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# Geographic variation in bone carbonate and water $\delta^{18}O$ values in Mendoza, Argentina and their relationship to prehistoric economy and settlement

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ABSTRACT

Questions of mobility, settlement pattern, and their relation to economic organization and resource use are central to ongoing work in central-western Argentina. Here we analyze geographic patterns in the distribution of 178 human bone carbonate $\delta^{18}O$ samples, 46 human tooth enamel carbonate $\delta^{18}O$ samples, and 48 water $\delta^{18}O$ samples from throughout the Andean Cordillera and Monte Desert and evaluate their implications for prehistoric mobility and economy. We confirm and refine previous generalizations regarding a highland/lowland dichotomy in water $\delta^{18}O$ values and show that the range of human carbonate $\delta^{18}O$ values generally reflect available water sources. While there is little within-lifetime change in patterns of water use, we show that most individuals have stable isotope signatures consistent with water use from multiple areas or areas other than where they were ultimately interred. These data indicate high levels of residential mobility, and we conclude by discussing their implications for our understanding of regional prehistory.



## 1. Introduction

Questions of mobility, settlement pattern, and their relation to economic organization and resource use remain central to archaeological studies of human adaptation (Bettinger, 1991; Binford, 2001; Kelly, 1995; Zeanah, 2004). They are particularly relevant to work in the province of Mendoza in central-western Argentina (Fig. 1), where debate continues over ethnohistoric and archaeological evidence for the presence, distribution, and interaction of hunter-gatherers and agriculturalists during the last two millenia (Durán, 2000; Gil, 2006; Johnson et al., 2009; Neme, 2007). Historic records and early archaeological work originally suggested a sharp division in prehistoric economies, with sedentary agriculturalists to the north and mobile hunter-gatherers to the south (Lagiglia, 1974, 1999; Michieli, 1983). This view has been undercut by more recent archaeological work, supplemented by stable carbon isotope analyses of human remains (Gil et al., 2006, 2009, 2010). Rather than a distinct break in economy and mobility, these studies suggest a fluid arrangement grading from greater sedentism and domesticate use in the north to more mobile hunting and gathering economies in the south.

In an effort to refine this picture, Gil et al. (in press) recently analyzed stable oxygen isotope ($\delta^{18}O$) data from 71 late Holocene burials throughout the region. Given reported variation in the $\delta^{18}O$ values of water sources in the region, the authors hypothesized that changes in economy and residential mobility would be mirrored by changes in the use of locally available water sources and the human bone carbonate $\delta^{18}O$ values derived from them. Interestingly, the study found no regional differences with either latitude or altitude, and suggested that prehistoric occupations throughout central-western Argentina were more variable and mobile than

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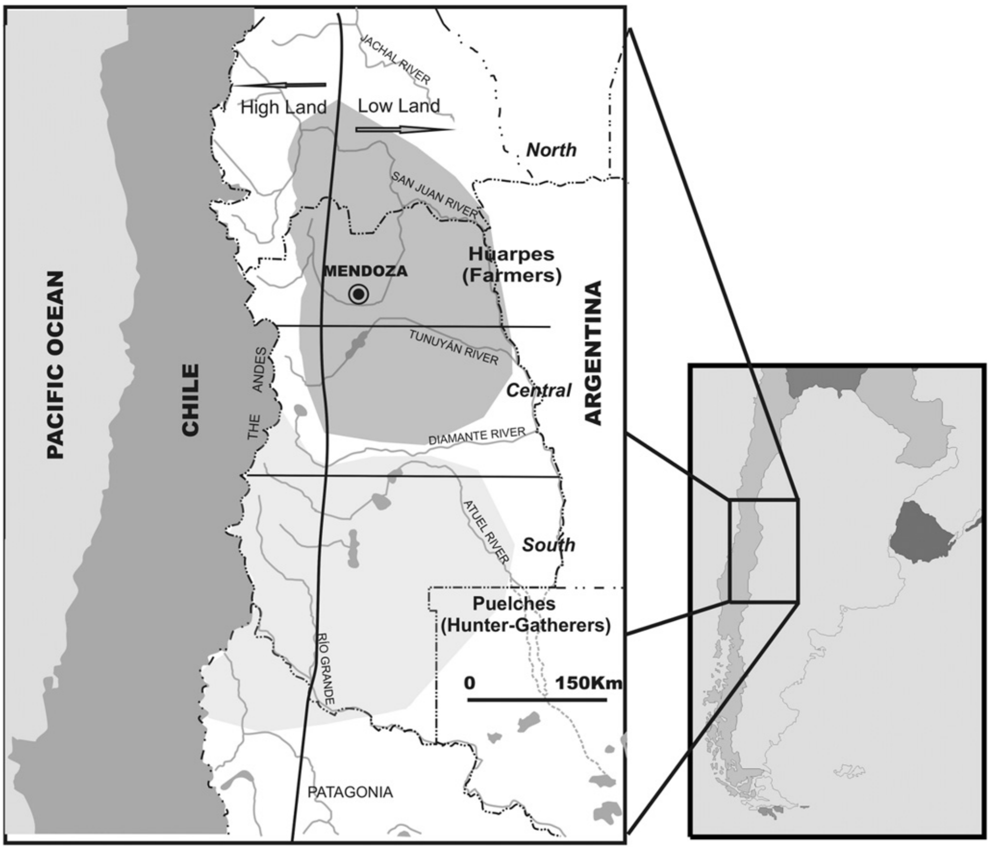


**Fig. 1.** Map of Mendoza, Argentina and surrounding region. Shaded areas show the approximate distribution of Huarpe agriculturalists and Puelche hunter-gatherers at the time of Spanish conquest.

previously supposed. While these conclusions are appropriate given the data, the analysis had some limitations. The number of human samples in some regions was small, no direct data from local water sources were available, and human carbonate values came solely from bones. This paper attempts to rectify these issues.

In the following sections we summarize the archaeological issues motivating the original analysis and the logic underlying the use of oxygen isotopes to study questions of prehistoric mobility. We then provide a direct analysis of deuterium and oxygen isotopes for 48 water sources throughout the Andean Cordillera and Monte Desert, confirming and refining previous generalizations regarding the distribution of water $\delta^{18}O$ values. We then analyze geographic patterns in the distribution of bone carbonate $\delta^{18}O$ values from 178 individuals in central-western Argentina, more than doubling the size of the original sample. We further show that the range of human carbonate $\delta^{18}O$ values generally reflects available water sources. Finally, we use matching enamel and bone carbonate date from 46 sets of human remains to identify within-lifetime changes in $\delta^{18}O$ and water use. We conclude by showing how these data continue to support the original inference of high residential mobility throughout the province and review their implications for our understanding of regional prehistory.

## 2. Background

At the heart of the current debate over late-Holocene economies in Mendoza are historic records that suggest that residential mobility in the region varied with latitude and economy. At contact, sedentary or semi-sedentary Huarpe agriculturalists occupied Southern San Juan Province and Mendoza north of the Rio Diamante (35°S; Fig. 1; Lagiglia, 1978; Michieli, 1983; Prieto, 1997–1998; but see García, 1998; Parissi, 1992, 1995 for a discussion), while Puelche and Pehuenche hunter-gatherers occupied the areas from the Diamante south to the province of Neuquén (35–40°S) (Durán, 2000; Lagiglia, 1978; Michieli, 1977). Archaeologists projected this division back 2000 years, associating its origin with the arrival of maize agriculture in the region (Lagiglia, 1974, 1999).

Recent work has complicated this picture, highlighting variability in prehistoric economies of northern and especially central Mendoza (Gil et al., 2010; Johnson et al., 2009). The late Holocene archaeological record from northern Mendoza and southern San Juan, for example, contains a variety of evidence for maize-based agriculturalists (Gambier, 2000; Johnson et al., 2009; Lagiglia, 1978). This includes maize macrofossils, more substantial architecture, more substantial internments, and larger quantities of decorated and simple ceramics from a range of vessel forms and sizes (Bárcena, 2001; Cortegoso, 2006; Rusconi, 1962). Nonetheless, isotope data from human remains in the north indicate that maize and other $C_4$ plants played a minor role in the diets of some and may have declined in importance after 500 years BP (Gil et al., 2006, 2009, 2010).

The archaeological record of central Mendoza accords well with more mobile hunters and gatherers, with little evidence for long term residences or substantial investment in residential structures, storage, or ceramics. There is clear, although limited, evidence of domesticated maize macrofossils however (Gil, 1997–1998, 2003, 2006; Llano, 2011). This is also reinforced by the isotopic evidence for human diet. Various collagen $\delta^{13}C$ values indicative of mixed $C_3$–$C_4$ diets ($\delta^{13}C$ −18 to −14‰) occur within the same span of time and have been held to indicate partial reliance on maize agriculture (Gil, 2003). Variation in space, time and among individuals was almost certainly the norm, but whether maize was ever a staple in this region remains questionable (Gil et al., 2009, 2010, 2011).

