Turkish Journal of Earth Sciences
http://journals.tubitak.gov.tr/earth/
Research Article

Turkish J Earth Sci
(2020) 29: 406-417
© TÜBİTAK
doi:10.3906/yer-1906-9

Stable carbon and oxygen isotopes as environmental indicators of the Late Pleistocene in El Arenoso, Sonora, Northwest Mexico

Víctor Adrían PÉREZ-CRESPO[1,*], **Tamara CRUZ-Y-CRUZ**[2,3], **Alejandro TERRAZAS-MATA**[3], **Pedro MORALES-PUENTE**[1,4], **Martha BENAVENTE**[5], **Edith CIENFUEGOS-ALVARADO**[1,4], **Francisco J. OTERO**[1,4]
[1]Institute of Geology, National Autonomous University of Mexico, Coyoacán, Mexico
[2]Postdoctoral Scholarship Program at UNAM, Institute of Anthropological Research, Coyoacán, Mexico
[3]Institute of Anthropological Research, National Autonomous University of Mexico, Coyoacán, Mexico
[4]National Laboratory of Geochemistry and Mineralogy (LANGEM), Mexico City, Mexico
[5]Laboratory of Prehistory and Human Evolution, Institute of Anthropological Research, National Autonomous University of Mexico, Coyoacán, Mexico

Received: 10.06.2019 • **Accepted/Published Online:** 31.10.2019 • **Final Version:** 16.03.2020

Abstract: The paleoenvironment conditions that existed in the Late Pleistocene at the archaeological-paleontological site of El Arenoso, Sonora, NW Mexico, were inferred using the carbon and oxygen stable isotopes from one bison, one mammoth, and thirteen horses as well as the pedological characteristics and the carbon isotopes of calcium carbonates from paleosoil. The values $\delta^{13}C$ of the bison (−1.4‰), the horses (−2.8‰), and the mammoth (−4.3‰) show that these animals fed mainly on C_4 plants and carbon isotopic values from profile horizons of locality 4Bgk (−3.4‰), 3Ck (−3.4‰), and 2Bgk2 (−5.7‰) indicated the presence of C_3/C_4 vegetation mixed in El Arenoso. The oxygen isotopic ratios of the bison (−4.3‰), the horses (−2.6‰), and the mammoth (−5.1‰) show that these animals inhabited an arid environment, consistent with the results from the analyses of paleosols.

Key words: Megafauna, paleosoils, stable isotopes, Sonora, environment

1. Introduction

Mexico was inhabited by various mammal species, especially of medium and large size, during the late Pleistocene, a geological epoch that ranges between 120,000 and 11,000 years before present (BP). Some of these mammals became extinct near the Holocene (Ferrusquia-Villafranca et al., 2010), which coincides with the arrival of the first humans to these lands (Lanata, 2011).

The oldest evidence of humans probably comes from Rancho La Amapola, Cedral, San Luis Potosí, a site dated between 33,000 and 2,480 years BP. Additionally, traces of human activity have been found in other areas of Mexico (Sánchez, 2001; Mirambell and Lorenzo, 2012; Stinnesbeck et al., 2017). One of these places is Sonora, a state that includes several localities with evidence of human presence during the late Pleistocene (Gaines and Sánchez, 2009; Gaines et al., 2009; Sánchez and Carpenter, 2016).

A key element to understand how the settlement of Mexico occurred is to determine the environmental conditions that prevailed during the late Pleistocene. To this end, paleoenvironmental studies are required using various approaches (Dincauze, 1987).

Cruz-y-Cruz et al. (2015, 2016) conducted isotopic carbon analyses of paleosols and dental enamel of the mastofauna discovered in the El Arenoso-Áigame region, Sonora, to understand environmental conditions. They concluded that this region was predominated by arid and cold conditions where a mixed C_3/C_4 vegetation developed. Although carbon isotope ratios provide information on the potential vegetation types that existed in a locality, Cruz-y-Cruz et al. (2016) used neither isotopic oxygen ratios of dental enamel, which give additional information about the climate that prevailed at a given site (Sánchez, 1997).

In this study, we report the results of carbon and oxygen isotopic analyses obtained from a series of samples of two horse (*Equus* sp.) molars, in addition to isotopic oxygen values obtained from bison (*Bison* sp.), horse, and mammoth (*Mammuthus columbi*) samples. These values were contrasted with $\delta^{13}C$ values of dental enamel samples of these same specimens and with the carbon isotopic data for paleosols reported by Cruz-y-Cruz et al. (2016) in

---

* Correspondence: vapc79@gmail.com

order to explore potential differences or similarities with the El Arenoso paleoenvironment previously proposed from carbon isotopic values of paleosols.

1.1. Stable carbon and oxygen isotopes

Carbon is found in the atmosphere mostly as CO_2 and enters living organisms through photosynthesis, mainly through three pathways (Koch, 1998): in the first, i.e. the Calvin–Benson cycle, ribulose-1-5-bisphosphate-carboxylase/oxygenase participates in the photosynthetic process, and its first product is a three-carbon molecule, thus called C_3 (Medrano and Flexas, 2000). Plants that display this photosynthetic pathway present carbon isotope values of –35‰ to –22‰; this pathway occurs mainly in trees, shrubs, and some grasses in cold areas (Lee-Thorp et al., 1989; van Deer Merwe and Medina, 1989; Koch, 1998).

In the second, the enzyme involved is phosphoenolpyruvate carboxylase and the first product is a four-carbon molecule, hence named C_4 or Hatch–Slack. The leaves of plants that show this photosynthetic pathway have an adaptation called Kranz anatomy, which emerged millions of years ago in grasslands with some dicotyledonous herbs, such as the Asteraceae, in addition to some trees and shrubs from warm areas, with $\delta^{13}C$ values ranging from –14‰ to –12‰ (Stowe and Teeri, 1978; Cerling, 1999; Cerling and Ehleringer, 2000; Keely and Rundel, 2003). The third photosynthetic pathway, called Crassulacean acid metabolism (CAM), shows $\delta^{13}C$ values ranging from –35‰ to –12‰, making it difficult to differentiate it from the other pathways (Andrade et al., 2007).

Carbon from plants is taken up by herbivores and incorporated in their tissues; consequently, the type of plants consumed by a given animal can be inferred. Carbon is incorporated into apatite in dental enamel from HCO_3^- derived from CO_2 in the blood (Schwarcz, 2000; Martínez del Río and Wolf, 2005). This reaction is controlled by body temperature, which results in a 14.1‰ increase in $\delta^{13}C$ values in apatite from dental enamel of medium-sized and large mammals (Cerling and Harris, 1999). Thus, herbivores that consume C_3 plants will have $\delta^{13}C$ values ranging from –19‰ to –9‰; those that fed on C_4 plants, from –2‰ to 2‰; and those who consumed both types, from –9‰ to –2‰ (MacFadden and Cerling, 1996).

In soil, carbon comes from the incorporation of plant organic matter into the mineral fraction by the action of microorganisms, which assimilate it from plants and incorporate it into soil through respiration or as humus. During this process, the fractionation of carbon isotopes is minimal. As a result, isotopic values for organic matter in soil are indicative of the relative abundance of plants with C_3 or C_4 metabolism, which depends on the climatic conditions (Guerrero and Berlanga, 2000). Calcium carbonates form during pedogenesis through a process involving the participation of CO_2 present in the microatmosphere of soil and produced by the respiration of organisms that feed on plant remains. When rainwater is leached into soil, it reacts with CO_2 in the edaphic microatmosphere forming H_2CO_3, thereby promoting the dissolution of preexisting minerals and the formation of secondary minerals, including calcium carbonates (Cerling, 1984; Doner and Lynn, 1989). Carbonates formed in ecosystems with C_3 vegetation have $\delta^{13}C$ values ranging between –12‰ and –9‰, while those from C_4 vegetation have values between 3‰ and 1‰ (Cerling, 1984; Cerling and Quade, 1993). In this way, variations in the $\delta^{13}C$ values of soil (humus and carbonates) indicate changes in the composition of the plant cover, which in turn point to changes in environmental conditions (Guerrero and Berlanga, 2000).

