2.7
Camel Bill	29.689275	109.653192	*Ilyocypris bradyi*	3	As1-2	-8.0	-7.3
Camel Bill	29.689275	109.653192	*Ilyocypris bradyi*	3	As1-2	-8.1	-8.0
Camel Bill	29.689275	109.653192	*Ilyocypris bradyi*	3	As1-2	-6.6	-7.5
Camel Bill	29.689275	109.653192	*Ilyocypris bradyi*	3	As1-2	-8.1	-7.9
Camel Bill	29.689275	109.653192	*Ilyocypris bradyi*	3	As1-2	-8.2	-8.8
Camel Bill	29.689275	109.653192	*Ilyocypris bradyi*	3	As1-2	-8.2	-8.2
Camel Bill	29.689275	109.653192	*Fabaeformiscandona caudata*	2	As1-2	-7.0	-5.8
Camel Bill	29.689275	109.653192	*Fabaeformiscandona caudata*	2	As1-2	-5.2	-5.0
Camel Bill	29.689275	109.653192	*Fabaeformiscandona caudata*	2	As1-2	-6.3	-4.3

O'Neil (1977) and the optimal (6°C to 12°C) and maximum (18°C) modern water temperature constraints for *F. caudata* (Curry, 1999), which was the most common ostracode in the Térapa sediments (Table 1) and comprised the bulk of the $\delta^{18}O_{OST}$ results (Figures 4 and 6; Table 2). The 6°C range in optimal water temperatures will produce about a 1.5‰ VSMOW range in the reconstructed $\delta^{18}O_{SW}$ estimates, which is sensitive enough for the purpose of this study.

Reconstructing surface water $\delta^{18}O$ values at Térapa

The ostracode-based surface water δ^{18}O reconstruction for Térapa ($\delta^{18}O_{SW\text{-}OST}$; VSMOW), using the optimal temperature range for *F. caudata* (6°C to 12°C) and assuming vital effects of 0‰ for both *Ilyocypris* and *Eucypris* and +2‰ to +3‰ for *F. caudata,* is -10 ± 1‰ (Figure 7). Increasing the temperature of calcification to the upper temperature limit for *F. caudata* (18°C) increases the $\delta^{18}O_{SW\text{-}OST}$ estimate to about -8 ± 1‰, with one maximum value of about -6‰ (Figure 7). More negative $\delta^{18}O_{SW\text{-}OST}$ estimates of about -12‰ at water temperatures of 6°C to 12°C and about-10‰ at a water temperature of 18°C are produced when the $\delta^{18}O_{ILY}$ values are corrected for a +2‰ vital effect.

The reconstructed $\delta^{18}O_{SW\text{-}OST}$ values for Térapa at 40–43 ka (Figure 7) indicate that the isotopic composition of the Térapa impoundment was dominated by winter precipitation and runoff. This result agrees with other speleothem (Szabo *et al.*, 1994; Wagner *et al.*, 2010; Asmerom *et al.*, 2010) and numerous paleolake/paleowetland studies in the southwestern U.S. and northwestern Mexico (Ortega-Guerrero *et al.*, 1999; Anderson *et al.*, 2002; Kirby *et al.*, 2006; Allen *et al.*, 2009; Pigati *et al.*, 2009, 2011; Roy *et al.*, 2010, 2012; Garcia *et al.*, 2014; Reheis *et al.*, 2015) that suggest increased winter moisture at about 40-45 ka, the time the Térapa sediments were deposited.

