

# Isotopic Evidence for Divergent Diets and Mobility Patterns in the Atacama Desert, Northern Chile, During the Late Intermediate Period (AD 900–1450)

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**ABSTRACT** The decline of the Tiwanaku state saw the emergence of two new cultures—Pica-Tarapacá and Atacama—during the Late Intermediate Period in northern Chile. Archeological evidence suggests that both groups practised maize agriculture and pastoralism, but that their interaction zones differed significantly. Marine resources are common at Pica-Tarapacá sites, even those far from coast, while Atacama sites in the desert oases and precordilleran area seem to have directed their networks towards the highlands. Here we apply stable carbon, nitrogen, and oxygen isotope analysis on human bone and enamel to test dietary patterns and residential mobility at two sites, Pica 8 and Quito 6, representing the Pica-Tarapacá and Atacama cultures, respectively. Our results show that diet at the two sites indeed dif-

fered: significant but variable consumption of marine resources and maize is indicated at Pica 8, despite being an inland site, while diet at Quito 6 was based mainly on terrestrial resources. The use of seabird guano and llama dung as fertilizers and extreme aridity may have contributed to the high nitrogen isotope values observed in Pica 8 humans. The  $\delta^{18}\text{O}$  values in Pica 8 individuals are generally lower than for Quito in spite of its greater distance from the Andes. All three isotopes suggest the presence of at least five nonlocals in the 30 measured at Pica 8. This evidence for human mobility is consistent with the high levels of trade and interaction observed in the archeological record, and begins to quantify the degree of movement of specific individuals. *Am J Phys Anthropol* 156:374–387, 2015. © 2014 Wiley Periodicals, Inc.

## INTRODUCTION

The Late Intermediate Period (AD 900–1450) in northern Chile is characterized by dramatic cultural changes involving the appearance of several new, culturally independent societies, in contrast with the previous Tiwanaku (AD 400–900) and subsequent Inka (AD 1450–1530) hegemonies. Following the pattern of Andean societies from Peru, Bolivia, and northern Argentina, populations in northern Chile displayed evidence for increased mobility and trade, particularly migration from highlands to lowlands and vice versa (Núñez, 1984; Schiappacasse et al., 1989).

The Tarapacá and Atacama regions, located in the Atacama Desert, witnessed the appearance of two new cultural complexes: Pica-Tarapacá and Atacama (also known as San Pedro). Both have been characterized as complex societies but with differing economic and political systems. Pica-Tarapacá communities inhabited the coast and interior with an intense degree of interaction between them, maintaining trade networks from the coast to the mountains, and exchanging mainly marine resources for textiles and crops such as maize (Moragas, 1995; González, 2006; Aguero 2006; Uribe, 2006). In contrast, Atacama communities appear to have had far less interaction with coastal populations as no evidence has been found for the use of marine resources (Schiappacasse et al., 1989). Instead, they focused their pastoralist and agricultural activities in the Atacama oases and the precordilleran area known as the Alto Loa (3000 meters above sea level).

These reconstructions are based on the archeological evidence of pottery and textiles together with zooarcheological and archaeobotanical data. However, the proportional con-

tributions to the diet of different food groups (e.g., fish vs. camelids, the importance of maize, etc.) are difficult to quantify with traditional methods. Here we apply stable light isotope analyses to human remains from two archeological sites—Pica 8 of the Pica-Tarapacá Cultural Complex, and Quito 6 of the Atacama Culture—to assess and compare the subsistence base of these two communities, and of their respective cultures. In addition to dietary comparisons we assess whether oxygen isotope ratios from bone apatite and tooth enamel can detect the presence of any nonlocal individuals. Both sites include well-preserved organic remains, with plants (including maize), textiles, and faunal, and human remains.

## THE LATE INTERMEDIATE PERIOD IN TARAPACÁ AND ATACAMA

The Late Intermediate Period (AD 900–1450) shows evidence for internal complex socio-economic organization with pronounced status differences, but social

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**Fig. 1.** Map of Northern Chile. The locations of Pica 8 and Quito 6 are indicated with black arrows. Rivers, lakes, and salt lakes are indicated in white.

prestige seems to have been associated with reciprocity and redistribution of goods (Schiappacasse et al., 1989; Uribe, 2006). There is good evidence for the development of intense interaction between neighboring regions, seen in high levels of trade and exchange from the coast to the highlands (Schiappacasse et al., 1989; Uribe et al., 2004; Uribe, 2006). Human movement likely accompanied the trade. Many details remain unclear, however, including the presence and extent of dietary differences between the different cultural groups, and the degree to which individual mobility played a role in the interactions seen in material culture and subsistence products.

Pica-Tarapacá communities were distributed from the coast to inland inside a range delimited by the Camiña and Loa Rivers to the north and south, respectively (Agüero, 2006) (Fig. 1). Each of the geographical zones related to economic specializations. On the coast, evidence for fishing, marine mammal hunting, and collection of marine resources is observed, while an intensification and consolidation of agricultural and pastoral activities apparently occurred in the valleys and *altiplano*. These regional specializations contributed to the exchange of resources between communities and zones, generating a classic system of economic complementarity (Moragas, 1995; Uribe, 2006). The LIP is divided into two chronological phases: Tarapacá (AD 900–1250) and Camiña (AD 1200–1430) (Uribe et al., 2007). The first phase is characterized by particularly strong coast-inland connections, with high levels of hierarchy and centralization of the activities of inland communities. During the Camiña phase contacts with the

*altiplano* communities became more frequent, while those with the coast apparently weakened.

Inland Tarapacá communities relied on wild plants and animals as well as on domestic crops and animals. Sites show evidence for the collection of wild fruits such as *algarrobo* (*Prosopis* sp.), *chañar* (*Geoffroea decorticans*), and *molle* (*Schinus molle*) (García and Vidal, 2006; Uribe, 2006). A complex system of cultivation terraces in the precordillera at 3200 masl, and frequent maize remains from sites in the oases indicate cultivation of maize (García and Vidal, 2006). Other plant foods found include *quinoa* (*Chenopodium quinoa*), potatoes (*Solanum tuberosum*), and pumpkin (*Cucurbita maxima* and *Lagenaria sp.*). Terrestrial fauna include camelids (*Lama glama*, *Vicugna pacos*, and *Vicugna vicugna*) and *cuy* (*Cavia porcellus*). However, most of the camelid evidence is in the form of coprolites and hair, pointing to use of these animals for textile production and transport rather than consumption (Uribe, 2006). The presence of Pacific coast fish, mussels and birds up to about 100 km from the coast provides clear evidence of exchange between these two areas (González, 2006; Uribe, 2006). Many transitory campsites between the Pica oases and the coast have been found in the Atacama Desert, following routes marked by the presence of geoglyphs associated with the Pica-Tarapacá Cultural Complex (Briones et al., 2005).