Oxygen is taken up by animals mainly through ingested water and, in lower amounts, from food and respiration, in balance with oxygen lost through sweat, urine, feces, and respiration (Koch et al., 1994; Bryant and Froelich, 1995; Koch, 2007). Since ingested water is the main source of oxygen and it comes from precipitation, there are several factors that affect the oxygen isotope ratios, including altitude, latitude, amount of precipitation, and, most of all, temperature. Therefore, isotopic oxygen relationships in dental enamel are used to infer paleoclimate and other paleoecological aspects (Dansgaard, 1964; Fricke and O'Neil, 1996; Sánchez, 1997; Grimes et al., 2008).

2. Materials and methods

2.1. Study area

The archaeological-paleontological site known as El Arenoso is located on the ranch of the same name, north of Caborca, Sonora, at 31°2′26″N, 112°3′22″W and 570 m a.s.l. (Figure 1). It is delimited to the NW by Sierra San Manuel and to the NE by Sierra del Humo, on an alluvial plain formed by alluvial deposits from the Quaternary that are currently eroded by the El Arenoso stream flowing from the NE. The main slope of the plain goes from NE to SW. The predominant climate is BWh (x'), very dry and semiwarm, with mean annual temperature between 18 °C and 22 °C; mean annual precipitation ranges between 200 and 300 mm, with a maximum in winter (Vidal, 2005).

El Arenoso includes a La Cantera profile, which Vidal Zepeda in which several archaeological materials have been found on the surface, while paleontological elements of Pleistocene fauna interstratified in the pedosedimentary profiles have been recorded in gullies associated with the margins of the El Segundo stream that runs to the southeast (Cruz-y-Cruz et al., 2018). It should be noted that although in El Arenoso there is no association between megafauna and archaeological evidence, nearby, in the same region, there are archaeological sites such as the Fin del Mundo (Sánchez et al. 2014) with similar ages,

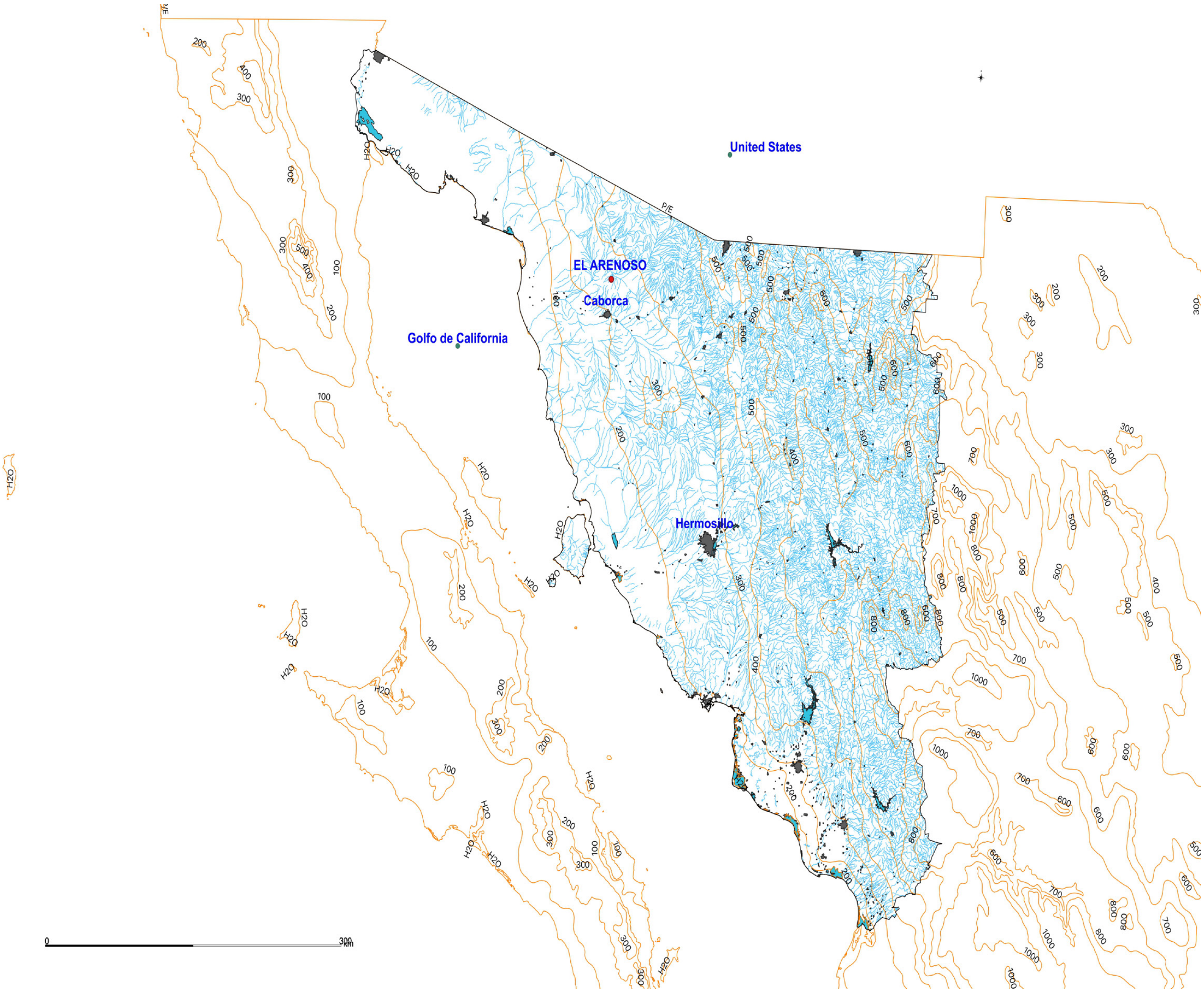

Figure 1. Map indicates the isohyets and main water currents. El Arenoso is located at annual precipitation zone between 200 and 300 mm.

so the paleoenvironmental reconstruction of El Arenoso is relevant in a regional context.

Previous studies showed that paleosols found in the La Cantera profile associated with fossils (Figure 2) formed during the late Pleistocene (MIS3, 31.12 ka BP and MIS2, 16.8 ka BP) (Cruz-y-Cruz et al., 2015) and contain remains of Pleistocene megafauna, including bison (*Bison bison*), horses (*Equus conversidens* and *Equus* sp.), mammoths (*Mammuthus columbis*), and tortoises (*Gopherus* sp.) as well as evidence of human activity in the early Holocene (Arredondo, in Terrazas-Mata and Benavente, 2013). Likewise, the ^{14}C analysis performed on two horse molars indicates an age of 13,252 ± 62 BP (16,145–15,720 cal 14 BP), similar to the age obtained from soils. The profile of La Cantera was described to 2.55 m depth, with a sequence of horizons of C / 2Bgk$_1$ / 2Bgk$_2$ / 3Ck / 4Bk / 5Ck / 6Bg / 6BCk / 7Ck / 8Bk / 9Bg. The profile shows a sequence of five paleosols interspersed with sedimentary deposits. The first paleosol shows moderate development, with horizons 2Bk$_1$ and 2Bk$_2$. The second paleosol, which underlies the first and a 3C sediment layer, is also moderately developed, with a well-structured 4Bk horizon and carbonate accumulation. The third paleosol, with horizons 6Bg and 6BCk, shows gleyic properties and carbonation. The fourth paleosol displays a moderately developed and carbonated 8Bk horizon. The last paleosol consists of a 9Bg horizon.