These observations, the difficulty of dry farming in much of the region, and the recognition of other resources capable of mimicking the elevated $\delta^{13}$C values of maize has led to debate about the precise nature of prehistoric economies. This includes whether maize farming was ever important anywhere south of San Juan and, to the degree that it was, what it may have been like and how it may have been organized. Some, for example, have favored the presence of fully sedentary farming groups even in the central area (Lagiglia, 1974, 1999), while others propose that hunter-gatherers populations interacted with more established farming groups both further north and in central Chile (Gil, 1997–1998, 2003, 2006).

Associated with this changing view of intraregional economics are related expectations regarding residential mobility. If maize farming dominated subsistence systems in the north, was mixed with hunting and gathering in the intermediate zones, and gave way to purely hunting and gathering in the south, those differences should be reflected in the degree of residential mobility and tethering. We might expect more localized resource use in the north than in the south, and a more diverse set of environments to be exploited pre-2000 BP (prior to substantial evidence for domesticates) than post-2000 BP. These differences should also be reflected in both the archaeological record and the physical remains of prehistoric peoples.

## 3. Water $\delta^{18}$O and mobility

Archaeologists regularly use oxygen isotopes ($^{16}$O/$^{18}$O) to assess mobility and residence patterns in ancient populations (Buzon et al., 2011; Dupras and Schwarcz, 2001; Knudson, 2009; Sanhueza and Falabella, 2010; Sponheimer and Lee-Thorp, 1999; Turner et al., 2009). These isotopes occur in the phosphate and carbonate components of bone and enamel hydroxyapatite and reflect the isotopic composition of body water at the time bone and enamel are formed. In humans, the isotopic composition of body water is determined primarily by that of imbibed water (Longinelli, 1984; Longinelli and Nuti, 1973; Luz et al., 1984; Sponheimer and Lee-Thorp, 1999; Turner et al., 2009; White et al., 2004), while the composition of imbibed water itself varies with latitude, elevation, rainfall patterns, and other environmental factors (Dansgaard, 1964; Gat, 1996; White et al., 1998, 2004). Where water $\delta^{18}$O varies sufficiently within a region, the oxygen isotope values from human bone and tooth enamel can inform on where an individual has been drinking (Dupras and Schwarcz, 2001; Turner et al., 2009; White et al., 2000, 2002, 2004).

In order to do so, an accurate assessment of geographic variation in the $\delta^{18}$O values of potential water sources is very important (Knudson, 2009). West-central Argentina is a temperate, arid region with three major environmental zones. These are the Andean cordillera and piedmont, with winter precipitation between 300 and 1000 mm/year; the dry oriental plains of the Monte Desert, with summer dominant precipitation below 250 mm/year; and the southeastern malpais of La Payunia, characterized by winter-dominant annual precipitation ranging from 200 to 400 mm/year (Abraham and Rodríguez, 2000; Capitanelli, 1972; Morales et al., 2009). The cordillera and piedmont form a continuous band along the western margin of the region. To the east, the Monte Desert dominates the northern and central lowlands while the volcanic region of La Payunia occurs almost exclusively in the south. These regions differ sharply from one another due to their relief, the dominant masses of maritime air that influence local weather patterns, and the season of the year in which precipitations occurs (Bruniard, 1982; Morales et al., 2009). The piedmont and oriental plains are predominately influenced by the Atlantic anticyclone and the western cordillera and La Payunia by the Pacific Ocean anticyclone.

Previous water isotope studies by Hoke et al. (2009), the IAEA (2011), Osterra and Dapeña (2003), and Vogel et al. (1975) have identified certain trends. First, water from melting snow feeds the majority of the streams and rivers that flow down from the Andes out onto the eastern lowland plains (Fig. 1). The precipitation generating this snow comes from the Pacific anticyclone (Norte, 2000), and water in the cordillera has very low $\delta^{18}$O values typical of higher-altitude precipitation. These become more positive as altitude declines. $\delta^{18}$O values in the Río Mendoza catchment, for example, vary from −18‰ (Vienna Standard Mean Ocean Water, VSMOW) at 5500 m asl to about −8‰ (VSMOW) at ca. 1000 m asl, or a change of roughly .48‰/100 m (Hoke et al., 2009). Vogel et al. (1975) report a difference of .3–.4‰/100 m based on a geographically more diverse set of data that includes samples from Mendoza.

The other major water sources are smaller wells or springs located throughout the lowland plains and La Payunia. Vogel et al. (1975) and Osterra and Dapeña (2003) show that underground aquifers and springs associated with major river valleys are recharged by river waters and have $\delta^{18}$O values similar to them. Finally, there are also springs that are recharged by local rain rather than rivers and which have still higher $\delta^{18}$O values. These springs are more common in La Payunia, where rivers are almost nonexistent, but should also characterize water sources throughout the lowland plains when they occur away from the wash-out basins of the major rivers.

These differences in the distribution of water $\delta^{18}$O values (more negative in the cordillera, more positive in the Monte Desert and la Payunia) and the suggestion that human residential patterns were more stable in the northern part of Mendoza than in the south provided the basis for expectations regarding the distribution of prehistoric human $\delta^{18}$O (Gil et al., in press). The region was divided into the western highlands (cordillera and piedmont) and eastern lowlands (Monte Desert and la Payunia). Mean human oxygen values were expected to differ between highland and lowland areas, particularly in the northern and central regions where occupations were supposedly more stable. Variability in human $\delta^{18}$O was also expected to be greater in the north, with more tethered individuals reflecting a range of different water sources rather than averaging over them.

## 4. Materials and methods

### 4.1. Water

In order to reevaluate these expectations we began by collecting a series of water isotope samples, paying particular attention to the central and southern parts of the province (Fig. 2). These complement the published water data for northern Mendoza reported by Hoke et al. (2009) and the newer human data from the central and southern region provided here. Sources included rivers, streams, springs, and lakes from all elevations, geographic settings, and seasons. The only exceptions were samples from the high Andes, which were only accessible from late Spring to early Fall. While extensive, samples do not include repeated, seasonal measurements from specific locations.

Water was collected in the field using a syringe, .45 μ polyethersulfone filter, and Wheaton 25 ml borosilicate scintillation vial. Water was run through the filter and syringe several times and a sample then placed into the vial. Vials were capped, labeled, and sealed with tape before returning to the lab. All samples were stored in a refrigerated environment prior to being sent to the

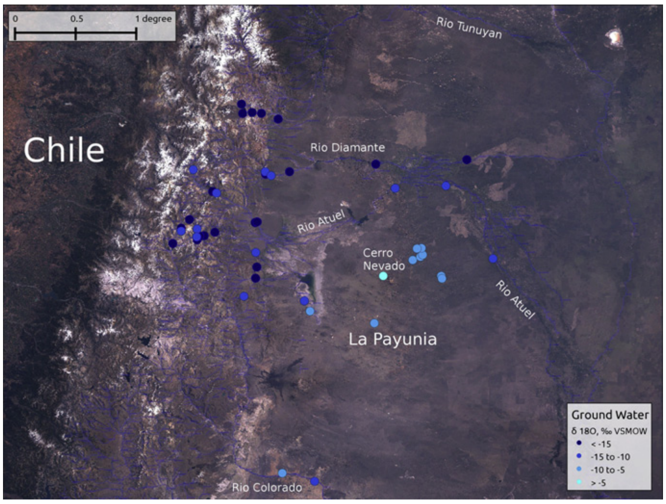


**Fig. 2.** Map of locations from which water samples were taken and their $\delta^{18}O$ values.

Stable Isotope Facility for Environmental Research (SIRFER) at the University of Utah. There samples were analyzed by isotope ratio infrared spectroscopy (IRIS) on a wavelength-scanned cavity ring-down spectrometer (WS-CRDS) model L1102-i water analyzer (Picarro, Sunnyvale, CA, USA). Samples were introduced to the vaporization chamber using a PAL auto sampler (Leap Technologies, Carrboro, NC, USA). Each samples was analyzed with four replicate injections and the average of the third and fourth injection used to generate the reported values. Samples were analyzed against three lab reference materials which have been calibrated to Vienna Standard Mean Ocean Water (VSMOW). Instrument precision is ±1.6‰ and ±.2‰ for hydrogen and oxygen respectively.

### 4.2. Bone and enamel carbonate

Human carbonate samples come from the hydroxyapaite of cortical bone and tooth enamel of independent burials. Seventy-seven bone carbonate samples were processed by the Laboratory for Archaeological Science at the University of South Florida and were previously reported by Gil et al. (in press). An additional 103 bone carbonate samples were prepared and analyzed at the Archaeological Center Research Facility, University of Utah, and the University of Wyoming Stable Isotope Facility. Preparation of the samples was similar in all cases, including grinding and weighing bone powder, soaking samples in 2% sodium hypochlorite to remove organics, and removing non-biogenic carbonates with an acetic acid solution. $\delta^{13}C$ and $\delta^{18}O$ values are reported relative to Vienna Pee Dee Belemnite (VPDB), and detailed descriptions of all procedures can be found in Gil et al. (2009, in press), Tykot (2004), and Ugan and Coltrain (2011).