The Pica 8 cemetery dates to AD 900–1300 (Núñez, 1976; Uribe et al., 2007) and is one of a group of oases located some 90 km from the coast. The site was excavated in 1964 by Lautaro Núñez, who suggested the presence of strong connections between groups from different regions, including the coast and the *altiplano*, and extending as far afield as the eastern side of the Andes, based mainly on the wide variety of offerings found, including maize, types of weapons, musical instruments, and even tropical birds such as the blue-and-yellow macaw (*Ara ararauna*) (Núñez, 1984; Zlatar, 1984). Núñez (1984) divided the cemetery into sectors (A–E and G–I), but in the absence of a published site plan there is no information concerning their placement relative to one another. Nevertheless, as discussed below, the sectors were clearly an important structuring factor in the cemetery's spatial organization. No information is available on burial positions. The economy of Pica was based on agricultural activities together with the production of pottery and textiles (Uribe, 2006). Nevertheless, it is likely that trade and caravan movements operated from the coast to oasis—seen in the presence of marine foodstuffs—and vice versa. A recent isotopic study on bone collagen  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  from a limited number of individuals ( $n = 6$ ) from the Pica 8 cemetery concluded that their diets contained very large proportions of marine foods (Petruzzelli et al., 2012). We revisit these preliminary findings in light of the new data presented below.

The affiliation of the cemetery to the LIP is based on ceramic seriation. The most frequent pottery types found at Pica 8 are known as *Pica Charcollo* (PCH), *Pica Chiza* (PCHZ), and *Pica Gris Alisado* (Catalán, 2006; Uribe et al., 2007). These three styles have been dated to AD 900–1445 by Thermoluminescence (TL) in other LIP cemeteries of northern Chile (Uribe et al., 2007). Of the three radiocarbon dates from Pica 8 published by Núñez (1976, p. 75), two on maize cobs fall post AD-1500, and so are far too recent to refer to the clearly pre-Columbian cemetery. This leaves a determination on a camelid textile from tomb 6 (IVIC-173:  $930 \pm 90$  BP; cal AD 902–1270 at 95.4% confidence) as the most reliable. It is worth noting that

one of the recent maize cobs came from the same burial as the camelid textile, and that the burial also included LIP Pica Chiza pottery (Núñez, 1976; Zlatar, 1986). Thus the maize cobs were presumably intrusive. Three human bone samples were also radiocarbon dated: individuals SDT11 (Beta 220922:  $1050 \pm 40$  BP; cal AD 900–1030), B0447 (Beta-220923:  $900 \pm 40$  BP; cal AD 1030–1230), and B0438 (Beta-220924:  $810 \pm 40$  BP; cal AD 1170–1280) (Uribe et al., 2007). However, since there is good evidence of marine resource consumption, the dates are likely influenced by the marine reservoir effect. An estimation of the proportion of marine protein in the diets of these individuals using their associated  $\delta^{13}\text{C}$  values is not possible due to the confounding factor of maize (a  $\text{C}_4$  plant). While  $\delta^{15}\text{N}$  values should help distinguish between protein of marine and terrestrial origin (though see below), they are not available for these particular individuals. Furthermore, the marine reservoir effect in this region is known to have varied significantly over time due to changing ocean currents and upwelling off the western coast of South America, so that corrections based on modern values cannot be used (Ortlieb et al., 2011). Further research is underway by the authors to resolve these issues, but in the meantime we cannot place any reliance on the human  $^{14}\text{C}$  determinations from Pica 8.

The Quitor 6 cemetery is located in the Atacama oases ~200 km from the coast (Costa, 1988). Radiocarbon dates obtained by Costa (1988) were calibrated by Hubbe et al. (2012), showing a range of dates between AD 899–1211 and AD 889–1485, and suggesting the site's placement in the LIP. This association is also indicated by the presence of Atacama LIP pottery types such as Dupont (Uribe et al., 2007) in the cemetery (Costa, 1988). Individuals were buried with an orientation to the east, in a crouched, seated position. The most common burial offerings included pottery, camelid feet, and *algarrobo* fruits (Costa, 1988).

In contrast to Pica-Tarapacá, sites of the Atacama culture found in the precordillera and Atacama oases (Fig. 1) show a predominance of camelids and rodents and a near-complete absence of marine fauna in the zooarcheological assemblages (Núñez, 1995). There is also evidence for the consumption of camelids, as opposed to their restricted use for transportation and wool (Schiappacasse et al., 1989). From the archaeobotanical evidence, the Atacama oases demonstrate an emphasis on maize agriculture, as well as on the collection of wild fruits (*algarrobo* and *chañar*) (Schiappacasse et al., 1989; Uribe, 2012). Previous strontium and oxygen isotope studies aimed at investigating mobility in the LIP population of the precordilleran site of Caspana, close to the Atacama oases, found no indication of obviously “nonlocal” individuals (Knudson and Torres-Rouff, 2009). Bone and tooth apatite  $\delta^{13}\text{C}$  measurements indicated the consumption of a mix of  $\text{C}_3$  and  $\text{C}_4$  plants, the latter consistent with the large amounts of maize found at the site.