2.2. Sample extraction and processing

Between 10 and 16 samples were obtained from molars #1971 and #1444 belonging to the genus *Equus* sp. These molars were selected because they were M3 and were complete, take four years to form, and, therefore, allow the detection of intradental isotopic variations produced by temperature during molar formation (Kohn et al., 1998; Higgins and MacFadden, 2004).

Figure 2. La Cantera profile, showing the Pleistocene paleosoil sampled section. The fossils were associated with profile 2Bgk$_2$, where a tortoise shell from the Pleistocene was recovered.

Also, in horses, molars 3 are formed after weaning, so the information they provide derives from the food and water consumed by the specimens; in contrast, in molars 1 and 2 there is a contribution from nursing milk and so the two aspects mentioned above are not reflected accurately (Feranec and MacFadden, 2000).

Each sample included approximately 10 mg of enamel obtained from the root-crown junction towards the occlusal zone and separated by between 1 and 2 mm. Once samples were extracted, these were processed following the methodology of Koch et al. (1997), as described below.

First, the dental enamel was ground with a mortar and agate pestle, then sieved through a 400 mesh to obtain a fine and uniform powder. Five milliliters of 30% hydrogen peroxide was added and left for at least 2 h to remove organic matter; subsequently, samples were centrifuged, oxygenated water was discarded, and samples were rinsed with distilled water three times, discarding the water after each rinse. Afterwards, a buffer solution of acetic acid + calcium acetate (1.0 M) was added and left to stand for 9 h. Then the buffer solution was discarded and samples were rinsed with distilled water three times again. Finally, ethyl alcohol was added to remove water, and samples were dried afterwards in an oven at 90 °C for 12 h.

The processed samples were sent to the Laboratorio de Isótopos Estables (Stable Isotope Laboratory) of the Instituto de Geología (Institute of Geology) at Universidad Nacional Autónoma de México (UNAM) for analysis with a Finnigan MAT 253 spectrometer. This apparatus has a dual sample introduction system and an auxiliary equipment called Gas Bench II with a GC Pal autosampler and an aluminum sample tray with controlled temperature (25 °C) coupled to the mass spectrometer (Revesz and Landwehr, 2002).

The results were reported as $\delta^{13}C_{VPDB}$ and $\delta^{18}O_{VPDB}$ and were normalized using NBS-19, NBS-18, and LSVEC following the procedure described by Coplen (1988), Coplen et al. (2006), and Werner and Brand (2001). With this technique, a standard deviation of 0.2‰ is obtained for carbon and oxygen from carbonates.

We also used the carbon isotopic values for one bison, one mammoth, and 11 horses reported by Cruz-y-Cruz et al. (2016), as well as those obtained from paleosols associated with the remains of these animals from the La Cantera profile in El Arenoso. This profile has a sequence of horizons of C / 2Bgk / 2Bgk2 / 3Ck / 4Bk / 5Ck / 6Bg / 6BCk / 7Ck / 8Bk / 9Bg. Also included were $\delta^{18}O$ values of the animals studied, which were not analyzed in the previous work.

2.3. Statistical analysis

Carbon and oxygen isotopic values obtained from the samples analyzed were plotted together following the model by Feranec and MacFadden (2000) to explore any changes in carbon values due to potential variations in $\delta^{18}O$ values.

In addition, the oxygen isotopic values of the enamel of the equid, bison, and mammoth specimens were converted to VSMOW using the formula of Faure (1977), $\delta^{18}O_{VSMOW} = 1.030901 * \delta^{18}O_{VPDB} + 30.91$, and transformed into $\delta^{18}O$ from water using the formula of Iacumin et al. (1996), $\delta^{18}Owater = (\delta^{18}O_{VSMOW} - 33.63) / 0.998$, for comparison with isotopic rainwater oxygen values calculated by Bowen and Wilkinson (2002), Bowen and Revenaugh (2003), Bowen et al. (2005), and Bowen (2008) for El Arenoso.

The $\delta^{13}C$ values of the specimens analyzed were compared with the classification of MacFadden and Cerling (1996), while those of paleosols were compared with the proposal of Cerling (1999), seeking to determine the types of plants that thrived and were consumed by animals at the study site. Finally, $\delta^{13}C$ and $\delta^{18}O$ values for the species studied were plotted to detect any similarities or differences between them.

3. Results

3.1. Serial samples

The serial samples obtained from specimen #1971 exhibit $\delta^{13}C$ values ranging from −3.2‰ to −4.2‰ with a mean of −3.7‰; in the case of $\delta^{18}O$, the mean value obtained was −3.7‰ with a peak value of −0.2‰ and a minimum of −1.4‰ (Table 1). Figure 3 shows a decrease in carbon isotopic values, from −3.4‰ in sample number 1 to −4.2‰ in sample 3. Subsequently, there is a steady rise in $\delta^{13}C$ until it reaches −3.2‰ in sample 11, then decreasing in sample 12 (−3.6‰) and increasing again to −3.3‰ in sample 13, finally rising again to −3.8‰.

In the case of $\delta^{18}O$ for the same sample, the values increase from sample 1 (−1.8‰) to sample 5 (−0.3‰). Subsequently, values decrease to −1.3‰ in sample 8 and increase to −0.2‰ in sample 10, then decreasing again (−0.6‰) in sample 11, increasing again (−0.1‰) in sample 12, and starting to decrease to finally increase again to reach −0.3‰ (Figure 2).

For specimen #1444, mean $\delta^{13}C$ is −2.0‰, with a maximum of −0.6‰ and a minimum of −3.6‰; for $\delta^{18}O$, values range from −2.0‰ to −2.9 with a mean of −2.5‰ (Table 2). In the case of carbon, the serial samples indicate an increase in $\delta^{13}C$ from −3.6‰ to −0.6‰ from sample 1 to sample 5, then decreasing to −2.6‰ in sample 8 and increasing again to 2.1‰ in the last sample (Figure 3). For oxygen, a decrease is also observed from −2.3‰ in sample 1 to −2.8‰ in sample 3, increasing to −2.0‰ in sample 7 and then decreasing to −2.9‰ in sample 9, to increase again to −2.7‰ in the last sample (Figure 4).

3.2. Complete fauna

Table 3 shows the $\delta^{13}C$ and $\delta^{18}O$ values obtained for all the samples analyzed. Carbon and oxygen isotopic values for the bison were −1.4‰ and −4.3‰, respectively; for the mammoth, they were −3.6‰ and −5.1‰, respectively. In the case of horses, the mean value for carbon was −2.8‰, ranging from −0.5‰ to −4.6‰; oxygen showed values of −0.6‰ to −4.8‰, with a mean of −2.6‰. The graph drawn from these data shows that horses are distributed to the

Table 1. Carbon and oxygen isotopic values for specimen #1971.