To complement these data, we provide information from 46 dental samples that were also analyzed for carbonate $^{18}O$. Unlike bone, which slowly turns over (ca. 2–3%/yr in cortical bone; Clarke, 2008: S134) and integrates isotopic inputs over years of an individual's life (Hedges et al., 2007), tooth enamel is laid down when the tooth forms and is not subsequently remodeled (Ash and Nelson, 2002). The crown of most adult teeth is laid down between 3.5 and 8 years of age (AlQahtani et al., 2010), while the third molars form by 14–15 years old. Because of this difference, isotope data from bones and teeth allows us to compare patterns of water use at different points during an individual's lifetime. Enamel samples were also done at South Florida, and each corresponds to an individual for which we have bone carbonate data.

Enamel samples at the USF facility were analyzed using a Finnigan MAT mass spectrometer coupled with a Kiel III device, those at the University of Wyoming Stable Isotope Facility with a Thermal Finnigan Delta Plus XP IRMS attached to a Thermal Finnigan Gas Bench II. The $\delta^{18}O$ results are reported in relation to Vienna Pee Dee Belemnite (VPDB) using standard delta ($\delta$) notation: $1\delta^{18}O = [(\text{sample } ^{18}O/^{16}O)/(\text{standard } ^{18}O/^{16}O)-1] \times 1000$. The stable isotope ratios produced have a precision of better than ±.1‰ and were calibrated against international standards analyzed along with each set of samples.

We did not assess recrystallization or other diagenetic changes associated with the incorporation of exogenous oxygen sources (Lee-Thorp, 2002; Pellegrini et al., 2011; Zazzo et al., 2004). All human remains reported here are less than a few thousand years old, exhibit good collagen preservation, and occur in dry to very dry contexts. These are all conditions that minimize isotopic exchange. We are also interested in oxygen isotope patterns in a region where water $\delta^{18}O$ values may vary by as much as 15–20‰, not in paleothermometry or other applications where precise measurements are critical.

Human samples are representative of all environments and are grouped into six spatial units that reflect the prehistoric use of various water sources (Fig. 2). From north to south these units include southern San Juan and Mendoza north of the Río Tunuyán (North, ca. 30–33°S latitude), central Mendoza between the Río Tunuyán and Río Atuel (Center, ca. 34–35°S), and southern Mendoza from the Río Atuel south to the Río Colorado (South, ca. 36°S). Each of these regions was further divided into highland-piedmont (HP) and lowland plains (LL) depending on elevation. These individuals represent a significant sample of the human collections available in the region and an almost complete census of known burial localities in the central and southern part of the province. Of the 79 individuals for which there are radiocarbon data, 74 date to within the last 3000 years (uncalibrated). Additional details on the samples can be found in Gil et al. (2011).

## 5. Results

### 5.1. Water $\delta^{18}O$ data

Results of water sampling are reported in Table 1. They include information on geographic location (name, latitude, and longitude), elevation in meters, and deuterium and oxygen isotope values relative to VSMOW. Sample locations span an elevation range from 400 to 3560 m above sea level, and their associated oxygen isotope values fall between −18.8 and −3.6‰.

Samples were also categorized by type of water source and geographic origin. Water sources included arroyos with small streams, lakes, rivers, springs, one pond and one shallow well. These can be broadly categorized by geographic area and elevation. Three groups, the High Andes (HA), Andes-Piedmont (AP), and Lowland Rivers (LR), contain water samples derived from the Andes and differ in elevation (listed high-to-low). A fourth group, Nevado–Payunia, contains samples from streams and springs containing groundwater and precipitation primarily of extra-Andean origin. The distribution of oxygen isotope values for these four groups are shown in Fig. 3.

There are sharp differences in $\delta^{18}O$ values for Andean and non-Andean samples. The Andean derived samples are all substantially more negative, even when recovered from low elevation locations well out into the oriental plains of the Monte Desert (Río Atuel and Río Diamante) or along the southern margins of la Payunia (Pata Mora, on the Río Colorado). Although the Andes-Piedmont subset is quite variable, the Andean derived waters as a group show a clear trend of more negative $\delta^{18}O$ values with altitude. This trend is

**Table 1**
Water isotope data for Mendoza, Argentina.

| Sample | Location | Lat | Long | Elev | Type | Group | $\delta^2$H ‰ | $\delta^{18}$O ‰ |
|---|---|---|---|---|---|---|---|---|
| H66 | Agua Buena | −34.83 | −69.95 | 2100 | A | AP | −126.0 | −15.8 |
| H05 | Agua del Médano | −34.70 | −69.47 | 1745 | S | AP | −100.0 | −11.9 |
| H61 | Arroyo Blanco | −35.14 | −70.08 | 2205 | A | AP | −113.4 | −13.7 |
| H13 | Arroyo Colorado | −35.20 | −70.08 | 2135 | A | AP | −106.4 | −13.6 |
| H43 | Arroyo el Desecho | −35.20 | −70.08 | 2120 | A | AP | −111.9 | −15.0 |
| H45 | Arroyo el Matadero | −35.45 | −69.59 | 1405 | A | AP | −113.7 | −15.1 |
| H46 | Arroyo la Jaula | −35.33 | −69.59 | 1430 | A | AP | −100.0 | −13.1 |
| H21 | Arroyo Las Amarillas | −35.19 | −70.02 | 2040 | A | AP | −116.4 | −15.2 |
| H34 | Arroyo Las Numeradas | −34.11 | −69.71 | 3385 | A | HA | −144.9 | −18.8 |
| H36 | Arroyo las Vacas | −35.30 | −68.27 | 895 | A | NP | −41.9 | −6.5 |
| H17 | Arroyo Los Alamos | −35.20 | −70.06 | 2065 | A | AP | −116.0 | −15.2 |
| H57 | Arroyo los Patos | −35.55 | −68.07 | 730 | A | NP | −50.9 | −7.0 |
| H38 | Arroyo los Toldos | −35.30 | −68.24 | 825 | A | NP | −43.3 | −6.7 |
| H32 | Arroyo Paramillo | −34.18 | −69.62 | 3555 | A | HA | −139.3 | −17.9 |
| H56 | Arroyo Punta del Agua | −35.52 | −68.07 | 740 | A | NP | −50.0 | −7.1 |
| H35 | Cruz de Piedra | −34.24 | −69.41 | 2575 | A | AP | −118.3 | −15.5 |
| H60 | El Sosneado | −35.08 | −69.58 | 1650 | S | AP | −118.5 | −15.1 |
| H67 | El Sosneado | −34.84 | −69.92 | 2100 | L | AP | −107.8 | −12.1 |
| H07 | Las Aucas 1 | −34.69 | −69.51 | 1750 | A | AP | −120.1 | −15.1 |
| H09 | Las Aucas 2 | −34.67 | −69.52 | 1860 | A | AP | −113.9 | −13.8 |
| H50 | Llancanelo Sur | −35.81 | −69.15 | 1340 | L | NP | −63.0 | −7.2 |
| H19 | Mallín Colorado | −35.23 | −70.07 | 2545 | S | AP | −117.3 | −15.3 |
| H42 | Portezuelo Ancho | −35.06 | −70.14 | 2710 | A | AP | −117.0 | −15.7 |
| H49 | Pozos El Carapacho | −35.73 | −69.20 | 1340 | S | AP | −104.0 | −13.6 |
| H40 | Puesto Agua de la Mula | −35.37 | −68.24 | 895 | A | NP | −50.2 | −8.2 |
| H64 | Puesto Cáceres | −37.14 | −69.38 | 740 | A | NP | −58.3 | −6.5 |
| H53 | Puesto Cupertino | −35.52 | −68.55 | 2300 | P | NP | −42.6 | −3.6 |
| H63 | Puesto La Ventana | −35.91 | −68.62 | 1820 | W | NP | −60.3 | −6.9 |
| H37 | Puesto Ortubia | −35.39 | −68.31 | 1085 | A | NP | −52.9 | −8.6 |
| H12 | Puesto Salamanca | −35.69 | −69.69 | 2285 | S | AP | −100.2 | −12.7 |
| H23 | Río Atuel | −34.79 | −68.04 | 535 | R | LR | −106.9 | −13.7 |
| H27 | Río Atuel | −35.09 | −69.60 | 1600 | R | AP | −122.7 | −16.3 |
| H47 | Río Atuel | −34.81 | −68.45 | 725 | R | LR | −108.0 | −13.6 |
| H58 | Río Atuel | −35.38 | −67.65 | 405 | R | LR | −107.5 | −13.0 |
| H59 | Río Atuel | −35.09 | −69.60 | 1650 | R | AP | −121.1 | −15.4 |
| H69 | Río Atuel | −34.83 | −69.95 | 2100 | R | AP | −122.1 | −16.0 |
| H65 | Río Colorado, Pata Mora | −37.21 | −69.11 | 610 | R | LR | −105.4 | −13.3 |
| H03 | Río Diamante | −34.67 | −69.32 | 1470 | R | AP | −129.2 | −16.9 |
| H25 | Río Diamante | −34.57 | −67.86 | 525 | R | LR | −118.6 | −15.4 |
| H48 | Río Diamante | −34.61 | −68.61 | 895 | R | LR | −126.5 | −16.1 |
| H30 | Río Grande | −35.26 | −70.27 | 2335 | R | AP | −117.0 | −15.7 |
| H31 | Río Grande | −34.19 | −69.70 | 3290 | R | HA | −129.7 | −16.1 |
| H44 | Río Malargue | −35.54 | −69.60 | 1470 | R | AP | −114.5 | −15.4 |
| H41 | Río Salado | −35.17 | −69.93 | 1900 | R | AP | −117.1 | −15.7 |
| H28 | Río Tordillo | −35.13 | −70.21 | 2230 | R | AP | −126.9 | −16.7 |
| H68 | Sominar | −34.65 | −70.11 | 2400 | A | AP | −114.8 | −14.4 |
| H29 | Valle Hermoso | −35.16 | −70.21 | 2220 | L | AP | −110.6 | −14.8 |
| H33 | Vega Yaucha | −34.19 | −69.55 | 3310 | A | HA | −142.4 | −18.4 |