### STABLE ISOTOPE ANALYSIS FOR PALEODIET AND MOBILITY STUDIES

Stable carbon isotopes ( $^{13}\text{C}/^{12}\text{C}$ , expressed as  $\delta^{13}\text{C}$ )<sup>1</sup> are frequently used to differentiate between the consumption

<sup>1</sup>Isotopic abundances are reported in the  $\delta$  notation in parts per thousand (‰) as deviation from an international standard using the expression  $\delta X = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 10^3$  where  $R_{\text{sample}}$  and  $R_{\text{standard}}$  represent the high- to low-mass isotope ratios of the sample and the standard, respectively.

of terrestrial and marine resources, and between  $\text{C}_3$  and  $\text{C}_4$  plants (and animals reliant on these plants).  $\text{C}_3$  plants show global values averaging about  $-26\text{‰}$  to  $-27\text{‰}$ ; whereas  $\text{C}_4$  plants are relatively enriched in  $^{13}\text{C}$ , averaging about  $-13\text{‰}$  (Smith and Epstein, 1971; O'Leary, 1981). These distinctions in  $\delta^{13}\text{C}$  values of  $\text{C}_3$  and  $\text{C}_4$  plants allow inferences to be made about the types of crops consumed by humans in the past. Since the main  $\text{C}_4$  crop in South America is maize,  $\delta^{13}\text{C}$  analysis can help identify its consumption. Where marine resources are also involved, however, interpretation becomes more complex, since they also tend to be relatively enriched in  $^{13}\text{C}$ , although not to the same degree as  $\text{C}_4$  plants.

Nitrogen is incorporated from the atmosphere and soils through plants, the primary producers, into the tissues of herbivores, omnivores, and carnivores following the trophic chain. A trophic-level enrichment in  $^{15}\text{N}$  of about 3–5‰ occurs between prey and consumer (Schoeninger and DeNiro, 1984). Food chains in the oceans are longer than in terrestrial ecosystems, so that piscivorous marine fish and mammals tend to have higher  $\delta^{15}\text{N}$  values than their terrestrial counterparts (Schoeninger and DeNiro, 1984). This observation can thus be used in combination with  $\delta^{13}\text{C}$  to help distinguish marine versus  $\text{C}_4$  terrestrial diets. However, a number of additional factors besides trophic level influence  $\delta^{15}\text{N}$  values in an ecosystem, such as aridity, soil mineralization, use of manure, herbivore gut physiology, diet quality, and physiological status, among others (Heaton, 1987; Ambrose, 1991; Schwarcz et al., 1999; Sponheimer et al., 2003; Hedges and Reynard, 2007; Szpak et al., 2012). Some of these factors are particularly relevant to the interpretation of  $\delta^{15}\text{N}$  values in the present study, including the aridity effect (given the sites' location in the Atacama Desert); the influence on marine fauna of the upwelling system in the adjacent Pacific Ocean (Tieszen and Chapman, 1992), and the use of fertilizers during pre-Columbian times (Szpak et al., 2012). These factors potentially complicate the use of  $\delta^{15}\text{N}$  to differentiate terrestrial and marine resources. High  $\delta^{15}\text{N}$  values have previously been observed in pre-Columbian human remains from northern Chile (Tieszen et al., 1992; Aufderheide et al., 1994; Knudson et al., 2010; Petruzzelli et al., 2012; Santana et al., 2012; Torres-Rouff et al., 2012).

Controlled feeding experiments (Ambrose and Norr, 1993; Tieszen and Fagre, 1993) have shown that in bone tissues protein carbon is preferentially routed directly to the organic collagen fraction, whereas the mineral phase (bioapatite) better reflects the overall diet, with contributions from proteins, carbohydrates, and lipids. It has been suggested that the routing of carbon from protein into collagen is on the order of 50–75% (Fernandes et al., 2012; Jim et al., 2006). The difference in the routing of carbon isotopes into the organic and mineral fractions of bone is potentially useful for paleodietary reconstruction especially when there is a mixed consumption of marine protein and  $\text{C}_4$  plants. Although higher values for  $\delta^{13}\text{C}$  are expected when  $\text{C}_4$  resources are eaten, typical human diets are more likely to show mixtures, making it difficult to differentiate between the inputs from  $\text{C}_4$  plants versus marine resources. To help distinguish the consumption of these two food sources, both collagen and apatite isotope analyses from bone and tooth were carried out, following the principle that bioapatite carbon reflects whole diet, while collagen will be strongly biased towards dietary protein (Ambrose and Norr, 1993; Lee-Thorp et al., 1989; Lee-Thorp, 2008).



TABLE 1. Carbon, nitrogen and oxygen stable isotope values from bone and teeth for Pica 8