Distance to root (mm)	$\delta^{13}C$ (enamel) $_{VPDB‰}$	$\delta^{18}O$ (enamel) $_{VPDB‰}$	$\delta^{18}O$ (enamel) $_{VSMOW‰\ (water)}$
0	−3.4	−1.8	−4.6
2.5	−4.1	−1.3	−4.1
3.9	−4.2	−0.7	−3.5
5.5	−4.0	−0.4	−3.2
7.1	−4.1	−0.3	−3.0
8.4	−4.0	−0.9	−3.7
9.9	−3.8	−1.4	−4.2
11.7	−3.6	−1.3	−4.1
13	−3.7	−0.9	−3.6
14.2	−3.4	−0.2	−2.9
16.1	−3.2	−0.6	−3.3
18	−3.6	−0.1	−2.8
19.3	−3.5	−0.5	−3.1
21.1	−3.3	−0.4	−3.1
22.8	−3.7	−0.5	−3.2
24.5	−3.8	−0.3	−3.0

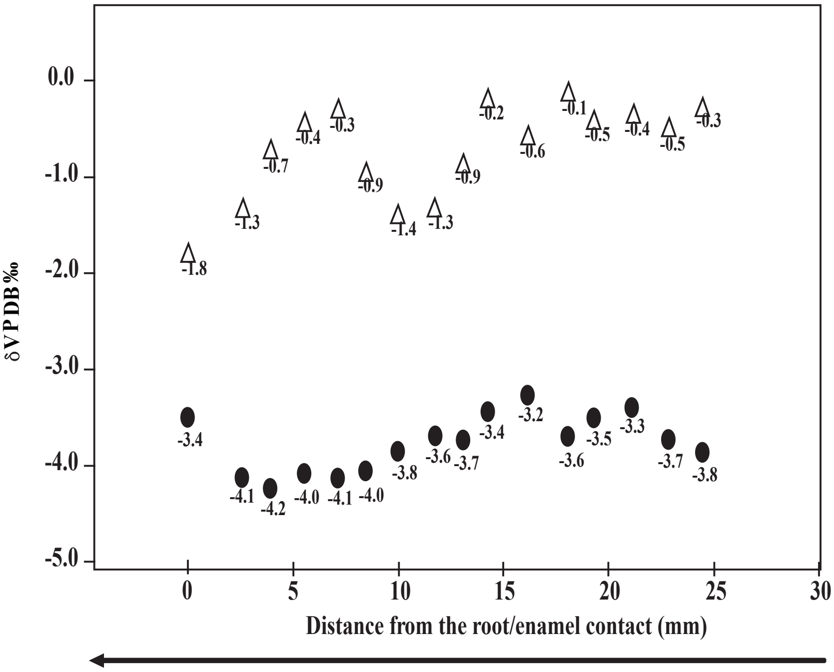

Figure 3. Carbon and oxygen isotopic values obtained for specimen #1971. Circles: $\delta^{13}C$; triangles: $\delta^{18}O$.

Table 2. Carbon and oxygen isotopic values for specimen #1444.

Distance to root (mm)	$\delta^{13}C$ (enamel) $_{VPDB‰}$	$\delta^{18}O$ (enamel) $_{VPDB‰}$	$\delta^{18}O$ (enamel) $_{VSMOW‰\ (water)}$
1.6	–3.6	–2.4	–5.1
3.6	–2.9	–2.1	–5.1
5.7	–1.9	–2.8	–5.7
7.8	–1.0	–2.5	–5.3
9.2	–0.6	–2.2	–5.0
11	–1.1	–2.1	–4.9
12.5	–2.3	–2.0	–4.8
12.7	–2.6	–2.7	–5.5
14.6	–2.4	–2.9	–5.7
16.2	–2.1	–2.7	–5.5

left, the mammoth is grouped together with some horses, and the bison is located to the right of the mammoth (Table 3; Figure 5).

3.3. Isotopic values of paleosols

Previous works have shown that the paleosols of the La Cantera profile share similar isotopic values throughout the sequence. We analyzed the calcium carbonate content of the following profile horizons: bottom (4Bgk horizon, dated at 30.5 ka Cal BP, $\delta^{13}C$ value of –3.4‰), intermediate (3Ck horizon, dated at 19.5 ka Cal BP, $\delta^{13}C$ value of –3.4‰), and top (horizon 2Bgk2, dated at 16.6 ka Cal BP, $\delta^{13}C$ value of –5.7‰) (Table 4) (Cruz-y-Cruz et al., 2015).

4. Discussion

4.1. Diet of the Pleistocene megafauna of El Arenoso

Bison consumed mainly C_4 plants. This type of diet has also been observed in other individuals from Cedral, Mexico, as well as in some US bison populations from Blackwater Draw, Dry Cave, Friesenhahn Cave, Howard Ranch, Murray Springs, and Valley Farms (Connin et al., 1998; Koch et al., 2004; Pérez-Crespo et al., 2014). Micro- and mesowear analyses indicate that this species consumed grasses but also leaves of trees and shrubs (Rivals et al., 2007).

The mammoth showed a mixed C_3/C_4 diet. This has also been reported in other studies on populations of this

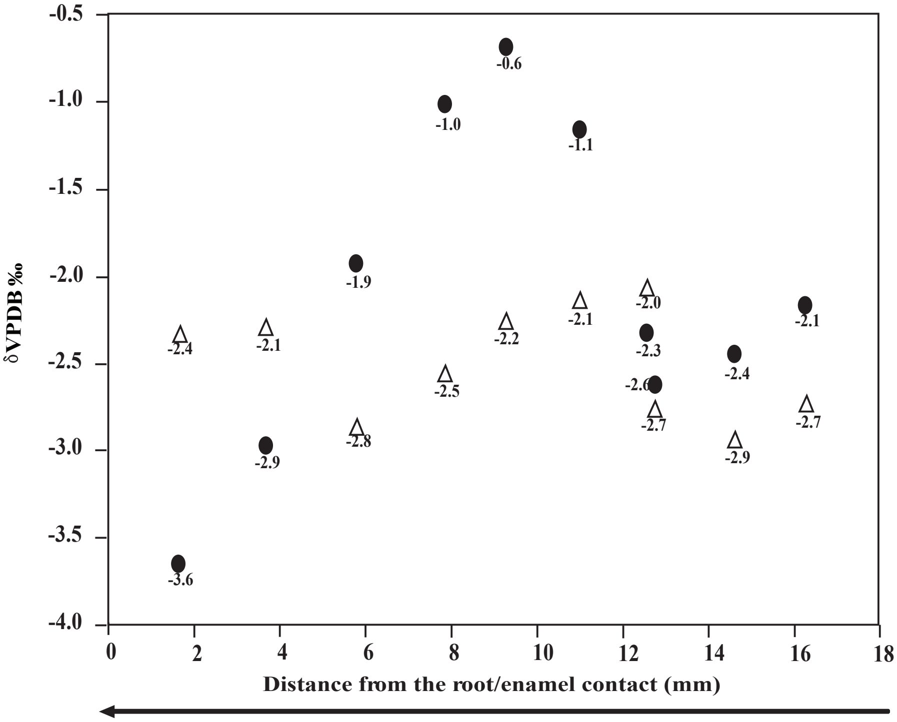

Figure 4. Carbon and oxygen isotopic values obtained for specimen #1444. Circles: $\delta^{13}C$; triangles: $\delta^{18}O$.

Table 3. Carbon and oxygen values of herbivores from El Arenoso.

Catalog number	Species	$\delta^{13}C$ (enamel) $_{VPDB‰}$	$\delta^{18}O$ (enamel) $_{VPDB‰}$	$\delta^{18}O$ (enamel) $_{VSMOW‰ (water)}$
656	*Bison* sp.	−1.4	−4.3	−7.2
1972.00	*Equus* sp.	−3.4	−4.8	−7.7
PTNOS-1448	*Equus* sp.	−2.0	−2.4	−5.2
PTNOS-2011	*Equus* sp.	−3.2	−3.5	−6.3
PTNOS-2009	*Equus* sp.	−3.6	−3.2	−6.0
PTNOS-794	*Equus conversidens*	−2.3	−2.6	−5.4
S/N	*Equus* sp.	−3.8	−3.3	−6.2
1969.00	*Equus* sp.	−4.6	−1.0	−3.8
PTNOS2007	*Equus* sp.	−2.6	−2.5	−5.3
PTNOS2009	*Equus* sp.	−3.0	−3.9	−6.7
PTNOS2832	*Equus* sp.	−2.9	−2.9	−5.7
S/N	*Equus* sp.	−3.2	−1.3	−4.1
1971	*Equus* sp.	−3.7	−0.7	−5.3
1444	*Equus* sp.	−2.0	−2.5	−3.5
S/N	*Mammuthus columbi*	−3.6	−5.1	−8.0

species from Laguna de las Cruces and Cedral, México, and Bonfire Shelter, Howell's Ridge Cave, Kincaid Cave, Laubach Cave, Leo Boathright Pit, Moore Pit, Roswell, Sandia Cave, Valley Farms, and Waco, USA, which reveals that some mammoth populations consumed this type of diet but others specialized in the consumption of C_3 or C_4 plants (Connin et al., 1998; Koch et al., 2004; Pérez-Crespo et al., 2014). This has been corroborated by the analysis of microwear and stable carbon isotopes (Rivals et al., 2012; Pérez-Crespo et al., 2016b).