Lat/Long is in decimal degrees, elevation in meters. $\delta^2$H and $\delta^{18}$O are reported relative to VSMOW. "Types": A-arroyo, L-lake, P-pond, R-river, S-spring, W-well. "Groups": HA-High Andes, AP-Andes-Piedmont, LR-Lowland River, and NP-Nevado–Payunia.

roughly .2‰/100 m (a 6 change over 3000 m), or somewhat less that that reported by either Hoke et al. (2009) or Vogel et al. (1975). This difference stems partly from a lack of extremely high elevation samples (4–6000 m) and partly from the fact that the lower elevation river waters here are 3 more negative than those published for northern Mendoza (Hoke et al., 2009).

The extra-Andean (Nevado–Payunia) water samples are at least 3.3‰ more positive. Contrasts can also be sharp geographically, as seen in the southernmost two samples of Fig. 2. The Pata Mora sample of the Río Colorado, for example, is 6.8‰ more negative than a sample taken from one of the river's tributaries at Puesto Cáceres ($\delta^{18}$O of −13.3‰ and −6.5‰), even though Puesto Cáceres sits only 25 km from Pata Mora and only 2 km from the Río Colorado itself. The difference is that the stream at Puesto Cáceres originates in La Payunia. We expect water sources associated with other parts of the eastern lowland to be similarly positive where they occur away from the major rivers and are predominately rain-recharged.

Overall the data mirror previously published findings and support the expectations cited by Gil et al. (in press). Given those previous studies and the data here we continue to expect a clear difference between water sources in the lowland plains and the western cordillera and piedmont, with the cordillera samples being more negative even at lower elevations and increasingly so moving upward. This difference will be less dramatic than shown in Fig. 3 for lowland individuals relying on water from the major rivers, and appears to be slightly less marked in the northern part of the province.

### 5.2. Human carbonates

Oxygen isotope values of bone and tooth enamel for the complete set of human remains are shown in Table 2, along with site names, museum codes, latitude, longitude, and the region to which each individual was assigned. The mean bone carbonate $\delta^{18}$O value for the entire sample is $-6.9 \pm 2.5$‰, with a range of −12.1 to .8‰. Values for enamel are similar, with a mean of $-6.2 \pm 2.6$‰ and a range of −11.7 to 2.2‰.

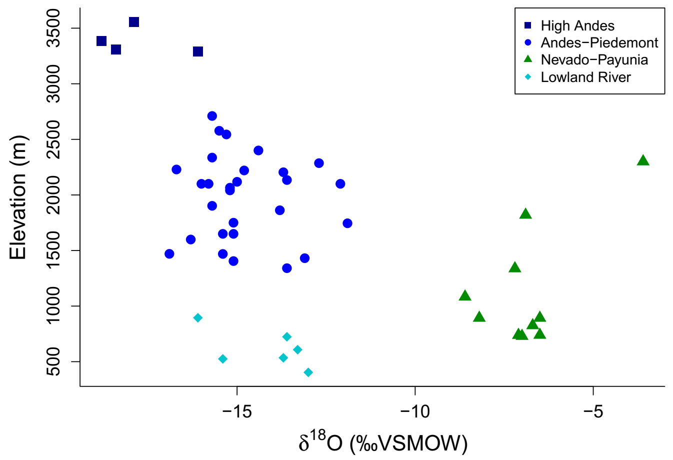


**Fig. 3.** Relationship between elevation and $\delta^{18}O$ values of waters sampled from central-western Argentina. The "Nevado–Payunia" group are the only samples not derived primarily from Andean snowpack. Rain-recharged water sources in other lowland areas should appear similar.

### 5.3. Comparison of bone carbonate and water $\delta^{18}O$

Human oxygen isotopes values are primarily dependent on the values of drinking waters. We compare human carbonate $\delta^{18}O$ values to the newly acquired water data using the relationships between VSMOW and VPDB standards, carbonate (c) and phosphate (p) $\delta^{18}O$ values (VSMOW), and phosphate and drinking water (dw) $\delta^{18}O$ (VSMOW) in Eqs. (1)–(3) (Iacumin et al., 1996; Luz et al., 1984; Sharp, 2007; following Buzon et al., 2011). Fig. 4 presents these data.

$$\delta^{18}O_{c,VSMOW} = \left(1.03092 * \delta^{18}O_{c,VPDB}\right) + 30.92‰ \quad (1)$$

$$\delta^{18}O_{c,VSMOW} = \left(8.50‰ + \delta^{18}O_{p,VSMOW}\right) / 0.98 \quad (2)$$

$$\delta^{18}O_{dw} = \left(\delta^{18}O_{p,VSMOW} - 22.70‰\right) / 0.78 \quad (3)$$

We recognize that estimating drinking water $\delta^{18}O$ from human bone carbonates can be problematic and limit ourselves to a few broad generalizations. First, there is general agreement between observed and predicted water isotope values, with human estimates somewhat more positive than observed waters. Some of this may be due to differences between regional water relationships and those used to derive Eqs. (1)–(3) (Pellegrini et al., 2011). At the same time, the lack of overlap in the most negative values is fully consistent with the nature of the sources. Waters with extremely negative $\delta^{18}O$ values only occur in very high elevation regions of the Andes. Access to these regions is limited to late Spring through early Fall, requiring that people also consume more positive, lower elevation water. That estimated drinking waters for some individuals are more positive than anything seen in the region could be a methodological artifact as well. However the most extreme contrasts a) come from just two individuals (Fig. 4) and, b) may reflect the reduced sampling of eastern lowlands where the most positive water sources are most likely to occur. They could also simply represent immigrants. Alternate derivations of drinking water values such as those proposed by Daux et al. (2008) extend the tails of the drinking water estimates a few per mil, slightly reducing perceived problems with the more negative values, slightly increasing those with more positive values, but otherwise having no effect. Caveats aside, the important point is that the vast majority of individuals have carbonate $\delta^{18}O$ values fully consistent with the use of locally available sources. Only a substantial error in the applicability of the methods cited in Eqs. (1)–(3) would change this.

The second important point involves the continuity of the two data sets. Observed water values (Table 1) can be divided into the more negative sources fed by waters from the Andes and the more positive springs and streams originating in La Payunia and Cerro Nevado (which are also expected to characterize other areas of the lowland plains away from the major rivers). On the basis of the present evidence, the $\delta^{18}O$ values of the two groups do not overlap and the gap between them is 3.3‰ (maximum of −11.9‰ for highland-derived waters, minimum of −8.6‰ for lowland samples).

Bone carbonate $\delta^{18}O$ values and those of imbibed waters estimated from them are continuous. Seventy six individuals from 37 different localities exhibit predicted drinking water values falling within this 3.3‰ gap (Fig. 5). Twenty five percent of them come from highland-piedmont regions and 75 percent from lowland areas, similar to the distribution of highland and lowland individuals for the entire sample. While individuals in lowland areas may have gone no farther than one of the nearby major rivers, individuals in highland-piedmont settings would have had no positive water sources nearby. This implies that individuals were consuming waters from both regions in order to produce the observed intermediate values and lends support to the hypothesis that many individuals throughout the region moved extensively (Gil et al., in press). Again, it would require large errors in the imbibed water estimates to change this.

Finally, eight lowland individuals have predicted water $\delta^{18}O$ values less than the average for the most negative lowland sources ("Planicies Orientales", mean $\delta^{18}O = -14.2‰$). Similarly, nine highland individuals exhibit predicted drinking water values of greater than −8.6‰. These individuals apparently spent much of their lives consuming water from one area but moved frequently and far enough to have died and been interred elsewhere, again underscoring the fluidity of prehistoric life in the region.

### 5.4. Geographic variation in carbonate $\delta^{18}O$

Based on the ethnohistoric, archaeological, and physiographic data available, human $\delta^{18}O$ values were initially expected to vary in two ways. Mean oxygen isotope values for individuals from highland areas were expected to be more negative than those from the lowland Monte Desert and La Payunia regions, and the variance in oxygen isotope values was expected to decline as one moves from north to south. Subsequent analysis showed no differences in either case (Gil et al., in press), however, and those results form the basis for our expectations here. Mean and variance in oxygen isotope values should be similar regardless of geographic origin.