N°	Sector	Sex	Sample	$\delta^{13}\text{C}$			$\delta^{15}\text{N}$			$\delta^{18}\text{O}$			
				Collagen VPDB	AIR	(%) Collagen	C/N	%N	%C	Apatite VPDB	Apatite VPDB	Enamel VPDB	Enamel VPDB
B0410	I	F	Rib	-10.5	22.9	22.5	3.7	14.3	45.3	-5.0	-7.9		
B0413	I	F	Rib, PM <sub>2</sub>	-10.0	21.0	21.1	4.2	12.9	46.7	-4.8	-8.3	-2.0	-7.8
B0415	D	M	R	-9.6	14.2	22.1	3.6	14.2	43.7	-3.9	-7.5		
B0419	G	F	Rib, M <sub>2</sub>	-9.9	13.4	23.3	3.3	14.9	42.4	-4.5	-6.3	-2.9	-8.7
B0420	E	F	Rib, M <sup>3</sup>	-18.6	10.9	23.6	3.4	15.1	44.5	-13.0	-9.6	-11.4	-11.3
B0421	B	F	Rib, M <sub>3</sub>	-10.5	15.9	22.5	3.8	13.8	45.4	-4.3	-8.6	-2.5	-8.4
B0423	D	F	Rib	-11.9	21.2	24.9	3.5	14.7	44.4	-6.2	-6.2		
B0424	I	F	Rib, M <sup>2</sup>	-14.1	24.4	23.8	3.6	15.3	46.8	-10.5	-5.7	-8.5	-3.7
B0426	I	F	Rib, M <sub>2</sub>	-9.4	18.4	19.4	3.4	14.9	43.6	-4.4	-8.0	-4.2	-8.0
B0427	D	M	Rib, M <sup>2</sup>	-16.9	12.9	13.2	3.9	13.4	45.3	-11.2	-9.4	-11.5	-10.9
B0428	I	F	Rib, M <sup>3</sup>	-9.5	23.3	18.3	3.6	15.1	47.1	-4.3	-8.3	-2.1	-8.8
B0430	F	F	Rib	-9.3	14.5	23.2	3.2	15.3	42.5	-4.0	-6.9		
B0431	G	M	Rib, M <sup>3</sup>	-13.9	12.8	21.3	3.3	15.0	42.8	-8.2	-7.8	-6.2	-7.9
B0432	-	F	Rib, M <sup>3</sup>	-12.3	14.6	23.6	3.7	16.8	53.4	-6.4	-8.1	-4.0	-9.2
B0435	G	M	Rib	-9.8	13.0	21.8	3.3	15.4	43.5	-4.5	-6.9		
B0439	A	F	Rib, M <sup>3</sup>	-10.8	16.2	16.1	3.3	14.9	41.9	-5.1	-8.1	-7.3	-7.2
B0440	A	M	Rib, PM <sup>2</sup>	-9.2	15.3	18.4	3.3	15.7	44.1	-4.6	-8.6	-0.6	-8.3
B0441	D	M	Rib, M <sub>2</sub>	-9.9	19.6	21.9	3.6	15.3	46.8	-4.4	-6.9	0.8	-8.6
B0447	I	M	Rib, M <sup>2</sup>	-10.4	21.0	21.8	3.7	14.3	45.7	-4.0	-8.2	-1.9	-9.6
B0453	I	F	Rib, M <sup>3</sup>	-12.0	20.5	29.0	3.6	15.4	48.1	-7.4	-9.2	-11.2	-11.0
B0463	G	F	Rib, M <sup>3</sup>	-10.0	13.2	8.0	3.2	14.9	41.4	-4.6	-7.6	-2.7	-8.2
B0466	-	M	Rib	-10.0	14.2	7.4	3.5	14.0	41.8	-5.1	-8.2		
B0467	D	M	Rib	-10.6	13.4	12.6	3.7	13.8	43.5	-3.9	-7.5		
B0468	I	F	Rib, M <sup>2</sup>	-9.0	21.5	7.1	3.4	13.8	40.8	-4.0	-8.0	-3.0	-7.6
B0469	O	M	Rib	-8.8	21.5	7.8	3.4	13.4	39.2	-4.1	-8.5		
B0470	D	F	Rib	-10.5	14.2	9.7	3.5	13.8	41.3	-4.7	-8.4		
B0483	G	F	Rib, M <sub>3</sub>	-13.3	20.3	11.9	3.2	15.8	43.8	-8.5	-6.3	-2.2	-9.2
B0484	A	F	Rib	-9.3	16.6	21.1	3.4	15.6	45.1	-4.8	-8.8		
B0492	D	U	Rib	-16.9	13.3	12.1	3.7	13.1	41.7	-11.7	-10.1		
B0493	G	M	Rib, M <sub>2</sub>	-9.9	14.2	5.4	3.3	13.1	37.2	-6.0	-8.9	-3.1	-8.0

Sex is indicated as F, Female; M, Male; and U, Unknown. The type of teeth is identified as PM, Premolar and M, Molar. Collagen quality indicators are also included. Samples with poor collagen preservation are indicated in italics for the C/N ratios. All samples presented are from adult individuals.

Oxygen isotopes are frequently applied to the study of residential mobility (e.g., White et al., 2004a,b; Knudson, 2009), often in combination with strontium isotopes (e.g., Knudson and Price, 2007). Enamel and/or bone  $\delta^{18}\text{O}$  values in an individual should reflect the isotopic composition mostly of liquids in the period during which the tissue formed. This is on the order of the last decade or more in the case of adult bone, and during enamel mineralization in infancy and childhood in the case of teeth. Meteoric water  $\delta^{18}\text{O}$  values vary according to the related effects of latitude, altitude, distance from moisture source, amount of rainfall, evaporation, and temperature (Dansgaard, 1964; Rozanski et al., 1993). For example, rivers in or close to the high Andes would be expected to show low  $\delta^{18}\text{O}$  values as compared to those closer to the coast where preferential evaporation of  $^{16}\text{O}$  leads to increasing enrichment along a river's course. However, the Atacama Desert has a complex hydrological system as only a few rivers actually reach the sea. Springs and oases fed by aquifers directly from the Andes are not subject to the strong  $^{18}\text{O}$ -enrichment effects of evaporation (Magaritz et al., 1990; Aravena, 1995). As a result oasis waters tend to have lower  $\delta^{18}\text{O}$  values.

Additionally, variability on annual or subdecadal scales in the Andes/Atacama is relevant to human lifetimes. They include the effects of ENSO (El Niño-Southern Oscillation) and changes in the amount of precipitation at high altitude in the Andes. Furthermore, cultural enrichment of  $^{18}\text{O}$  can occur, through processes

such as boiling water or brewing *chicha de maíz* (White et al., 2004a,b; Knudson, 2009; Turner et al., 2009).

## MATERIAL AND METHODS

### Samples

Samples from Quito 6 were collected from the Instituto de Investigaciones Arqueológicas and the Museo R.P. Padre Le Paige, while those from Pica 8 were collected from the Department of Anthropology of the Universidad de Chile. The skeletons were sexed and aged by Costa (1988) in the case of Quito 6, and by Retamal et al. (2012) for Pica 8. Only adults were sampled, in order to avoid complications in the interpretation of  $\delta^{15}\text{N}$  results caused by elevated nursing signals (Schurr, 1998). We sampled the ribs or, where these were unavailable, the middle hand phalanges, of 16 individuals from Quito 6 and 30 from Pica 8 (Tables 1 and 2). Bone samples were divided leaving one half for collagen analysis and the other for bioapatite analysis. Nineteen teeth from different individuals were obtained from Pica 8. Most were second and third molars, but three were premolars. It was not possible to obtain teeth from Quito 6.