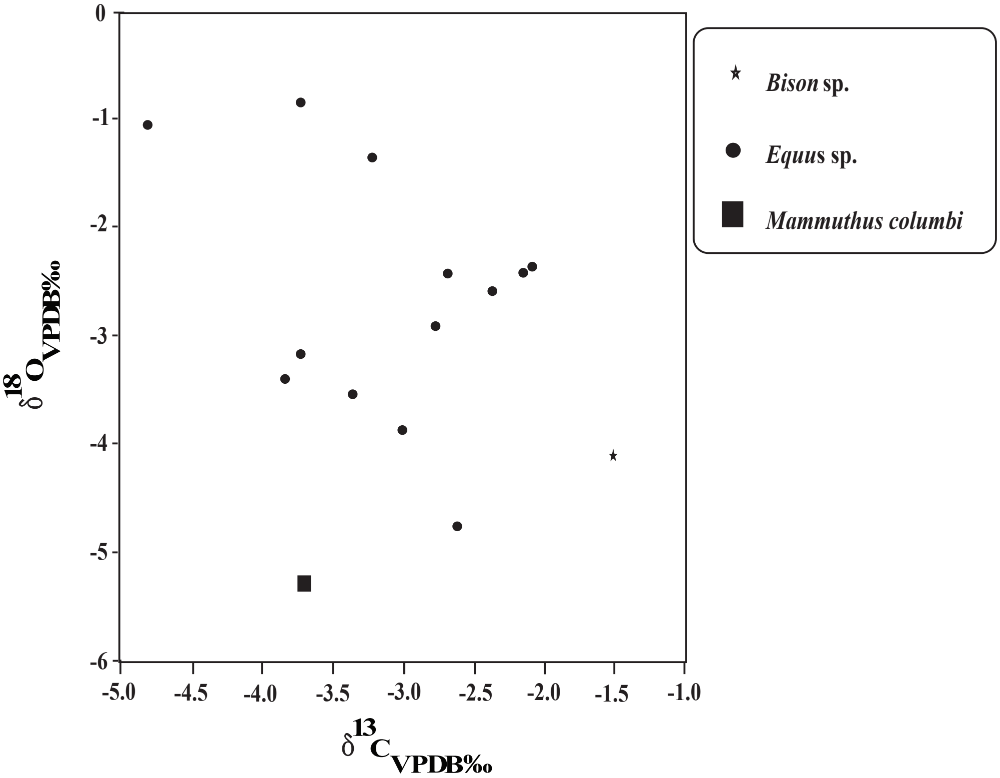

Figure 5. Comparisons of $\delta^{13}C$ and $\delta^{18}O$ values for herbivores from El Arenoso.

Table 4. Carbon isotopic values obtained at La Cantera, El Arenoso, Sonora.

Profile	$\delta^{13}C‰_0$ (MO)	Mean age Cal PP	MIS
$2Bgk_2$	–5.7	16612	2
3Ck	–3.4	19506	2
4Bgk	–3.4	30555	3/2

For their part, horses show that most of these animals had a mixed diet and only two individuals specialized on C_4 plants. In the case of specimen #1444, whose mean $\delta^{13}C$ value indicates that it was a specialist that fed on C_4 plants, the serial samples indicate that at some stages during the mineralization and formation of molars, this individual included small amounts of C_3 plants in the diet. By contrast, the serial samples of specimen #1971 showed that during the formation of molars, this individual was a mixer feeder with a variable intake of C_4 plants. Isotopic as well as meso- and microwear analyses for several Mexican equid populations from Barranca del Berrendo, Barranca Piedras Negras, Barranca San Augustín, Cedral, El Barrio, and Las Cajas show that these animals had generalist feeding habits (Bravo-Cuevas et al., 2011; Barrón-Ortiz et al., 2014; Pérez-Crespo et al., 2016a). Marin-Leyva et al. (2015, 2016), who conducted isotopic and micro- and mesowear analyses in horses of La Cinta-Portalitos and La Piedad-Santa Ana, Michoacán, reported that these animals were mixer feeders during certain stages of their life, while others fed on C_4 plants, as observed for specimen #1444.

4.2. Environmental evidence

The values of $\delta^{18}O$ from serial samples show different patterns between specimens, as the minimum and maximum $\delta^{18}O$ values in specimen #1971 were –1.8‰ and –0.1‰, respectively, representing a difference of –1.7‰. This is similar for individual #1444, where the difference between the minimum and maximum $\delta^{18}O$, –2.0‰ and –2.7‰, respectively, was –0.7‰.

Feranec and MacFadden (2000) suggested that changes in $\delta^{13}C$ values represent variations in the local abundance of C_3 and C_4 plants in the study site due to changes in temperature, which are reflected in oxygen values. At temperatures below 25 °C, C_3 plants become more abundant while C_4 plants become more scarce (Medrano and Flexas, 2000). Accordingly, in zones with warm summer and cold winter, serial samples obtained from a hypsodont molar will show a sinusoidal pattern; the high $\delta^{13}C$ and $\delta^{18}O$ values will evidence high abundance of C_4 plants and high temperatures, while low $\delta^{13}C$ and $\delta^{18}O$ values will reflect high abundance of C_3 plants and low temperatures.

In specimen #1971, higher $\delta^{18}O$ values are associated with lower $\delta^{13}C$ values. Only in samples 9 to 13, both values increase and decrease concurrently, but afterwards, while carbon isotopic values decrease, those of oxygen increase (Figure 3). In specimen #1444, $\delta^{18}O$ values first decrease and then increase; isotopic carbon values increase from sample 1 to sample 5 and later decrease to sample 8, for which it increases, and it is only in sample 9 that $\delta^{13}C$ y $\delta^{18}O$ values increase concurrently (Figure 4).

The lack of a sinusoidal pattern between carbon and oxygen isotopic values that is observed in both serial samples indicate that the local climate during the period of molar formation was stable, with no temperature rises that would increase the abundance of C_3 plants, thus being most favorable for the proliferation of C_4 plants. Cruz-y-Cruz et al. (2015, 2016) contrasted carbon isotopic values from paleosoils with those observed in bison, horses, and mammoths and found that both approaches indicated the presence of a mixed C_3/C_4 vegetation that throve in a cold and semiarid environment with a lower evaporation rate compared to the present.

Likewise, in the Late Pleistocene, the soil cover of El Arenoso was made of gleysols, with general characteristics (morphology and analytics) indicative of moderate development. These include weathering of primary minerals, formation of secondary minerals, and gleyzation due to moisture saturation of soil that promoted reductomorphy and provided a grayish coloration and carbonation (Cruz-y-Cruz et al., 2015). Taken together, these characteristics indicate alternation between humid and less humid periods.