Fig. 6 shows the distribution of carbonate $\delta^{18}O$ values throughout central-western Argentina. Sample variances are homogeneous with no significant differences among the six regions (Bartlett Test for homogeneity of variance, $K^2 = 8.988$, $df = 5$, $p = 110$). The same holds true if the highland and lowland samples are collapsed and comparisons are made strictly on the basis of latitude ($K^2 = 2.400$, $p = .301$). There are no sex differences in carbonate $\delta^{18}O$ signals in the samples for which we have data (49 females, 59 males; $t = -.057$, $df = 106.8$, $p = .572$), nor is sex a significant predictor of variation in $^{18}O$ when broken down by region ($F = .336$, $p = .564$). These results agree with Gil et al., in press.

Sample means are not the same, however (ANOVA of $\delta^{18}O \sim NCS*HPLL$, $F = 3.107$ on 5172 $df$, adj $R^2 = .056$, $p = .010$). The difference is driven entirely by the southern lowland sample (Fig. 6), which is more positive than all other regions and significantly more so than the southern highlands and central lowlands (Tukey's HSD for LL.S vs HP.S, difference of 2.47‰, $p_{adj} = .012$; LL.S

**Table 2**
Human isotope data for Mendoza, Argentina.

| Sample | Code | Lat | Long | Elev | Region | $\delta^{18}O_{ap}$ | $\delta^{18}O_{en}$ | Tooth |
|---|---|---|---|---|---|---|---|---|
| Agua Buena | 523 | −34.83 | −69.94 | 2100 | HP-N | −9.1 | | |
| Agua del Médano | 2012 | −34.68 | −69.52 | 1860 | HP-N | −8.5 | | |
| Agua del Toro | 10 | −36.77 | −68.83 | 1080 | LL-S | −5.7 | | |
| Agua del Toro | AF-1082 | −36.77 | −68.83 | 1080 | LL-S | −3.9 | | |
| Alto Verde, Rivadavia | MMy-1471 | −33.20 | −68.40 | 650 | LL-N | −7.3 | −6.4 | M1 |
| Angualasto | SJ10-ENT-1 | −30.10 | −69.14 | 1580 | LL-N | −3.7 | | |
| Angualasto | SJ4-ENT-2 | −30.10 | −69.14 | 1580 | LL-N | −3.3 | | |
| Arbolito, El Nihuil | AF-1083 | −35.08 | −68.69 | 1300 | LL-C | −7.7 | −8.3 | M2 |
| Arbolito, El Nihuil | 2041 | −35.08 | −68.69 | 1300 | LL-C | −8.5 | | |
| Arroyo el Tigre | 2008 | −34.58 | −68.58 | 880 | LL-C | −4.0 | | |
| Arroyo Imperial | 2002 | −34.60 | −69.12 | 1440 | LL-C | −8.6 | | |
| Arroyo los Jilgueros | 2004 | −34.74 | −68.48 | 850 | LL-C | −7.1 | | |
| Arroyo Mechenquil | MRM-8 | −36.18 | −69.78 | 1320 | HP-S | −7.3 | | |
| Arroyo Negro de de Pincheira | MRM-24 | −35.52 | −69.80 | 1770 | HP-S | −7.6 | | |
| Barrancas Yacimiento 1 | MMy-1241 | −33.10 | −68.74 | 750 | LL-N | −6.6 | −1.1 | M2 |
| Barrancas Yacimiento 2 | MMy-1263 | −33.10 | −68.74 | 750 | LL-N | −9.9 | −11.7 | M3 |
| Buta Mallín | MRM-16 | −35.71 | −69.80 | 2070 | HP-S | −5.5 | | |
| Calingasta | SJ2 | −31.34 | −69.42 | 1416 | LL-N | −4.8 | −8.4 | PM |
| Campos las Julias | 1103 | −34.25 | −68.70 | 1180 | LL-C | −8.7 | | |
| Cañada de las Vizcachas | MRM-4 | −35.75 | −69.20 | 1350 | HP-S | −6.1 | −6.7 | M3 |
| Cañada Seca | AF-2019 | −34.74 | −68.23 | 610 | LL-C | −3.7 | −4.9 | M |
| Cañada Seca | AF-2018 | −34.74 | −68.23 | 610 | LL-C | −2.8 | −4.7 | M2 |
| Cañada Seca | AF-2020 | −34.74 | −68.23 | 610 | LL-C | −2.5 | −4.2 | M3 |
| Cañada Seca | 61 | −34.74 | −68.23 | 610 | LL-C | −7.2 | | |
| Cañada Seca | 10,004 | −34.74 | −68.23 | 610 | LL-C | −7.2 | | |
| Cañada Seca | 10,008 | −34.74 | −68.23 | 610 | LL-C | −6.0 | | |
| Cañada Seca | 10,015 | −34.74 | −68.23 | 610 | LL-C | −6.0 | | |
| Cañada Seca | CS-10,001 | −34.74 | −68.23 | 610 | LL-C | −5.4 | | |
| Cañada Seca | 10,005 | −34.74 | −68.23 | 610 | LL-C | −7.7 | | |
| Cañada Seca | 10,013 | −34.74 | −68.23 | 610 | LL-C | −4.8 | | |
| Cañada Seca | 88 | −34.74 | −68.23 | 610 | LL-C | −1.3 | | |
| Cañada Seca | REM-5 | −34.74 | −68.23 | 610 | LL-C | −4.3 | | |
| Cañada Seca | REM-6 | −34.74 | −68.23 | 610 | LL-C | −5.4 | | |
| Cañada Seca | REM-4 | −34.74 | −68.23 | 610 | LL-C | −1.7 | | |
| Cañada Seca | 84 | −34.74 | −68.23 | 610 | LL-C | −1.8 | | |
| Cañada Seca | 65 | −34.74 | −68.23 | 610 | LL-C | −7.3 | | |
| Cañada Seca | 66 | −34.74 | −68.23 | 610 | LL-C | −6.8 | | |
| Cañada Seca | 10,007 | −34.74 | −68.23 | 610 | LL-C | −7.2 | | |
| Cañada Seca | 10,009 | −34.74 | −68.23 | 610 | LL-C | −7.9 | | |
| Cañada Seca | 10,012 | −34.74 | −68.23 | 610 | LL-C | −7.8 | | |
| Cañada Seca | REM-1 | −34.74 | −68.23 | 610 | LL-C | −6.8 | | |
| Cañada Seca | REM-2 | −34.74 | −68.23 | 610 | LL-C | −7.1 | | |
| Cañada Seca | REM-3 | −34.74 | −68.23 | 610 | LL-C | −7.8 | | |
| Cañon del Atuel | 1089 | −34.90 | −68.62 | 1040 | LL-C | −8.8 | | |
| Capiz Alto | ENT-2 | −33.68 | −68.99 | 940 | LL-C | −6.9 | −4.6 | |
| Casa de Piedra | MRM-22 | −35.84 | −69.79 | 1460 | HP-S | −6.4 | | |
| Caverna de las Brujas | 12 | −35.80 | −69.82 | 1870 | HP-S | −3.3 | | |
| Cerro Mesa | AF-508 | −35.37 | −69.67 | 1610 | HP-S | −8.0 | −11.4 | M3 |
| Cerro Mesa | AF-510 | −35.37 | −69.67 | 1610 | HP-S | −5.0 | −8.1 | M3 |
| Cerro Mesa | 509 | −35.37 | −69.67 | 1610 | HP-S | −10.7 | | |
| Cerro Mesa | 515 | −35.37 | −69.67 | 1610 | HP-S | −10.1 | | |
| Cerro Mesa | 369 | −35.37 | −69.67 | 1610 | HP-S | −11.8 | | |
| Cerro Mesa | 513 | −35.37 | −69.67 | 1610 | HP-S | −11.1 | | |
| Cerro Meson | 2016 | −34.55 | −68.80 | 1400 | LL-C | −10.0 | | |
| Cerro Negro | AF-2000 | −34.81 | −68.38 | 920 | LL-C | −4.8 | −5.9 | M3 |
| Cerro Trapal | AF-2077 | −35.61 | −69.20 | 1420 | LL-S | −3.1 | | |
| Cerro Trapal | AF-2081 | −35.61 | −69.20 | 1420 | LL-S | −5.3 | | |
| Cienaga de Borbarán | MRM-12 | −35.95 | −68.51 | 1660 | LL-S | −4.7 | −4.4 | M3 |
| Dique 25 de Mayo | 258 | −34.59 | −68.56 | 860 | LL-C | −10.2 | | |
| Dique 25 de Mayo | 679 | −34.59 | −68.56 | 860 | LL-C | −9.5 | | |
| El Alambrado | MRM-15 | −36.27 | −69.86 | 1600 | HP-S | −6.6 | −4.3 | M2 |
| El Alambrado | MRM-19 | −36.27 | −69.86 | 1600 | HP-S | −7.3 | −6.9 | M2 |
| El Chacay | ENT-3 | −35.36 | −69.63 | 1460 | LL-S | −4.7 | −6 | M |
| El Chacay, Pto Adobe | MRM-10 | −35.36 | −69.63 | 1460 | HP-S | −8.3 | −7.9 | M3 |
| El Chequenco | MRM-22 | −35.83 | −69.78 | 1560 | HP-S | −6.4 | | |
| El Desecho | AF-2038 | −35.20 | −70.05 | 2060 | HP-S | −7.3 | | |
| El Durazno | 1105 | −34.73 | −68.69 | 1190 | HP-C | −9.6 | | |
| El Mallín | | −34.30 | −69.27 | 2600 | HP-C | −6.4 | | |
| El Manzano | AF-673 | −36.11 | −69.77 | 1320 | HP-S | −3.7 | −8.1 | PM |
| El Manzano | 1084 | −36.05 | −69.43 | 1320 | HP-S | −11.5 | | |