Bone apatite is poorly crystalline and may exchange with the burial environment, making its use in isotope studies controversial. However, several studies have shown that recent (sub-fossil) bone apatite can provide reliable isotopic information (e.g., Koch et al., 1997; Lee-Thorp and Sponheimer, 2003; Harrison and Katzenberg,

TABLE 2. Carbon, nitrogen and oxygen stable isotope values from bone and teeth for Quito 6

N°	Sex	Sample	$\delta^{13}\text{C}$			$\delta^{15}\text{N}$			$\delta^{18}\text{O}$		
			Collagen VPDB	AIR	%	C/N	%N	%C	Apatite VPDB	Apatite VPDB	
T02	M	R	-13.2	11.9	22.4	3.2	14.8	40.9	-7.7	-3.7	
T09	F	R	-14.8	10.6	19.4	3.4	13.4	39.1	-7.9	-3.9	
T11	M	R	-15.3	11.6	25.2	3.2	16.1	44.3	-9.0	-4.5	
T19	M	R	-17.4	11.4	9.3	<b>3.8</b>	11.4	37.2	-8.0	-5.0	
T31	M	R	-14.5	11.4	17.1	3.2	15.5	42.7	-8.6	-4.7	
T34	F	R	-	-	-	-	-	-	-8.5	-4.8	
T35	M	P	-15.3	10.1	5.4	3.4	14.3	42.1	-8.7	-4.0	
T36	M	R	-13.8	11.2	23.1	3.3	15.8	44.1	-7.9	-4.5	
T39	F	R	-	-	-	-	-	-	-8.1	-4.3	
T42	F	R	-14.2	11.0	16.8	3.2	14.4	39.7	-9.8	-4.1	
T45	U	R	-14.8	9.5	16.2	3.2	15.3	41.9	-8.4	-2.9	
T46	F	R	-14.1	11.8	20.5	3.2	15.0	40.6	-8.6	-4.0	
T47	F	R	-15.5	10.6	9.0	3.3	13.9	39.3	-8.9	-3.5	
T50	U	R	-14.8	10.6	23.8	3.3	15.2	43.7	-8.2	-2.6	
T52	F	R	-11.6	11.5	30.5	3.2	17.1	46.7	-8.6	-3.9	
T54	F	R	-15.3	10.8	9.8	3.5	11.6	34.2	-	-	

Sex is indicated as F, Female; M, Male; and U, Unknown. The type of bone is identified as R, Rib and P, Phalange. Quality controls for collagen preservation are also included. Samples with poor collagen preservation are indicated in italics for the C/N ratios. All samples presented are from adult individuals.

2003; Garvie Lok et al., 2004). This is particularly the case in very dry environments, such as those prevailing in the Atacama region of northern Chile [one of the world's most arid deserts (Ericksen, 1983; Latorre et al., 2005)], as they do not present the conditions that typically promote exchange between the bone and surrounding soil (principally fluxes of water). Aside from its utility in addressing the energy/carbohydrate component of the diet, bone apatite has the useful property of representing the last years of diet and residence, and so can be compared with tooth enamel, which reflects a period in childhood, depending on the tooth. In the text below, we distinguish between bone apatite and enamel  $\delta^{13}\text{C}$  values as  $\delta^{13}\text{C}_{\text{apatite}}$  and  $\delta^{13}\text{C}_{\text{enamel}}$ , respectively.

## Methods

Collagen extraction was carried out following a modified method from Longin (1971) as described by Honch et al. (2006). Given the prevalence of very high  $\delta^{15}\text{N}$  values from northern Chile (e.g., Tieszen et al., 1992; Aufderheide et al., 1994; Petruzzelli et al., 2012; Santana et al., 2012; Torres-Rouff et al., 2012), we developed a new  $^{15}\text{N}$ -enriched internal laboratory standard using marine seal bone collagen ( $\delta^{13}\text{C} = -13.3 \pm 0.11\text{‰}$ ;  $\delta^{15}\text{N} = 17.3 \pm 0.29$ ;  $n = 25$ ), which was calibrated against international standards N-1, N-2, and C6. In addition to the seal collagen, we used laboratory standard Alanine ( $\delta^{13}\text{C} = -26.9 \pm 0.1$ ;  $\delta^{15}\text{N} = -1.63 \pm 0.28$ ) (calibrated against IAEA standards) together with international standard C6 and Bovine Liver (SRM-1577) for calibration of sample carbon and nitrogen isotope ratios. Collagen samples were determined in duplicate on a SERCON 20/22 continuous flow ratio mass spectrometer coupled with an elemental analyzer. Analytical precision was estimated as  $\pm 0.1\text{‰}$  and  $\pm 0.3\text{‰}$  for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ , respectively, based on multiple determinations of the standards.

To extract bone apatite, we used a pretreatment method developed by Smith (2005) for recent archeological bone. This protocol is designed to limit the effects of harsh, prolonged acid treatments that may easily lead to recrystallization and certainly also alter the isotope ratios (Lee-Thorp and van der Merwe, 1991; Smith, 2005). It comprises a wash in 1.5% (v/v) sodium hypo-

chlorite solution to eliminate the organic phase (3 h), at least three cycles of centrifugation and rinsing in distilled water, followed by brief (5 min) immersion in 0.1M acetic acid, and again centrifugation and rinses. Samples were freeze-dried overnight. The clean dry powders were analysed for  $^{13}\text{C}/^{12}\text{C}$  and  $^{18}\text{O}/^{16}\text{O}$  in the Stable Light Isotope Laboratory of the University of Cape Town, on a Finnigan MAT 252 mass spectrometer coupled to a Gasbench II. The standards used for calibration were an internal marble standard and NBS 18 and 19 (IAEA standards). Analytical precision was better than 0.1‰ and 0.35‰ for carbon and oxygen isotopes, respectively, as indicated by multiple replicates.

Purification of tooth enamel followed protocols described in Sponheimer (1999), in which a brief (30 min) wash in 1.5% (v/v) sodium hypochlorite solution was followed by a 10 min wash in 0.1M acetic acid (interspersed with rinses in purified water, as above for bone apatite). Samples were freeze-dried overnight, before measurement in a Thermo Finnigan Delta V Advantage mass spectrometer equipped with a Gasbench II in the Stable Light Isotope Laboratory, University of Bradford. International standards CO-1 (Calcite) and NBS19 were used together with an internal enamel standard (Bos Enamel Standard-BES). Analytical precision as indicated by multiple replicates was better than 0.1‰ for both  $^{13}\text{C}/^{12}\text{C}$  and  $^{18}\text{O}/^{16}\text{O}$ . Results for laboratory standards from the University of Cape Town and Bradford have been compared showing that values for the internal standard BES, and for NBS 18 and NBS 19 are comparable within error (e.g.,  $\pm 0.1\text{‰}$ ) (Hare and Sealy, 2013; Pellegrini et al., 2011; Pellegrini, personal communication).