Thus, we here propose that between 30 and 16.8 ka cal BP, a mosaic of C_3 and C_4 vegetation prospered in the study site, probably related to a predominantly cold and semiarid environment, leading to a lower evaporation rate due to glaciation and, in particular, to the Last Maximum Glacier (Isotopic Stage MIS 2). This same is confirmed in Figure 5, showing that carbon and oxygen isotopic values from animal samples indicate that these animals lived in grasslands where there were shrubs, trees, and C_3 grasses. Oxygen isotopic values of water, analyzed through animal enamel, were –5.8‰, while the current value for this same site is –7.7‰; the difference between both is –1.9‰, suggesting that the conditions when these animals were alive were arid (Table 3 and 5). These environmental conditions were also reported by Cruz-y-Cruz et al. (2018) towards the end of the Pleistocene in the Fin del Mundo and Rancho San Francisco, Sonora, located also in semiclosed basins like El Arenoso. For example, in the present, the climate of Fin del Mundo is BW (h´) (x´) (very dry warm), with annual rainfall of 200–300 mm, a temperature between 18 °C and 22 °C, and desert scrub (Vidal Zepeda, 2005; Sánchez et al., 2014). However, carbon and oxygen isotopic analyses from gomphotheres from the Late Pleistocene in this locality indicated the presence of grassland with forest nearby (Pérez-Crespo et al., 2019). Thus, in this geological epoch, the Fin del Mundo was more humid than at present. This is similar to El Arenoso, where environmental conditions during the Late Pleistocene were less arid than present and allowed the presence of C_3 and C_4 plants and development of gleysols in the locality.

Although there are no pollen data for El Arenoso, palynological, paleosoil, and *Neotoma* packrat analyses conducted in other sites of the Sonora and southern USA showed the presence of C_3 and C_4 grasses and xerophilous scrubs associated with low precipitation during the Late Pleistocene (Van Devender, 1990; Ballenger et al., 2011; Roy et al., 2012; Ortega-Rosas et al., 2016). This observation is also similar to the findings from carbon isotopic analyses of paleosoils and $\delta^{13}C$ and $\delta^{18}O$ values of herbivorous mammals from El Arenoso.

The geomorphological characteristics of the site, located at the bottom of a semienclosed basin bordered by the surrounding mountains, together the climate conditions, allowed the accumulation of sufficient humidity to promote the leaching of carbonates and their buildup in soil, as well as the development of the gleysols found in the study site.

5. Conclusions

The $\delta^{13}C$ and $\delta^{18}O$ values obtained from the serial samples of the two horse molars show that C_4 plants were an important food source, and that no local climatic variations occurred that would have promoted the proliferation of C_3 plants in the area. The oxygen isotopic values of water consumed by the local fauna show that the study area was arid. This is consistent with carbon isotopic analyses of

Table 5. Water oxygen isotopic values at El Arenoso inferred by Bowen and Wilkinson (2002), Bowen and Revenaugh (2003), Bowen et al. (2005), and Bowen (2008). J: January, F: February, M: March, A: April, Ma: May, Ju: June, Jul: July, Ag: August, S: September, O: October, N: November, D: December, μ: Mean. $\delta^{18}O$ values in V-SMOW‰.

J	F	M	A	Ma	Ju	Jul	Ag	S	O	N	D	μ
–8.5	–7.4	–7.1	–3.9	–4.2	–6.7	–8.0	–6.9	–7.2	–6.6	–7.6	–7.7	–7.7

paleosoils and dental enamel of mammals found in the site studied, which indicate that El Arenoso was characterized by arid conditions that favored C_4 and some C_3 plants in the locality, and the arid conditions of El Arenoso are similar to those found in other localities in the northwest of Mexico and the southwest of the USA that show the presence of mixed C_3/C_4 vegetation.

The isotopic values obtained from the fauna indicate that arid conditions prevailed in the study site during this period of time, being even arid; these results support the hypothesis that the formation of gleysols strongly depends on the local geomorphological conditions.

Acknowledgments

The authors wish to thank PAPIIT, CONACYT, and the Postdoctoral Scholarship Program at Instituto de Investigaciones Antropólogicas, UNAM, for providing funding (IA104017, IA102719, IN400611, IN281333). Thanks also to Laboratorios de Isótopos Estables - LANGEM and Laboratorio Nacional de Espectrometría de Masas (LEMA) at UNAM, as well as to R. Puente M., for analytical assistance. María Elena Sánchez-Salazar edited the English manuscript. Also, two anonymous reviewers provided valuable comments and critiques for improving the quality of this manuscript.

References

Andrade JL, de la Barrera E, Reyes-García C, Ricalde MF, Vargas-Soto G et al. (2007). El metabolismo ácido de las crasuláceas: diversidad, fisiología ambiental y productividad. Boletín de la Sociedad Botánica de México 87: 37-50 (in Spanish).

Ballenger JAM, Holliday VT, Kowler AL, Reiteze WT, Prasciunus MM et al. (2011). Evidence for Younger Dryas global climate oscillation ad human response in the America Southwest. Quaternary International 242 (12): 502-519. doi: j.quaint.2011.06.040

Barron-Ortiz CR, Theodor JM, Arroyo-Cabrales JA (2014). Dietary resource partitioning in the Late Pleistocene horses from Cedral, north-central Mexico: evidence from the study of dental wear. Revista Mexicana de Ciencias Geológicas 31 (2): 260-269.

Bowen GJ (2008). The Online Isotopes in Precipitation Calculator, Version 2.2. http://www.waterisotopes.org.

Bowen GJ, Revenaugh J (2003). Interpolating the isotopic composition of modern meteoric precipitation. Water Resources Research 39: 1299. doi: 10.129/2003WR002086

Bowen GJ, Wilkinson B (2002). Spatial distribution of $\delta^{18}O$ in meteoric precipitation. Geology 30 (4): 315-318. doi: 10.1130/0091-7613(2002)030<0315:SDOOIM>2.0.CO;2

Bowen GJ, Wassenaar LI, Hobson KA (2005). Global applications of stable hydrogen and oxygen isotopes to wildlife forensics. Oecologia 143 (3): 337-348.

Bryant JD, Froelich PN (1995). A model of oxygen isotope fractionation in body water of large mammals. Geochimica et Cosmochimica Acta 59 (21): 4523-4537. doi: 10.1016/0016-7037(95)00250-4

Cerling TE, (1984). The stable isotopic composition of modern soil carbonate and its relationship to climate. Earth and Planetary Science Letters 71 (2): 229-240. doi:org/10.1016/0012-821X(84)90089-X"doi.org/10.1016/0012-821X(84)90089-X

Cerling TE (1999). Paleorecords of C4 plants and ecosystems. In: Sage RF, Monson RK (editors). C4 Plant Biology. 1st ed. San Diego, CA, USA: Academic Press, pp. 445-469.

Cerling TE, Ehleringer JR (2000). Welcome to the C4 world. In: White RD (editor). Phanerozoic Terrestrial Ecosystems. The Paleontological Society Papers 6. 1st ed. New Haven, CT, USA: Yale University Reprographics & Imaging Services, pp. 273-286. doi: 10.1017/S1089332600000802

Cerling, TE, Harris, JM (1999). Carbon isotope fractionation between diet and bioapatite in ungulate mammals and implications for ecological and paleoecological studies. Oecologia 120 (3): 347-336.

Cerling TE, Quade J (1993). Stable carbon and oxygen isotopes in soil carbonates. In: Swart PK, Lohmann KC, McKenzie J, Savin S (editors). Climate Change in Continental Isotopic Records. 1st ed. Washington, DC, USA: Geophysical Union, pp. 217-231. doi: 10.1029/GM078p0217

Connin SL, Betancourt J, Quade J (1998). Late Pleistocene C4 plant dominance and summer rainfall in the Southwestern United States from isotopic study of herbivore teeth. Quaternary Research 50 (2): 179-193. doi.org/10.1006/qres.1998.1986

Coplen TB (1988). Normalization of oxygen and hydrogen isotope data. Chemical Geology 72 (4): 293-297.