**Table 2** (*continued* )

| Sample | Code | Lat | Long | Elev | Region | $\delta^{18}O_{ap}$ | $\delta^{18}O_{en}$ | Tooth |
|---|---|---|---|---|---|---|---|---|
| El Nihuil | SRMNH-21 | −35.01 | −68.40 | 1300 | LL-C | −6.7 | | |
| El Nihuil | MRM-21 | −35.01 | −68.40 | 1300 | LL-C | −9.6 | | |
| El Payen | MRM-11 | −36.42 | −69.22 | 2700 | LL-S | −2.5 | −2.9 | M2 |
| El Perdido | MRM-20 | −34.67 | −69.48 | 1900 | HP-C | −2.9 | | |
| El Sosneado | 504 | −35.04 | −69.35 | 1600 | HP-C | −10 | | |
| El Sosneado | 2013 | −35.04 | −69.35 | 1600 | HP-C | −10.8 | | |
| Estancia las Chacras | MRM-13 | −35.60 | −69.54 | 1390 | LL-S | −6.7 | −7.2 | M3 |
| Finca Vergara | 2037 | −34.60 | −68.42 | 760 | LL-C | −8.8 | | |
| Gruta del Indio | AF-2021 | −34.77 | −68.37 | 690 | LL-C | −.1 | −.3 | d |
| Gruta del Indio | AF-828 | −34.77 | −68.37 | 690 | LL-C | −5.2 | | |
| Gruta del Indio | 49 | −34.77 | −68.37 | 690 | LL-C | −6.5 | | |
| Gruta del Indio | 50 | −34.77 | −68.37 | 690 | LL-C | −8.3 | | |
| Gruta del Indio | 51 | −34.77 | −68.37 | 690 | LL-C | −9.7 | | |
| Gruta del Indio | 213 | −34.77 | −68.37 | 690 | LL-C | −11.2 | | |
| Gruta del Indio | GIRA-27 | −34.77 | −68.37 | 690 | LL-C | −7.1 | | |
| Gruta del Indio | GIRA-70 | −34.77 | −68.37 | 690 | LL-C | −6.1 | | |
| Gruta del Indio | 114 | −34.77 | −68.37 | 690 | LL-C | −9.2 | | |
| Gruta del Indio | AF-13894 | −34.77 | −68.37 | 690 | LL-C | .8 | | |
| Gruta del Indio | AF-830 | −34.77 | −68.37 | 690 | LL-C | −4.7 | | |
| Gruta del Indio | GIRA-831 | −34.77 | −68.37 | 690 | LL-C | −2.3 | | |
| India Embarazada | AF-2036 | −35.19 | −70.05 | 2080 | HP-S | −11.1 | −8.4 | M |
| Jaime Prats | JP/J4 | −34.87 | −67.80 | 500 | LL-C | −8.6 | −8.6 | M |
| Jaime Prats | JP-1155 | −34.87 | −67.80 | 500 | LL-C | −6.7 | −5.8 | M3 |
| Jaime Prats | JP-1352 | −34.87 | −67.80 | 500 | LL-C | −5.8 | −3 | M3 |
| Jaime Prats | 1212bis | −34.87 | −67.80 | 500 | LL-C | −7.8 | | |
| Jaime Prats | 1145 | −34.87 | −67.80 | 500 | LL-C | −6.5 | | |
| Jaime Prats | 1306 | −34.87 | −67.80 | 500 | LL-C | −6.6 | | |
| Jaime Prats | 1152 | −34.87 | −67.80 | 500 | LL-C | −8.0 | | |
| Jaime Prats | 1179 | −34.87 | −67.80 | 500 | LL-C | −8.6 | | |
| Jaime Prats | 1197 | −34.87 | −67.80 | 500 | LL-C | −8.2 | | |
| Jaime Prats | 1262 | −34.87 | −67.80 | 500 | LL-C | −5.9 | | |
| Jaime Prats | 1174 | −34.87 | −67.80 | 500 | LL-C | −6.8 | | |
| Jaime Prats | 1259 | −34.87 | −67.80 | 500 | LL-C | −8.2 | | |
| Jaime Prats | 1261 | −34.87 | −67.80 | 500 | LL-C | −8.0 | | |
| Jaime Prats | 1301 | −34.87 | −67.80 | 500 | LL-C | −8.7 | | |
| Jaime Prats | 1189 | −34.87 | −67.80 | 500 | LL-C | −8.1 | | |
| Jaime Prats | 1236 | −34.87 | −67.80 | 500 | LL-C | −7.6 | | |
| Jaime Prats | 1154 | −34.87 | −67.80 | 500 | LL-C | −9.1 | | |
| Jaime Prats | 1303 | −34.87 | −67.80 | 500 | LL-C | −6.4 | | |
| Jaime Prats | 1304 | −34.87 | −67.80 | 500 | LL-C | −4.9 | | |
| Jaime Prats | 1184 | −34.87 | −67.80 | 500 | LL-C | −7.8 | | |
| Jaime Prats | 1243 | −34.87 | −67.80 | 500 | LL-C | −5.2 | | |
| Jaime Prats | 1187 | −34.87 | −67.80 | 500 | LL-C | −8.8 | | |
| Jaime Prats | 1212 | −34.87 | −67.80 | 500 | LL-C | −8.0 | | |
| Jaime Prats | 1305 | −34.87 | −67.80 | 500 | LL-C | −9.1 | | |
| Jaime Prats | 1308 | −34.87 | −67.80 | 500 | LL-C | −8.5 | | |
| Jaime Prats | 1177 | −34.87 | −67.80 | 500 | LL-C | −8.1 | | |
| Jaime Prats | 1185 | −34.87 | −67.80 | 500 | LL-C | −7.1 | | |
| Jaime Prats | 1220 | −34.87 | −67.80 | 500 | LL-C | −7.8 | | |
| Jaime Prats | 1251 | −34.87 | −67.80 | 500 | LL-C | −6.9 | | |
| Jaime Prats | 1319 | −34.87 | −67.80 | 500 | LL-C | −6.7 | | |
| Jaime Prats | 1153 | −34.87 | −67.80 | 500 | LL-C | −9.7 | | |
| Jaime Prats | 1162 | −34.87 | −67.80 | 500 | LL-C | −8.8 | | |
| Jaime Prats | 1315 | −34.87 | −67.80 | 500 | LL-C | −7.3 | | |
| La Cabeza | AF-2080 | −36.19 | −68.27 | 1200 | LL-S | −6.1 | | |
| La Hedionda | 2011 | −34.48 | −68.48 | 850 | LL-C | −9.2 | | |
| La Herradura | 506 | −35.00 | −68.90 | 1310 | LL-C | −2.4 | | |
| La Matancilla | AF-505 | −36.75 | −68.80 | 1200 | LL-S | −3.9 | | |
| Las Ramadas | AF-2072 | −35.10 | −69.60 | 1650 | HP-C | −4.6 | −7.1 | M3 |
| Llancanelo | MRM-25 | −35.60 | −69.10 | 1300 | LL-S | −5.5 | −7.4 | M |
| Llancanelo | MRM-5 | −35.60 | −69.10 | 1300 | LL-S | −6.6 | −6.3 | M1 |
| Llancanelo | MRM-6 | −35.60 | −69.10 | 1300 | LL-S | −5.7 | −4.9 | M1 |
| Llancanelo | MRM-7 | −35.60 | −69.10 | 1300 | LL-S | −5.4 | −5.0 | M3 |
| Llancanelo | MRM-17 | −35.60 | −69.10 | 1300 | LL-S | −5.4 | | |
| Llancanelo | MRM-23 | −35.60 | −69.10 | 1300 | LL-S | −1.7 | | |
| Llancanelo Norte | MRM-1 | −35.45 | −69.15 | 1340 | LL-S | −4.9 | −5.5 | M1 |
| Llancanelo Oeste | MRM-18 | −35.60 | −69.10 | 1300 | LL-S | −7.2 | | |
| Loma del Eje | 507 | −34.70 | −68.30 | 650 | LL-C | −9.8 | | |
| Los Coroneles | 518 | −34.60 | −68.55 | 890 | LL-C | −9.4 | | |
| Los Huaicos | 1081 | −36.34 | −68.53 | 1300 | LL-S | −6.7 | | |
| Los Manantiales | 1091 | −35.10 | −68.70 | 1300 | LL-C | −6.7 | | |
| Los Reyunos | 1097 | −34.57 | −68.68 | 1080 | LL-C | −8.9 | | |
| Médano Puesto Díaz | AF-681 | −34.70 | −69.20 | 1600 | LL-C | −4.3 | −4.7 | PM |
| Médano Puesto Díaz | 2015 | −34.70 | −69.20 | 1600 | LL-C | −8.4 | | |