Statistical analyses were carried out using MATLAB. As not all of the data were normally distributed (as assessed with Shapiro Wilk tests), Mann-Whitney-Wilcoxon and Kruskal-Wallis nonparametric tests were used.

## RESULTS

### Bone collagen

Most samples from both sites gave molecular C/N ratios, collagen yields and carbon and nitrogen percentages that indicated well-preserved collagen (Tables 1

TABLE 3. Descriptive statistics of the isotopic values (bone collagen and apatite) obtained for Quitor 6 and Pica 8 divided by site and sex

	$\delta^{13}\text{C}_{\text{collagen VPDB}}$				$\delta^{15}\text{N}_{\text{AIR}}$				$\delta^{13}\text{C}_{\text{Apatite VPDB}}$				$\delta^{18}\text{O}_{\text{Apatite VPDB}}$			
	Mean	SD	Max	Min	CV	Mean	SD	Max	Min	CV	Mean	SD	Max	Min	CV	
<b>Quitor 6</b>																
Females	-14.6	1.3	-11.6	-17.4	0.08	10.8	0.8	11.9	9.5	0.06	-8.4	0.5	-7.7	-9.8	0.08	
Males	-14.2	1.4	-11.6	-15.5		10.7	0.8	11.8	10.6		-8.6	0.6	-7.8	-9.8		
<b>Pica 8</b>																
Females	-14.9	1.5	-13.2	-17.4	0.22	11.3	0.4	11.9	10.1		-8.3	0.5	-7.7	-9.0	0.43	
Males	-11.1	2.4	-8.8	-18.6		17.3	3.9	24.4	10.9		-5.9	2.6	-3.9	-13.0		
<b>Quitor 6</b>																
Females	-11.3	2.4	-9.0	-18.6		17.9	4.2	24.4	10.9		-5.9	2.4	-4.0	-13.0		
Males	-10.2	1.4	-8.8	-13.9		15.9	3.4	21.5	12.8		-5.4	2.3	-3.9	-11.2		

CV is the Coefficient of Variation.

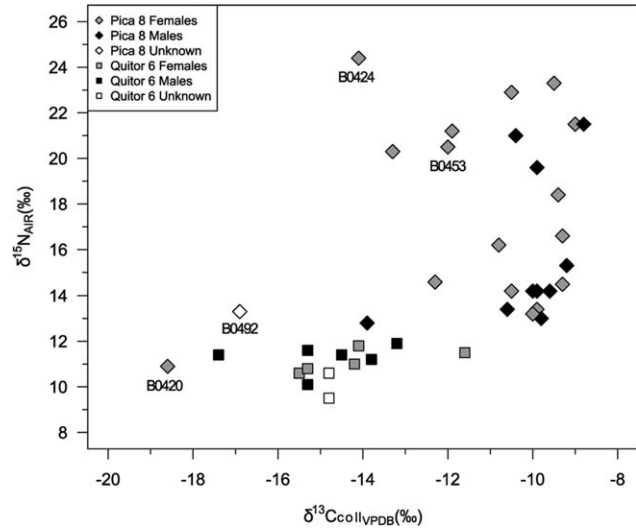
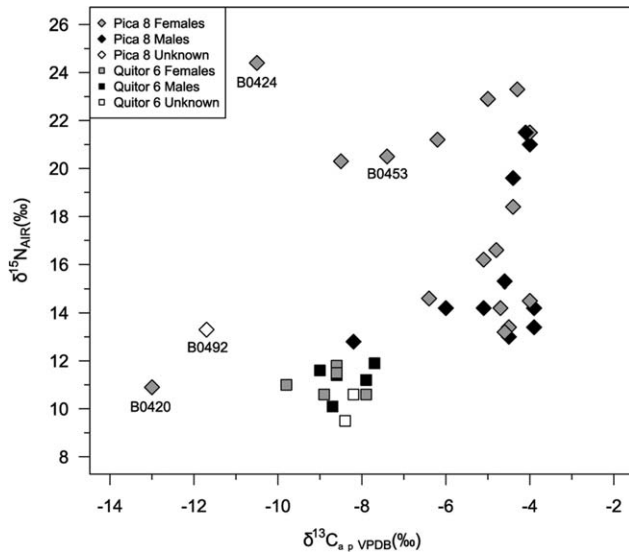


Fig. 2. Bivariate plot of  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  obtained from bone collagen for Pica 8 and Quitor 6 individuals, separated into males, females, and those of indeterminate sex. Outlier individuals are indicated by their reference number.

and 2). Three individuals from Pica 8 with high C/N ratios (above 3.8) were excluded from further analyses. Five individuals gave C/N ratios of 3.7, just above the generally accepted upper limit of 3.6 (DeNiro, 1985; Ambrose, 1990), but their collagen yields, and C% and N% were within acceptable limits. The effects of including or excluding these values were considered and found not to substantially alter the results, so they were retained in subsequent analyses. Two samples from Quitor 6 yielded insufficient collagen for analysis, while one was discarded because of its high C/N ratio.

The individuals from Pica 8 average  $-10.9 \pm 2.4\text{‰}$  (median  $-10.0\text{‰}$ ) for  $\delta^{13}\text{C}_{\text{collagen}}$  and  $17.0 \pm 4.0\text{‰}$  for  $\delta^{15}\text{N}$  (median  $15.3\text{‰}$ ) ( $n = 27$ ), the high standard deviations indicating considerable isotopic variability. Mann-Whitney  $U$ -tests show that the variability is not due to sex-based differences ( $\delta^{13}\text{C}_{\text{collagen}}$ ,  $Z = -1.11$ ,  $P = 0.267$ ;  $\delta^{15}\text{N}$ ,  $Z = -1.37$ ,  $P = 0.169$ ). The results from Quitor 6 average  $-14.4 \pm 1.0\text{‰}$  (median  $-14.8\text{‰}$ ) for  $\delta^{13}\text{C}_{\text{collagen}}$  and  $11.0 \pm 0.7\text{‰}$  (median  $11.0\text{‰}$ ) for  $\delta^{15}\text{N}$  ( $n = 13$ ), demonstrating considerably less variability than at Pica 8. Again, there are no significant differences between males and females ( $\delta^{13}\text{C}_{\text{collagen}}$ ,  $Z = -0.18$ ,  $P = 0.926$ ;  $\delta^{15}\text{N}$ ,  $Z = -0.73$ ,  $P = 0.502$ ) (Table 3 and Fig. 2).