Comparing ostracode-based and tooth enamel-based surface water $\delta^{18}O$ reconstructions for Térapa

We also compared our $\delta^{18}O_{OST}$ with both bulk and serial $\delta^{18}O$ values from herbivore tooth enamel ($\delta^{18}O_{EN}$) previously recovered from Térapa (Nunez *et al.*, 2010). Enamel $\delta^{18}O$ values are often used to reconstruct paleo-water $\delta^{18}O$ values (*e.g.*, Widga *et al.*, 2010; Metcalfe *et al.*, 2011; Pérez-Crespo *et al.*,2012), and Térapa affords the opportunity to compare $\delta^{18}O_{SW}$ reconstructions from the same site based on two commonly used archives; ostracode calcite and tooth enamel. The $\delta^{18}O_{EN}$ values (VPDB) from Nunez *et al.* (2010) were converted to surface water values ($\delta^{18}O_{SW\text{-}EN}$, VSMOW) using the equations provided in their results section.

Several studies have demonstrated that the $\delta^{18}O_{EN}$ values from large herbivores are strongly positively correlated with $\delta^{18}O_{SW}$ (Huertas *et al.*, 1995; Kohn *et al.*, 1996; Hoppe *et al.*, 2004). The strength of the correlation between $\delta^{18}O_{SW}$ and $\delta^{18}O_{EN}$ increases with the body size of the herbivore because larger animals are preferentially obligate drinkers (*e.g.*, Bryant and Froelich, 1995; Hoppe *et al.*, 2004). Smaller herbivores are better able to meet their water requirement through the food that they eat which weakens or eliminates the correlation between $\delta^{18}O_{SW}$ and $\delta^{18}O_{EN}$ in small animals (Huertas *et al.*, 1995). Instead, the $\delta^{18}O_{EN}$ in small herbivores correlate better with humidity as it relates to evaporation and water stress on vegetation (Huertas *et al.*, 1995). Leaves, especially in arid environments, can have $\delta^{18}O$ values as much as 20‰ higher than the water absorbed at the plant root (Förstel, 1978; Kohn *et al.*, 1996).

In order to generate the best comparison, we excluded the bulk tooth $\delta^{18}O_{EN}$ data from two small herbivores (peccary; +0.9‰; capybara, -5.3‰; Nunez *et al.* (2010)) and a very high outlier from a llama (+4.4‰; Nunez *et al.* (2010)). This produced an average bulk $\delta^{18}O_{SW\text{-}EN}$ estimate of about -4 ± 3‰ (n = 19). This value is dominated by the results from numerous horse teeth that cluster with consistently high $\delta^{18}O_{SW\text{-}EN}$ values (-3 ± 3‰; n = 10). Nunez *et al.* (2010) produced serial $\delta^{18}O_{EN}$ values from a bison and a horse tooth that captured 1 and 2 years of hydrologic information, respectively. When converted to $\delta^{18}O_{SW\text{-}EN}$ values, the serial bison and horse teeth results are also on the order of -4‰ to +2‰. We recognize that both the bulk and serial horse $\delta^{18}O_{SW\text{-}EN}$ values may be slightly too high because of a potential offset between $\delta^{18}O_{EN}$ and $\delta^{18}O_{SW}$ that has been reported for modern horses (Hoppe *et al.*, 2004), but that does not change the observation that the majority of $\delta^{18}O_{SW\text{-}EN}$ estimates at Térapa are roughly 4‰ to 12‰ higher than the $\delta^{18}O_{SW\text{-}OST}$ estimate (Figure 7).