(*continued on next page*)

**Table 2** (*continued* )

| Sample | Code | Lat | Long | Elev | Region | $\delta^{18}O_{ap}$ | $\delta^{18}O_{en}$ | Tooth |
|---|---|---|---|---|---|---|---|---|
| Médano Puesto Díaz | 682 | −34.70 | −69.20 | 1600 | LL-C | −7.3 | | |
| Morillos, Gruta 1 | SJ7-ENT-2 | −31.62 | −69.64 | 2400 | HP-N | −5.1 | −5.6 | PM |
| Morillos, Gruta 1 | SJ6-ENT-8 | −31.62 | −69.64 | 2400 | HP-N | −6.6 | | |
| Morillos, Gruta 1 | SJ1-ENT-7 | −31.62 | −69.64 | 2400 | HP-N | −5.7 | | |
| Potreros las Colonias | MMy-284 | −32.59 | −69.34 | 1900 | HP-N | −7.6 | −5.3 | M1 |
| Pozos de Carapacho | MRM-14 | −35.73 | −69.20 | 1340 | LL-S | −8.8 | −8.2 | M2 |
| Pto Agua del Zapallo | 2007 | −34.60 | −68.55 | 890 | LL-C | −9.0 | | |
| Pto Aizol | 2006 | −34.89 | −68.49 | 1090 | LL-C | −6.3 | | |
| Pto el Alto | AF-2079 | −35.28 | −69.52 | 1420 | HP-C | −8.8 | | |
| Pto la Huertita | 2023 | −34.53 | −68.32 | 1100 | LL-C | −8.9 | | |
| Pto la Huertita | 2024 | −34.53 | −68.32 | 1100 | LL-C | −8.3 | | |
| Pto la Huertita | 2074 | −34.53 | −68.32 | 1100 | LL-C | −4.9 | | |
| Puesto Tamando | 2031 | −35.21 | −69.75 | 1840 | LL-C | −10.8 | | |
| Punta del Barro | SJ3-ENT-3 | −30.10 | −69.14 | 1580 | LL-N | −4.9 | −7.2 | M |
| Reparo Pata de Puma | 677 | −34.58 | −68.54 | 850 | LL-C | −11.8 | | |
| Respolar el Nihuil | 20 | −35.01 | −68.40 | 1300 | LL-C | −11.4 | | |
| Rincón de la Olla | 81 | −34.87 | −67.78 | 490 | LL-C | −7.2 | | |
| Rincón del Atuel | AF-503 | −34.76 | −68.37 | 660 | LL-C | −3.7 | −3.7 | M3 |
| Rincón del Atuel | 501 | −34.76 | −68.37 | 660 | LL-C | −3.7 | | |
| Rincón del Atuel | 502 | −34.76 | −68.37 | 660 | LL-C | −2.8 | | |
| Rincón del Atuel | AF-500 | −34.76 | −68.37 | 660 | LL-C | −3.5 | | |
| RQ-1 | MGA-1 | −35.47 | −68.25 | 1490 | LL-S | −3.0 | −6.0 | M3 |
| San Carlos | MMy-1223 | −33.77 | −69.04 | 960 | LL-C | −10.1 | −9.6 | M2 |
| San Carlos | MMy-1221 | −33.77 | −69.04 | 960 | LL-C | −7.2 | −5.8 | M2 |
| Tierras Blancas | AF-2025 | −35.06 | −69.62 | 1630 | HP-S | −7.7 | −7.8 | PM |
| Uspallata | MMy-259 | −32.59 | −69.36 | 1890 | HP-N | −7.9 | | |
| Uspallata Tmulo I | MMy-229 | −32.59 | −69.36 | 1890 | HP-N | −6.3 | −5.6 | PM |
| Uspallata Tmulo II | MMy-239 | −32.59 | −69.36 | 1890 | HP-N | −8.9 | −8.6 | M2 |
| Uspallata Tmulo II | MMy-243 | −32.59 | −69.36 | 1890 | HP-N | −8.2 | −8.9 | M3 |
| Uspallata Tmulo II | MMy-245 | −32.59 | −69.36 | 1890 | HP-N | −8.3 | | |
| Uspallata Tmulo III | MMy-1097 | −32.59 | −69.36 | 1890 | HP-N | −6.4 | | |
| Villa 25 de Mayo | 680 | −34.58 | −68.55 | 860 | LL-C | −12.1 | | |
| Villa Vieja | 1100 | −34.58 | −68.54 | 850 | LL-C | −11.1 | | |
| Viluco | MMy-1197 | −33.87 | −69.05 | 1000 | LL-C | −8.7 | −6.4 | M1 |

Lat/Long is in decimal degrees, elevation in meters. $\delta^{18}O$ for bone and teeth are reported relative to VPDB. Region designations: HP-highland-piedmont, LL-lowland, N-north, C-center, S-south. Teeth are coded M1, M2, M3—first to third molar; M-unidentified molar; PM-premolar; C-canine; d-unidentified deciduous tooth.

vs LL.C, difference of 1.93‰, $p_{adj} = .011$). These results differ from those published previously (Gil et al., in press).

Patterns in the mean and variance are maintained if samples older than 2000 radiocarbon years BP are excluded. The only exception is that the mean northern lowland $\delta^{18}O$ values become more positive as well. The total number of observations from the region becomes reduced to only six samples however, highlighting the need for more data from the northern region and more thorough dating of all human remains.

### 5.5. Bone versus enamel carbonate $\delta^{18}O$

Enamel $\delta^{18}O$ values are taken to indicate water sources used by an individual as a juvenile, when tooth enamel is first formed, while

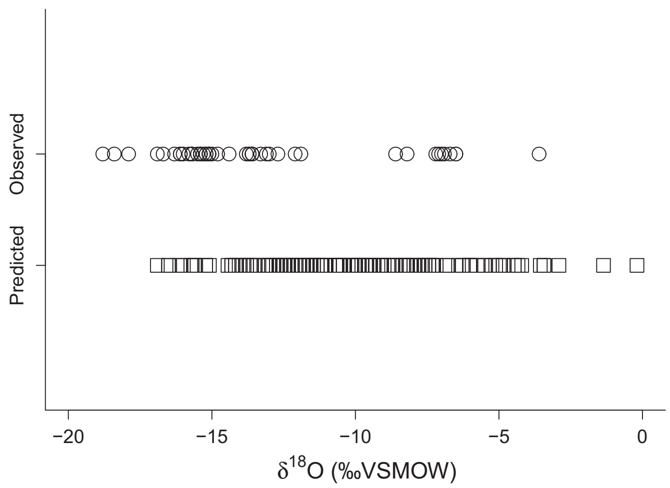


**Fig. 4.** Distribution of water $\delta^{18}O$ values from central-western Argentina. Top, observed source water values (Table 1). Bottom, predicted drinking water values based on human bone carbonate data (Table 2) and Eqs. (1)–(3).

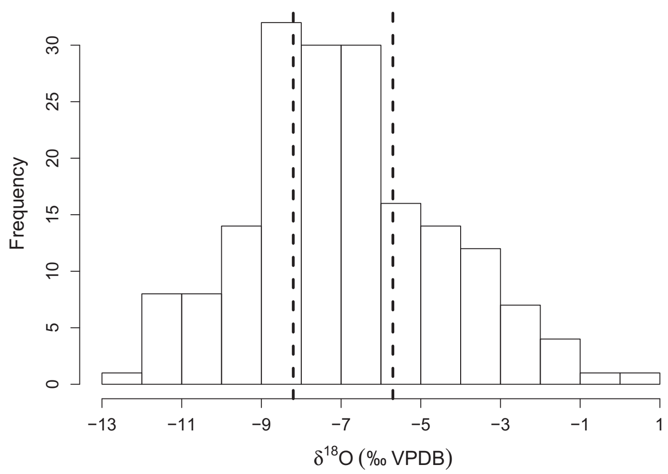


**Fig. 5.** Histogram of human carbonate $\delta^{18}O$ values from central-western Argentina. Many observations correspond to imbibed water $\delta^{18}O$ values of −11.9 to −8.6 VSMOW (dashed lines), for which no sources have been observed.

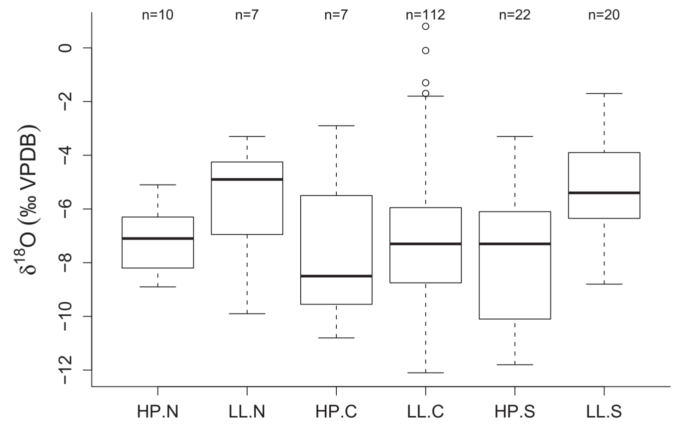


**Fig. 6.** Boxplot of human carbonate $\delta^{18}O$ values from central-western Argentina. Codes are HP-highland piedmont, LL-lowland, N-north, C-center, and S-south.