Coplen T, Brand WA, Gehre M, Groning M, Meijer Harro AJ et al. (2006). New guidelines for $\delta^{13}C$ measurements. Analytical Chemistry 78 (7): 2439-2441. doi: 10.1021/ac052027c

Cruz-y-Cruz T, Pérez-Crespo VA, Morales-Puente P, Sedov S, Tovar-Liceaga RE et al. (2016). Paleosol (organic matter and pedogenic carbonates) and paleontological $\delta^{13}C$ records applied to the paleoecology of Late Pleistocene - Holocene in Mexico. Quaternary International 418:147-164. doi: 10.1016/j.quaint.2015.12.093

Cruz-y-Cruz T, Sánchez G, Sedov S, Terrazas-Mata A, Solleiro-Rebolledo E et al. (2015). Spatial variability of Late Pleistocene–Early Holocene soil formation and its relation to early human paleoecology in Northwest Mexico. Quaternary International 365: 135-149. doi: 10.1016/j.quaint.2014.11.042

Cruz-y-Cruz T, Sánchez-Miranda G, Carpenter, J, Terrazas-Mata A, Sedov S et al. (2018). Pleistocene paleosols associated with megafauna in Northwestern Mexico: paleoecological inferences. Spanish Journal of Soil Science 8 (2): 130-147. doi: 10.3232/SJSS.2018.V8.N2.01

Dansgaard W (1964). Stable isotopes in precipitation. Tellus 16 (4): 436-468. doi: 10.1111/j.2153-3490.1964.tb00181.x

Dincauze DF (1987). Strategies for paleoenviromental reconstruction in archeology. Advances in Archaeological Method and Theory 11: 255-336. doi: 10.1016/B978-0-12-003111-5.50008-7

Doner HE, Lynn W (1989). Carbonate, halide, sulfate, and sulfide minerals. In: Dixon JB, Weed SB (editors). Minerals in Soil Environments. 2nd ed. Madison, WI, USA: Soil Science of America Book Series, pp. 279-330. doi: 10.2136/sssabookser1.2ed.c6

Faure G (1977). Principles of Isotope Geology. 1st ed. New York, NY, USA: John Wiley & Sons.

Feranec RS, MacFadden BJ (2000). Evolution of the grazing niche in Pleistocene mammals from Florida: evidence from stables isotopes. Paleogeography, Palaeoclimatology, Palaeoecology 162 (1-2): 155-169. doi: 10.1016/S0031-0182(00)00110-3

Ferrusquia-Villafranca I, Arroyo-Cabrales J, Martínez-Hernández E, Gamma-Castro J, Ruíz-González J et al. (2010). Pleistocene mammals of México: a critical review of regional chronofaunas, climate change response and biogeography provinciality. Quaternary International 217 (1-2): 53-104. doi.org/10.1016/j.quaint.2009.11.036

Fricke HC, O'Neil JR (1996). Inter- and intra-tooth variation in the oxygen isotope composition of mammalian tooth enamel phosphate: implications for palaeoclimatological and palaeobiological research. Paleogeography, Palaeoclimatology, Palaeoecology 126 (1-2): 91-99. doi: 10.1016/S0031-0182(96)00072-7

Gaines EP, Sánchez G (2009). Current Paleoindian research in Sonora, Mexico. Archaeology Southwest 23 (3): 4-5.

Gaines EP, Sánchez G, Holliday VT (2009). Paleoindian archaeology in Northern and Central Sonora, México. Kiva 74 (3): 305-335. doi: 10.1179/kiv.2009.74.3.003

Grimes ST, Collinson ME, Hooker JJ, Mattey DP (2008). Is small beautiful? A review of the advantages and limitations of using small mammal teeth and direct fluorination analysis technique in the isotopic reconstruction of past continental climate change. Palaeogeography, Palaeoclimatology, Palaeoecology 256 (1-2): 39-50. doi: 10.1016/j.palaeo.2008.03.014

Guerrero R, Berlanga M (2000). Isótopos estables: fundamento y aplicaciones. Actualidad SEM - Boletín Informativo de la Sociedad Española de Microbiología 30: 17-23 (in Spanish).

Higgins P, MacFadden BJ (2004)."Amount effect" recorded in oxygen isotopes of Late Glacial horse (*Equus*) and bison (*Bison*) teeth from the Sonoran and Chihuahan deserts, southwestern United States. Paleogeography, Palaeoclimatology, Palaeoecology 206 (3-4): 337-353. doi: 10.1016/j.palaeo.2004.01.011

Iacumin P, Bocherens H, Mariotti A, Longinelli A (1996). Oxygen isotope analyses of co-existing carbonate and phosphate in biogenic apatite: a way to monitor diagenetic alteration of bone phosphate? Earth and Planetary Science Letters 142 (1-2): 1-6. doi: 10.1016/0012-821X(96)00093-3

Keeley JE, Rundel PW (2003). Evolution of CAM and C4 carbon-concentrating mechanisms. International Journal Plants Science 164 (Suppl. 3): S55-S77. doi: 10.1086/374192

Koch PL (1998). Isotopic reconstruction of past continental environments. Annual Review Earth Planetary Science 26: 573-613. doi: 10.1146/annurev.earth.26.1.573

Koch PL (2007). Isotopic study of the biology of modern and fossil vertebrates. In: Michener R, Lajtha K (editors). Stable Isotopes in Ecology and Environmental Science. 1st ed. Boston, MA, USA: Blackwell Publishing, pp. 99-154. doi: 10.1002/9780470691854.ch5

Koch PL, Diffenbaugh NS, Hoppe KA (2004). The effects of late Quaternary climate and *P*CO2 change on C4 plant abundance in the south-central United States. Palaeogeography, Palaeoclimatology, Palaeoecology 207 (3-4): 331-357. doi: 10.1016/j.palaeo.2003.09.034

Koch PL, Fogel ML, Tuross N (1994). Tracing the diets of fossil animals using stable isotopes. In: Lajtha K, Michener RH (editors). Stable Isotopes in Ecology and Environmental Science. 1st ed. Boston, MA, USA: Blackwell Scientific Publications, pp. 63-92.

Koch PL, Tuross N, Fogel ML (1997). The effects of sample treatment and diagenesis on the isotopic integrity of carbon in biogenic hydroxylapatite. Journal of Archaeological Science 24 (5): 417-429. doi: 10.1006/jasc.1996.0126

Kohn MJ, Schoeninger MJ, Valley JW (1998). Variability in oxygen isotope composition of herbivore teeth: reflections of seasonality or developmental physiology? Chemical Geology 152 (1-2): 97-112. doi: 10.1016/S0009-2541(98)00099-0

Lanata JL (2011). Discutiendo diferentes modelos de la dispersión humana en las Américas. In: Jiménez López JC, Serrano Sánchez C, González González C, Aguilar Arrellano FJ (editors). IV Simposio Internacional. El hombre temprano en América. 1st ed. Mexico City, Mexico: Instituto Nacional de Antropología e Historia, Instituto de Investigaciones Antropológicas, Universidad Nacional Autónoma de México y Museo del Desierto, pp. 121-148 (in Spanish).

Lee-Thorp JA, Van der Merwe N, Brain CK (1989). Isotopic evidence for dietary differences between two extinct baboon species from Swartkrans. Journal of Human Evolution 18 (3): 183-190.

MacFadden BJ, Cerling TE (1996). Mammalian herbivore communities, ancient feeding ecology, and carbon isotopes: a 10 million- year sequence from the Neogene of Florida. Journal of Vertebrate Paleontology 16 (1): 103-115.

Marin-Leyva AH, Arroyo-Cabrales J, García-Zepeda ML, Ponce-Saavedra J, Schaaf P et al. (2016). Feeding ecology and habitat of Late Pleistocene *Equus* horses from west-central Mexico using carbon and oxygen isotopes variation. Revista Mexicana de Ciencias Geológicas 33 (2): 157-169.