The dissimilarity between $\delta^{18}O_{SW\text{-}OST}$ and $\delta^{18}O_{SW\text{-}EN}$ at Térapa was unexpected and intriguing. The $\delta^{18}O_{SW\text{-}OST}$ and $\delta^{18}O_{SW\text{-}EN}$ values lead to very different paleohydrologic interpretations; the $\delta^{18}O_{SW\text{-}OST}$ estimate favors winter-derived moisture, whereas the $\delta^{18}O_{SW\text{-}EN}$ estimate favors significant amounts of monsoon-derived moisture or possibly a very evaporative environment. If we assume that the $\delta^{18}O_{SW\text{-}EN}$ estimate is correct, then to generate the measured $\delta^{18}O_{OST}$ values would require either the absence of any vital effects and calcification in 18–20°C water, or the presence of vital effects and calcification in >28°C water. Both of these options seem unreasonable based on the available literature regarding $\delta^{18}O$ systematics in ostracode calcite (*e.g.*, von Grafenstein *et al.*, 1999) and the ecological tolerances of the ostracodes used in this study (Forester, 1991; Curry, 1999) which are admittedly skewed towards ostracode occurrences at higher latitudes than Térapa. Diagenetic alteration of the $\delta^{18}O_{EN}$ values is not a likely cause for the discrepancy because alteration typically changes $\delta^{18}O_{EN}$ by about ±1‰ (Kohn *et al.*, 1999), which is much less than the offset between the $\delta^{18}O_{SW\text{-}OST}$ and $\delta^{18}O_{SW\text{-}EN}$ values reported here. The most likely explanation for the offset is that the ostracodes consistently calcified their valves during the spring or early summer when the runoff feeding the impoundment was still dominated by winter precipitation. Additionally, the high $\delta^{18}O_{EN}$ values from the large mammals may suggest that the animals consistently drank from evaporated water sources (*e.g.*, Hoppe *et al.*, 2004; Wigda *et al.*, 2010) or incorporated a higher than expected proportion of evaporated leaf-water in their diet (*e.g.*, Feranec and MacFadden, 2006; Zanazzi and Kohn, 2008; Pérez-Crespo *et al.*, 2016), or perhaps the animals (especially the horses) migrated through the Térapa area. If the large herbivores are migrants then their $\delta^{18}O_{EN}$ values may include contributions from non-local water sources (*e.g.*, Pérez-Crespo *et al.*, 2012).

Ostracode $\delta^{13}C$ values and paleovegetation reconstruction

The $\delta^{13}C$ value in ostracode calcite ($\delta^{13}C_{OST}$) faithfully records the $\delta^{13}C$ value of dissolved inorganic carbon ($\delta^{13}C_{DIC}$) of the water the ostracode calcified its valves in (von Grafenstein *et al.*, 1999). The isotopic fractionation of carbon between aqueous carbon dioxide (CO_2) and inorganic calcite produces a calcite $\delta^{13}C$ value that, over the range of 10°C to 25°C, is approximately +12‰ higher than the $\delta^{13}C$ value of the dissolved CO_2 in the host water (Romanek *et al.*, 1992).