Clear differences are seen between the sites, with both  $\delta^{13}\text{C}_{\text{collagen}}$  and  $\delta^{15}\text{N}$  values being significantly higher at Pica 8 ( $\delta^{13}\text{C}_{\text{collagen}}$ ,  $Z = 4.13$ ,  $P < 0.000$ ) ( $\delta^{15}\text{N}$ ,  $Z = 4.96$ ,  $P < 0.000$ ). As noted above, the results for Pica 8 are also considerably more variable. A substantial portion of the variability can be related to the sectors of the cemetery to which the burials have been attributed. The four sectors (A, D, G, and I) represented by three or more individuals differ significantly in  $\delta^{15}\text{N}$  (Kruskal-Wallis ANOVA,  $P = 0.005$ ;  $df = 3$ ;  $n = 22$ ). It is clearly sector I that stands out as different, having the consistently highest values, averaging  $21.7 \pm 2.0\text{‰}$ , while sectors A, D, and G average about  $14.5\text{--}16.0\text{‰}$ . This is confirmed by ANOVA tests (used with some caution given the non-normal distribution of the data), which indicate that sector I differs from the three other sectors in pair-wise *post hoc* tests. As discussed further below, this must be



**Fig. 3.** Bivariate plot of  $\delta^{13}\text{C}$  from bone apatite, and bone collagen  $\delta^{15}\text{N}$  for Pica 8 and Quitor 6, separated into males, females, and those of indeterminate sex. Most of the individuals with very high  $\delta^{15}\text{N}$  (above  $+19\text{‰}$ ) show  $\delta^{13}\text{C}_{\text{bone apatite}}$  values above  $-8\text{‰}$  suggesting a  $\text{C}_4$  diet contribution in addition to high protein marine foods. Outlier individuals are indicated by their reference number.

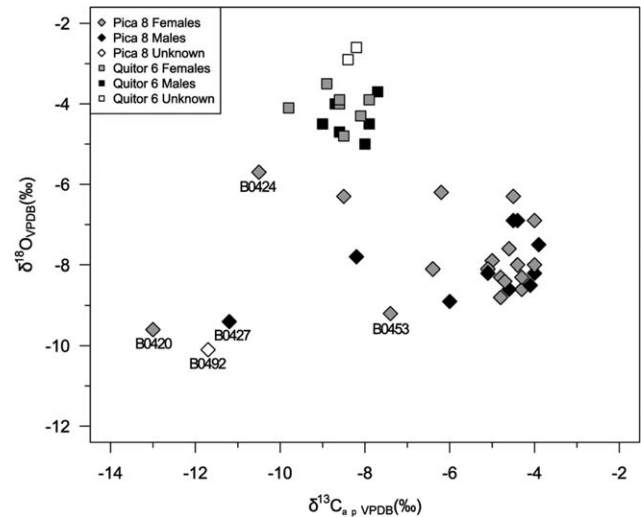
due to the substantial contribution of marine foods by all individuals analyzed from sector I, as well as a small number of individuals apparently more randomly distributed through the other sectors. The absence of a site plan is particularly frustrating, as some of these graves may have been immediately adjacent to sector I, and so might belong with it. No significant differences are seen in  $\delta^{13}\text{C}_{\text{collagen}}$ , presumably as a result of the conflation of marine and  $\text{C}_4$  protein sources.

### Bone and enamel apatite

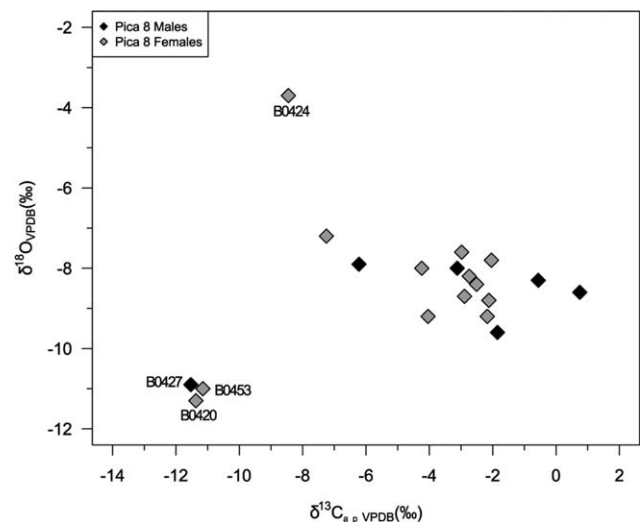
Pica 8  $\delta^{13}\text{C}_{\text{apatite}}$  values average  $-5.9 \pm 2.6\text{‰}$  (median  $-4.8\text{‰}$ ), with maximum and minimum values of  $-3.9\text{‰}$  and  $-13.0\text{‰}$  reflecting considerable variability. As with the bone collagen results, this does not relate to sex, as no significant differences are observed between males and females ( $Z = 1.61$ ,  $P = 0.107$ ). Quitor 6  $\delta^{13}\text{C}_{\text{apatite}}$  results average  $-8.4 \pm 0.5\text{‰}$  (median  $-8.5\text{‰}$ ). As with the collagen data,  $\delta^{13}\text{C}_{\text{apatite}}$  values are relatively homogeneous in their distribution, with a low coefficient of variation (Table 3). Again, there are no significant differences between females and males in  $\delta^{13}\text{C}_{\text{apatite}}$  values ( $Z = -0.65$ ,  $P = 0.559$ ). An intergroup comparison between Pica 8 and Quitor 6 shows that their  $\delta^{13}\text{C}_{\text{apatite}}$  values were significantly different ( $Z = 3.65$ ,  $P < 0.000$ ).

Values for  $\delta^{13}\text{C}_{\text{apatite}}$  from both archeological sites were plotted against  $\delta^{15}\text{N}$  (Fig. 3). As can be seen, Pica 8 presents a wide range of values for carbon and nitrogen isotopes. In contrast, Quitor 6 shows far less variation.