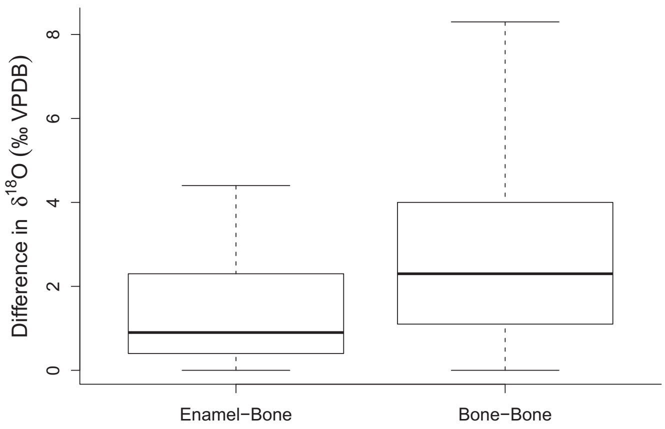


**Fig. 7.** Boxplot of differences in human carbonate $\delta^{18}O$ values. "Enamel–Bone"–differences between enamel and bone $\delta^{18}O$ from the same individual. "Bone–Bone"–differences in bone carbonate $\delta^{18}O$ values for all individuals in Table 2 (all pairwise comparisons).

bone carbonate values indicate average water use over a period of years preceding an individual's death. Consistent use of similar water sources throughout life should lead to similar $\delta^{18}O$ values in both tissues, and the difference between apatite and enamel values should be low (closer to zero). The use of divergent water resources would result in different enamel and bone carbonate values.

A boxplot of bone-enamel differences for the 46 individuals for which we have enamel data (37 adults, 1 juvenile, 8 unknown) are shown in the left hand side of Fig. 7. Mean and median differences are 1.4 and .9, with an interquartile range of 1.9. To put these in context, Fig. 7 also plots pairwise differences in bone apatite $\delta^{18}O$ for all individuals in Table 2 (mean and median 2.8 and 2.3, IQR 2.9). As can be seen, differences within the lifetimes of a given individual are approximately half of those seen between any two individuals. Thus people in the region appear to have exploited water resources as adults in much the same fashion that they did as juveniles. Any variation in that behavior appears small compared to that seen between different persons.

## 6. Discussion

The current results generally support previous inferences concerning variation in oxygen isotope values and human mobility in central-western Argentina, but also necessitate some changes. Individuals from most areas have a similar range of $\delta^{18}O$ values, averaging about −7 VPDB. The associated isotopic values of imbibed water for these same individuals is −10.3 VSMOW, a value for which no corresponding source waters have (yet) been identified. This suggests that many individuals were imbibing water from both the more negative, Andean pool and more positive water sources of la Payunia, Cerro Nevado, and the lowland plains. By extension, they would have been moving between the lowland and highlands over the course of the year or between the major lowland rivers and lowland interior. While seasonal variation in water $\delta^{18}O$ values might also play a role, data from elsewhere in the Andes suggest that such differences are smaller then those observed here (three sample sets, average seasonal difference .63; Webb et al., 2011).

There are good reasons to expect either pattern. Access to many parts of the Andes is limited from late Fall through early Spring. Seasonal occupations are the norm (Durán, 2000; Durán et al., 2006; Gil, 2006; Neme, 2007), and the region is host to a variety of important wild resources during the rest of the year. These include not only artiodactyls like guanaco (*Lama guanicoe*, the largest game animal), but also smaller yet important taxa such as viscacha (*Lagidium viscacia*), cuis (*Microcavia* sp.), fish, and waterfowl (Fam. Anatidae). It also includes highly productive plant taxa such as molle (*Schinus polygamus*), uva de la cordillera (*Berberis empetrifolia*), ephedra (*Ephedra chilensis*), and cebolla de la zorra (*Rhodphialla mendocina*), among others. The simultaneous presence of important plant and animal taxa permits complementary foraging opportunities for men and women and serves to minimize schedule conflicts within the seasonal round (Zeanah, 2004).

Lowland areas are accessible year-round and so are lowland resources such as guanacos, a variety of medium to large rodents, Rheas, and certain cacti, among others. All of these are well adapted to arid conditions and widely dispersed, requiring individuals to move away from the rivers in order to exploit them. This tendency would have been even stronger during the wetter, summer months when particularly lucrative and/or storable plant resources such as mesquite (*Prosopis flectuosa*), chañar (*Geoffrea descorticans* and opuntia fruits (*Opuntia sulfurea*) become available (Llano, 2011; Llano and Ugan, 2010). The movement implied by the underlying oxygen isotope data and inherent in either pattern of resource exploitation, whether upland to lowland or within the lowland, continues to support the previous analysis and suggest a high degree of residential mobility throughout much of the region.

The only exception to the pattern of variation in the oxygen data occurs in southern Mendoza. With the addition of the new samples, the signal of individuals from the lowlands of southern Mendoza appear distinctly different (c.f., Gil et al., in press). Human remains have significantly more positive isotope values consistent with a more local pattern of water exploitation. Local geography provides some idea of why.

Unlike the central and northern plains, southern Mendoza is dominated by the volcanic badlands of La Payunia and the Cerro Nevado highlands. These predominately igneous deposits are more resistant to erosion, and waters originating in the Andes pass to the north, along the Río Atuel, to the south, along the Río Colorado, or collect at the base of the Andes in the Laguna Llancanelo basin (Fig. 1). With no rivers crossing the region, residents must rely solely on locally available water sources. This is true for local *puesteros* (herders) today, and would have been equally as true in the past. The more difficult terrain, the absence of east-west trending river valleys, and overall distance would also have limited exchange with the Andean highlands. Residential moves may have been frequent, but local, producing distinctive isotopic signatures.

The variation observed here also helps to underscore the potential richness of people movements in the past. Rather than stereotype prehistoric peoples of the area as simply more or less "mobile", these data underscore the various forms that movements may have taken: within a region of similar water sources, between two different sources within the same region, and between different water sources in two distinct regions. Given minimal evidence for longer-term residence in the region, such movements were likely often seasonal rather than instances of residential cycling, though individuals may have also shifted territories over the course of their life. Finally, it is also important to realize that the descriptions here speak to averages. Even outside the southern lowlands there were individuals who generally relied on waters distinctive to the area in which they were found ($^{18}O$ depleted in the uplands, more enriched in lower elevations).

This pattern continues to imply a different view of regional prehistory from that often offered, particularly in the northern periphery. A picture of peoples regularly moving into and out of the Andes and the lowlands differs sharply with the historic record for northern Mendoza, implying that the ethnohistoric context was distinctive. This extends similar observations concerning a disconnect between the ethnohistoric and archaeological records in the central region (e.g., Gil et al., 2009, 2011) further north, forcing us to consider a flexible farming-hunter/gatherer system, with strong variation in time and space and where greater mobility was the norm.

For example, even where there is evidence of grinding tools, $^{13}C$ enriched isotope signals, and cultivars such as maize, they may have been part of an overall subsistence strategy focused primarily on the use of wild resources. Analogs might include ethnographic patterns documented among the Apache of the American Southwest (Goodwin, 1935), or archaeological patterns observed in parts of the late Archaic or Mogollon sequence in the American Southwest (O'Laughlin, 2001; Lekson, 2009; Reid and Whittlesey, 1999). A similar economic system would match the simple nature of the archaeological record in much of central-western Argentina. It would account for the physical presence of maize and other cultivars, their geographic distribution (Gil, 1997–1998, 2006; Hernández et al., 2001–2002; Llano, 2011), and the limited and equivocal evidence for field investments or irrigation systems (Mafferra, 2010 : 2086), as well as allow for the positive $\delta^{13}C$ values seen in some human remains. Finally, such a system would also allow for and agree with evidence for wide-ranging contact with groups both further north and particularly on the western side of the cordillera (Neme and Gil, 2005). While ethnohistoric documents often emphasize the stable, agricultural nature of Huarpe occupations at the time of Spanish contact, a thorough reading suggests that there is room for a more residentially mobile, mixed economy here as well (Gil et al., in press). Descriptions of prehistoric occupations range from fully sedentary farming villages to more ephemeral farmers with substantial reliance on wild resources (Gambier, 2000; Michieli, 1983 : 23–24; Prieto, 1997–1998 : 59–60). The human oxygen isotope data for much of the province strongly supports the latter.

## 7. Conclusions

This paper has presented new oxygen isotope data from both natural water sources and prehistoric human bone carbonates in central-western Argentina. The water data show substantial geographic patterning reflecting the origins of samples, and the range of directly measured water values and drinking water values estimated from human bone carbonate data correspond closely. The geographic distribution of human $\delta^{18}O$ values and the values of local water sources do not commonly correspond, however. These differences suggest a more mobile residential pattern than often inferred for central-western Argentina, and a more nuanced one, enriching our understanding of prehistoric life in the region. To the extent that they mirror similar observations in other parts of the world, they draw attention to the importance of underlying culture process and enrich our understanding of other regions as well.

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