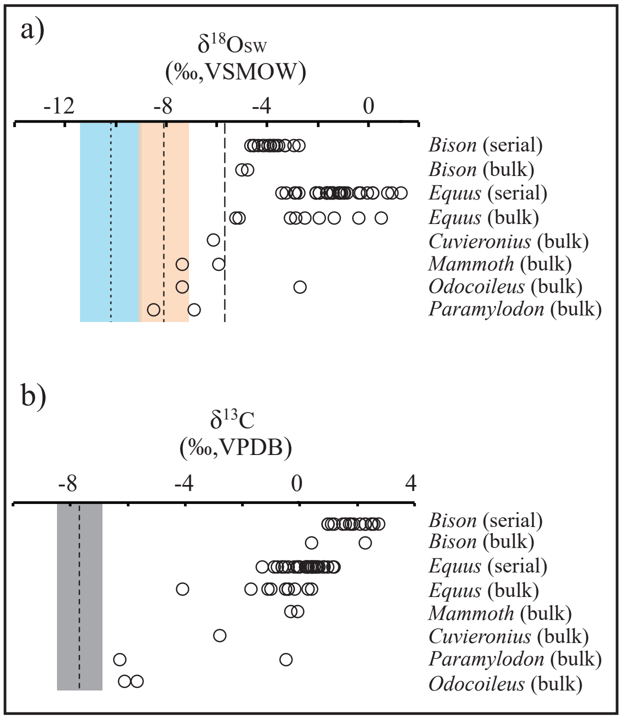

Figure 7. Comparisons of (a) reconstructed $\delta^{18}O_{SW}$ values (‰, VSMOW) of surface/meteoric water based on ostracode calcite and herbivore tooth enamel (open circles), and (b) the range of $\delta^{13}C$ values in ostracode calcite and herbivore tooth enamel (open circles) at Térapa, Sonora, Mexico, during mid-OIS 3. Open circles in (a) and (b) are values derived from bulk and serial analysis of enamel from the teeth of large herbivores collected throughout the deposit (Nunez *et al.*, 2010). Finest dashed vertical line and faint blue box in (a) are the mean and 1σ standard deviation, respectively, of $\delta^{18}O_{SW}$ values calculated from all ostracode calcite samples corrected for various vital effects and calcified over the preferred water temperature range of 6°C to 12°C. Medium dashed vertical line and faint orange box in (a) are the mean and 1σ standard deviation, respectively, of $\delta^{18}O_{SW}$ values calculated from all ostracode calcite samples corrected for various vital effects and calcified at the maximum water temperature estimate of 18°C. Coarsest dashed vertical line in (a) is the highest reconstructed $\delta^{18}O_{SW}$ value (see text for discussion). Medium dashed vertical line and grey box in (b) are the mean and 1σ standard deviation, respectively, of $\delta^{13}C$ values from all ostracode calcite samples.

In this study, we are interested in using $\delta^{13}C_{OST}$ values from *Ilyocypris bradyi*, an ostracode with a strong affinity for streams and flowing water (Curry, 1999; Quade *et al.*, 2003), to reconstruct the $\delta^{13}C_{DIC}$ value of the streams feeding the Térapa impoundment, and from that, broadly estimating the relative proportion of paleovegetation types present in the Térapa watershed at 40–43 ka.

Variables that influence ostracode $\delta^{13}C$ values

The $\delta^{13}C_{DIC}$ value of springs and streams is largely derived from respired soil CO_2 ($\delta^{13}C_{SOIL}$), which itself is derived from the surrounding plant community, although contributions from water-rock interactions, for instance the dissolution of marine carbonate bedrock ($\delta^{13}C \approx 0‰$), may be present in groundwater as well. Terrestrial vegetation can be subdivided into C_4, C_3, and Crassulacean Acid Metabolism (CAM) groups, with each group having a representative range of $\delta^{13}C$ values. Grasses and other plants that use the C_4 photosynthetic pathway generally have higher $\delta^{13}C$ values (-13 ± 2‰) than woody plants and shrubs that use the C_3 photosynthetic pathway (-28 ± 3‰; O'Leary, 1981). Plants that use the CAM photosynthetic pathway (*e.g.*, cactus, agave, yucca) have intermediate $\delta^{13}C$ values (-13‰ to -27‰; O'Leary, 1981) that overlap with C_3 and C_4 plants. Obligate CAM plants have $\delta^{13}C$ values closer to C_4 plants, whereas facultative CAM plants tend to have $\delta^{13}C$ values that are closer to C_3 plants (Griffiths, 1992). Thus, the $\delta^{13}C$ value of CAM plants overlaps those of C_3 and C_4 plants, rendering them isotopically invisible as a group. As a result, our discussion of plant communities is restricted to an estimate of the apparent abundances of C_3 and C_4 plants, recognizing that the C_3 category may contain contributions from facultative CAM plants and that the C_4 category may contain contributions from obligate CAM plants. And finally, aquatic vegetation typically has very low $\delta^{13}C$ values (-25 to -30‰; Keeley and Sandquist, 1992).

Further complicating the issue is the fact that some ostracode species live within the top few cm of sediment (epifaunal; Decrouy *et al.*, 2012) and may calcify their valves within the sediment. Epifaunal species may record the $\delta^{13}C_{DIC}$ value of sediment pore water rather than of the overlying water body (Decrouy *et al.*, 2012). Consequently, $\delta^{13}C_{OST}$ of epifaunal ostracodes may be lower than expected because the valves were calcified in an environment where decaying organic matter often leads to pore water that is enriched in respired ^{12}C (*e.g.*, Keeley and Sandquist, 1992; Decrouy *et al.*, 2011).