Marin-Leyva AH, DeMiguel D, Garcia-Zepeda ML, Ponce-Saavedra J, Arroyo-Cabrales J et al. (2016). Diet adaptability of Late Pleistocene *Equus* from West Central Mexico. Palaeogeography, Palaeoclimatology, Palaeoecology 441 (4): 748-757. doi: 10.1016/0047-2484(89)90048-1

Martin JE, Tacail T, Balter V (2017). Non-traditional isotope perspectives in vertebrate paleobiology. Paleontology 60 (4): 1-18. doi: 10.1111/pala.12300

Martínez del Rio C, Wolf BO (2005). Mass-balance models for animal isotopic ecology. In: Starck MJ, Tobias W (editors). Physiological and Ecological Adaptations to Feeding in Vertebrates. 1st ed. Enfield, NH, USA: Science Publishers, pp. 141-174.

Medrano H, Flexas J (2000). Fotorrespiración y mecanismos de concentración del dióxido de carbono. In: Azcón-Bieto J, Talón M (editors). Fundamentos de Fisiología Vegetal. 1st ed. Madrid, Spain: McGraw-Hill Interamericana, pp. 187-201 (in Spanish).

Mirambell LE, Lorenzo JL (2012). Restos de materiales de cultura. In: Mirambell LE (editor). Rancho "La Amapola", Cedral. Un Sitio Arqueológico-Paleontológico Pleistocénico- Holocenico con Restos de Actividad Humana Colección Interdisciplinaria, Serie Memorias. 1st ed. Mexico City, Mexico: Instituto Nacional de Antropología e Historia, pp. 71-86 (in Spanish).

Ortega-Rosas CI, Peñalba MC, Guiot J (2016). The Late Glacial Interstadial at the southeastern limit of the Sonoran Desert, Mexico; vegetation and climate reconstruction based on pollen sequences from Ciénega San Marcial and comparison with the subrecent record. Boreas 45 (4): 773-789. doi: 10.1111/bor.12188

Pérez-Crespo VA, Arroyo-Cabrales J, Alva-Valdivia LM, Morales-Puente P, Cienfuegos-Alvarado E et al. (2014). Marcadores biogeoquímicos $\delta^{13}C$ y $\delta^{18}O$: Inferencias sobre la dieta y hábitat de mamíferos que habitaron el Pleistoceno tardío de México. Monografías del Instituto de Geofísica 20. 1st ed. Mexico City, Mexico: Universidad Nacional Autónoma de México-Instituto de Geofísica (in Spanish).

Pérez-Crespo VA, Arroyo-Cabrales J, Alva-Valdivia LM, Morales-Puente P, Cienfuegos-Alvarado E et al. (2016a). Inferences of feeding habits of Late Pleistocene *Equus* sp. from eight Mexican localities. Neues Jahrbuch für Geologie und Paläontologie 279: 107-121. doi: 10.1127/njgpa/2016/0544

Pérez-Crespo VA, Prado JL, Alberdi MT, Arroyo-Cabrales J, Johnson E (2016b). Diet and habitat for six American Pleistocene proboscidean species using carbon and oxygen stable isotopes. Ameghiniana 53 (1): 39-51. doi: 10.5710/AMGH.02.06.2015..2842

Pérez-Crespo VA, Arroyo-Cabrales J, Morales-Puente P, Castillo-Ochoa P (2019). Paleoambiente de cuatro sitios mexicanos del Pleistoceno tardío con actividad humana inferidos a partir de la fauna. Boletín de la Sociedad Geológica Mexicana 71 (2): 343-358 (in Spanish). doi: 10.18268./BSGM2019v71n2a7

Révész KM, Landwehr JM (2002). $\delta^{13}C$ and $\delta^{18}O$ isotopic composition of $CaCO_3$ measured by continuous flow isotope ratio mass spectrometry: statistical? evaluation and verification by application to Devils Hole core DH – 11 calcite. Rapid Communications in Mass Spectrometry 16: 012-2114. doi: 10.1002/rcm.833

Rivals F, Semprebon G, Lister A (2012). An examination of dietary diversity patterns in Pleistocene proboscideans (*Mammuthus*, *Paloeoloxodon*, and *Mammut*) from Europe and North America as revealed by dental microwear. Quaternary International 255: 188-195. doi: 10.1016/j.quaint.2011.05.036

Rivals F, Solounias N, Mihlbanchér MC (2007). Evidence for geographic variation in diets of Late Pleistocene and Early Holocene Bison in North America, and differences from the diets of recent Bison. Quaternary Research 68 (3): 338-346. doi: 10.1016/j.yqres.2007.07.012

Roy PD, Caballero M, Lozano S, Jonathan MP, Sánchez JL et al. (2012). Provenance of sediments deposited at paleolake San Felipe, western Sonora Desert: Implications to regimes of summer and winter precipitation during last 50 cal kyr BP. Journal of Arid Environments 81: 47-58. doi: 10.1016/j.jaridenv.2012.01.008

Sánchez B (1997). Estudio de las variaciones climáticas durante el final del Neogeno a partir del análisis de $\delta^{18}O$ (PO_4^{3-}) en fósiles de mamíferos. In: Calvo JP, Morales J (editors). Avances en el conocimiento del Terciario Ibérico. 1st ed. Madrid, Spain: Universidad Complutense de Madrid, Facultad de Ciencias Geológicas-CSIC Museo Nacional de Ciencias Naturales, pp. 197-200 (in Spanish).

Sánchez G (2001). A synopsis of Paleo-Indian archaeology in México. Kiva 67 (2): 119-136. doi: 10.1080/00231940.2001.11758451

Sánchez G, Carpenter J (2016). Tracking the first people of Mexico: a review of archaeological record. In: Kornfield M, Huckell BB (editors). Stones, Bones, and Profile. Exploring Archaeological Context, Early American Hunter-Gatherers, and Bison. 1st ed. Boulder, CO, USA: University Press of Colorado, pp. 75-101.

Sanchez G, Holliday VT, Gaines EP, Arroyo-Cabrales J, Martínez-Tagüeña N et al. (2014). Human (Clovis) gomphothere (*Cuvieronius* sp.) Association ~13,390 calibrated yBP in Sonora. Proceedings of the National Academy of Science of the United States of America 111 (30): 10972-10977. doi: 10.1073/pnas.1404546111

Schwarcz HP (2000). Some biochemical aspects of carbon isotopic paleodiet studies. In: Ambrose H, Katzenberg MA (editors). Biogeochemical Approaches to Paleodietary Analysis. 1st ed. New York, NY, USA: Kluwer Academic, pp. 189-209.

Stinnesbeck W, Becker J, Hering F, Frey E, Gonzalez AG et al. (2017). The earliest settlers of Mesoamerica date back to the late Pleistocene. PLoS One 12 (8): e0183345

Stowe LG, Teeri JA (1978). The geographic distribution of C4 species of the dicotyledonae in relation to climate. The American Naturalist 112 (985): 609-623. doi: 10.1371/journal.pone.0183345

Terrazas Mata A, Benavente M (2013). Poblamiento temprano en el Noroeste de Sonora: Región El Arenoso-El Sásabe. Informe técnico final. Mexico City, Mexico: Instituto de Investigaciones Antropológicas, UNAM (in Spanish).

Van der Merwe NJ, Medina E (1989). Photosynthesis and 12C/13C ratios in Amazonian rain forest. Geochimica et Cosmochimica Acta 53 (5): 1091-1094. doi: 10.1016/0016-7037(89)90213-5

Van Devender TR (1990). Late Quaternary vegetation and climate of the Sonoran Desert, United States and Mexico. In: Betancou JL, Van Devender TR, Martín PS (editors). Packrat Middens. The Last 40,000 Years of Biotic Change. 1st ed. Tucson, AZ, USA: University of Arizona Press, pp. 134-163.

Vidal Zepeda R (2005). Las regiones climáticas de México. 1st ed. Mexico City, Mexico: Instituto de Geografía, UNAM (in Spanish).

Werner RA, Brand WA (2001). Referencing strategies and techniques in stable isotope ratio analysis. Rapid Communications in Mass Spectrometry 15 (7): 501-519. doi: 10.1002/rcm.258