Reconstructing ground cover at Térapa

The modern flora of the Sonoran Desert consists of roughly 50% annuals and 50% perennials (*e.g.*, Venable and Pake, 1999). The winter annual flora is populated exclusively by C_3 plants whereas the summer annual flora is dominated by C_4 plants (summer annual C_3:C_4 = 35:65; Mulroy and Rundel, 1977). Perennials are comprised mostly of C_3 and CAM plants (Drennan and Nobel, 1997). Packrat middens dating to the last glacial period (60 to ~13 ka) indicate that much of the Sonoran Desert landscape between about 300 and 1,300 m a.s.l. was dominated by pinyon-juniper-oak woodlands and chaparral (Van Devender, 1990). Similar packrat midden studies and the isotopic analysis of megaherbivore (e.g, mammoth, bison, horse) tooth enamel have suggested that summer monsoon precipitation supported C_4 grasslands throughout much of the southwestern U.S. and northern Mexico during the last glacial period (*e.g.*, Connin *et al.*, 1998; Holmgren *et al.*, 2006, 2007).

The average $\delta^{13}C$ value (VPDB) for *I. bradyi* ($\delta^{13}C_{ILY}$) is about -8‰ (Figure 6; Table 2). Reducing this value by 12‰ (*e.g.*, Romanek *et al.*, 1992) produces a $\delta^{13}C$ value (VPDB) for dissolved aqueous CO_2 of about -20‰. Subtracting an additional 4‰ for the kinetic fractionation of CO_2 in soil profiles (Cerling, 1984) the $\delta^{13}C_{OST}$ value could have been derived from a landscape with a $\delta^{13}C_{SOIL}$ value of about -24‰. The C_3 and C_4 vegetation at Térapa was assigned end member values of -28‰ and -13‰, respectively, based on previous studies in similar desert environments (Mooney *et al.*, 1989; Biedenbender *et al.*, 2004). If Térapa had a $\delta^{13}C_{SOIL}$ value of about -24‰ then that would suggest ground cover with a C_3:C_4 ratio of about 75:25.

Comparing ostracode-based and tooth enamel-based paleovegetation reconstructions for Térapa

At face value, a C_3-dominated flora surrounding Térapa at 40–43 ka contrasts with the enamel results of Nunez *et al.* (2010), where they concluded that C_4 grasses and perhaps obligate CAM plants were abundant around Térapa and comprised a significant portion of the diet of even typically obligate browsing herbivores (*i.e.*, *Odocoileus*; Figure 7). The discrepancy between our C_3-dominated interpretation and Nunez *et al.*'s (2010) C_4-rich interpretation (Figure 7) may be explained by several factors. First, the $\delta^{13}C_{ILY}$ and $\delta^{13}C_{EN}$ values are derived from two very different processes. The $\delta^{13}C_{ILY}$ values likely reflect the averaged $\delta^{13}C_{SOIL}$ composition of the surrounding watershed during the season that the ostracodes preferentially calcified their valves, whereas the $\delta^{13}C_{EN}$ values undoubtedly incorporate a selective dietary preference for each animal (*e.g.*, Feranec and MacFadden, 2006). Second, the $\delta^{18}O_{OST}$ values suggest a winter-dominated precipitation regime. If so, then the $\delta^{13}C_{DIC}$ of runoff was probably dominated by a winter vegetation signal that would have been skewed towards C_3 plants. Similarly, we suspect that the streams that fed the Térapa impoundment drained the highlands to the east (Figure 2) and may have had $\delta^{13}C_{DIC}$ values that were skewed towards the low values typical of a woodier C_3-dominated mountainous ecosystem. And finally, *I. bradyi* may have calcified in ^{12}C-enriched microhabitats such that their $\delta^{13}C$ values would be lower than the bulk stream value. This would suggest that additional factors that should have increased the $\delta^{13}C_{DIC}$ value, such as the absorption of atmospheric CO_2 ($\delta^{13}C \approx -6.7‰$; Köhler *et al.*, 2010) or the decay of C_4 organic material that might have washed into the streams, were outweighed by the decay of aquatic vegetation within the streams. A combination of these seasonal and habitat-specific factors likely produced $\delta^{13}C_{ILY}$ values that significantly underestimate the abundance of C_4 plants on the landscape. In spite of their aquatic origin and likely seasonal bias, the $\delta^{13}C_{ILY}$ values still require about 25% input from C_4 plants, suggesting that C_4 plants were perhaps abundant near Térapa, as Nunez *et al.* (2010) concluded.

CONCLUSIONS

A fossil ostracode fauna and stable isotope ($\delta^{18}O$ and $\delta^{13}C$) analyses have been used to reconstruct the paleoenvironment during the deposition of a unique megafauna vertebrate assemblage at Térapa, Sonora, Mexico, during mid-OIS 3 (about 40–43 ka). The fossil ostracode fauna was comprised of 12 genera and 13 species. Species that reflect flowing water and more quiescent conditions were found intermixed. Most of the ostracode species are common, wide-spread temperate species, but two, *C. arcuata* and *Stenocypris* sp., have tropical affinities. The mix of temperate and tropical ostracode species mirrors the mix of temperate and tropical vertebrate fossils recovered from the site. Based on the presence of tropical ostracode species, summer temperatures at Térapa at 40–43 ka were at most ~5°C cooler than at present. The fresh-water ostracode fauna and low $\delta^{18}O_{OST}$ values suggest that the water body at Térapa was through-flowing. Our ostracode-based TDS estimate for the impoundment is on the order of 200–600 $mg \cdot L^{-1}$.

The $\delta^{18}O_{OST}$ and $\delta^{13}C_{ILY}$ values from throughout the deposit suggest that winter precipitation dominated the hydrologic cycle and that the surrounding vegetation community was dominated by C_3 plants. The

$\delta^{18}O_{SW-OST}$ estimate for Térapa at 40-43 ka was approximately -10 ± 2‰ VSMOW, indicating that increased winter precipitation dominated the surface runoff. This finding is consistent with other paleoclimatic studies from the southwestern U.S. and northern Mexico at 45–40 ka. The $\delta^{18}O_{SW-OST}$ estimate is roughly 4‰ to 12‰ lower than the $\delta^{18}O_{SW-EN}$ estimates derived from teeth of large herbivores collected from the same site, however. The $\delta^{13}C_{ILY}$ results suggest that C_3 plants dominated the landscape (perhaps 75%), although associated herbivore tooth enamel suggests a strong C_4 (*i.e.*, grass) component was present. Because of the season and aquatic setting in which the ostracode valves were likely calcified, the $\delta^{13}C_{OST}$ values probably underestimate the proportion of C_4 plants that were on the landscape.

The Térapa vertebrate site is an excellent example of how different isotopic archives can produce very different paleoenvironmental interpretations from the same deposit. Térapa provides a cautionary example of how using a single isotopic archive to reconstruct desert paleohydrology may be misleading. When used individually, the ostracode and enamel $\delta^{18}O$ and $\delta^{13}C$ values suggested opposing precipitation and vegetation regimes. The ostracode results favor a winter-dominated hydrology and a C_3-rich vegetation community whereas the tooth enamel results favor a summer-dominated or more evaporative hydrology and a C_4-rich vegetation community. A more complete interpretation emerged when both datasets were used together. Interpretive differences arose because the processes that produced the $\delta^{18}O$ and $\delta^{13}C$ values in the ostracode calcite and herbivore enamel captured paleoenvironmental information at different spatial, temporal, and seasonal scales.

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