The  $\delta^{18}\text{O}$  data for Quitor 6 and Pica 8 fall into two distinct, nonoverlapping groups (Fig. 4). For Quitor 6,  $\delta^{18}\text{O}$  values average  $-4.0 \pm 0.7\text{‰}$  (median  $-4.0\text{‰}$ ), as compared with  $-8.0 \pm 1.0\text{‰}$  (median  $-8.1\text{‰}$ ) at Pica 8 ( $Z = -5.41$ ,  $P < 0.000$ ). Neither site shows any sex-based differences. The three individuals (B0420, B0427, and B0492) with the most negative  $\delta^{18}\text{O}$  values ( $\leq -9.0\text{‰}$ ) at Pica 8 also exhibit the most negative  $\delta^{13}\text{C}_{\text{apatite}}$  values. However, the single



**Fig. 4.** Bivariate plot of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  from bone apatite for Pica 8 and Quitor 6 individuals, showing males, females, and those of indeterminate sex. Outlier individuals are indicated by their reference number.



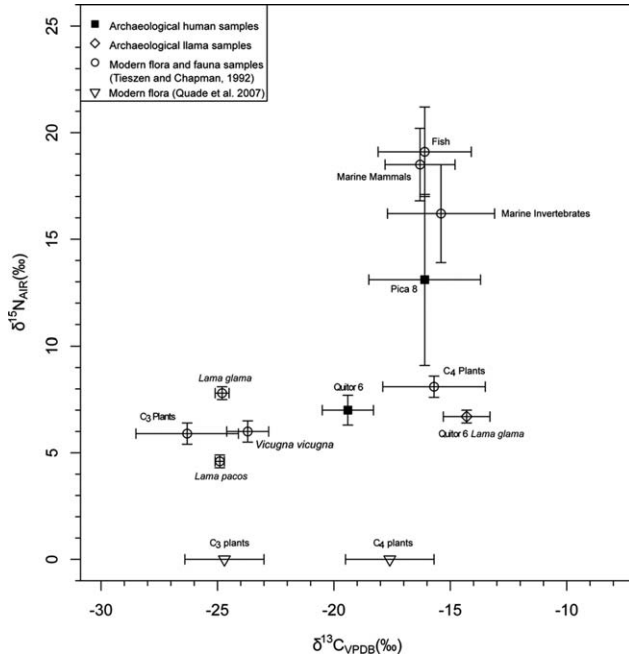
**Fig. 5.** Bivariate plot of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  obtained from tooth enamel for Pica 8, showing males and females. Outlier individuals are indicated by their reference number.

individual (B0424) with a relatively higher  $\delta^{18}\text{O}$  value ( $-5.7\text{‰}$ ) also shows a low  $\delta^{13}\text{C}_{\text{apatite}}$  value.

Results for Pica 8 enamel samples are enriched in  $^{13}\text{C}$  for most individuals, with some exceptions (Fig. 5). Mean  $\delta^{13}\text{C}_{\text{enamel}}$  is  $-4.6 \pm 3.7\text{‰}$  (median  $-3.0\text{‰}$ ). Some of the individuals show an offset of up to  $+2\text{‰}$  in their  $\delta^{13}\text{C}_{\text{enamel}}$  when compared to  $\delta^{13}\text{C}_{\text{apatite}}$ . At least four individuals show low values for  $\delta^{13}\text{C}_{\text{enamel}}$  (ca.  $-11\text{‰}$ ) that fall beyond the main group; they correspond to three individuals with low  $\delta^{13}\text{C}_{\text{apatite}}$  values (B0420, B0424, and B0427). No teeth were available for analysis from the fourth individual (B0492).

Most of the  $\delta^{18}\text{O}$  values obtained are similar to those observed for bone apatite, averaging  $-8.5 \pm 1.6\text{‰}$  (median  $-8.4\text{‰}$ ). However, there are three individuals with low  $\delta^{18}\text{O}_{\text{enamel}}$ , B0420 and B0427, B0453, which





**Fig. 6.** Bivariate plot showing  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  as means and standard deviations for modern floral and faunal resources analyzed by Tieszen and Chapman (1992), as compared with dietary  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values for Pica 8 and Quitor 6 individuals. Diet values were estimated using an offset of  $+5\text{‰}$  for  $\Delta^{13}\text{C}_{\text{diet-collagen}}$  and  $+4\text{‰}$  for  $\Delta^{15}\text{N}_{\text{diet-collagen}}$  in humans, and  $+4\text{‰}$  for  $\Delta^{13}\text{C}_{\text{diet-collagen}}$  in animals. The  $\delta^{13}\text{C}$  values of modern  $\text{C}_3$  and  $\text{C}_4$  plants from Northern Chile (Calama/Paso Jama, Socompa, and Paposo) (Quade et al., 2007) are shown as means and standard deviations immediately above the X-axis;  $\delta^{15}\text{N}$  values were not reported. All modern terrestrial sample  $\delta^{13}\text{C}$  values were corrected for the fossil fuel effect to preindustrial (1750AD)  $\delta^{13}\text{C}_{\text{CO}_2}$  values, using a correction of  $-1.6\text{‰}$  for 2007 and  $-1.9\text{‰}$  for 1992 (CO<sub>2</sub> data from CDIAC <http://cdiac.ornl.gov/trends/co2/iso-sio/iso-sio.html>). No corrections were applied to the marine fauna.

also have low  $\delta^{18}\text{O}_{\text{apatite}}$  values. However,  $\delta^{18}\text{O}_{\text{enamel}}$  for individual B0424 is even more enriched in  $^{18}\text{O}$  ( $-3.7\text{‰}$ ) than its bone apatite value ( $-5.7\text{‰}$ ).

## DISCUSSION

The results suggest that the community represented at Quitor 6 relied largely on a terrestrial diet comprising  $\text{C}_3$  and  $\text{C}_4$  resources. A significant contribution of  $\text{C}_4$  plants, in this case maize, is seen in the elevated  $\delta^{13}\text{C}_{\text{collagen}}$  values of about  $-14\text{‰}$  as well as the  $\delta^{13}\text{C}_{\text{apatite}}$  values of about  $-8\text{‰}$ . The  $\delta^{13}\text{C}$  results for collagen and apatite are grouped tightly, with low variability. Quitor 6  $\delta^{15}\text{N}$  values are as high as  $+11.8\text{‰}$ , somewhat elevated for a population relying completely on terrestrial resources. Since there is a lack of marine faunal remains in the zooarcheological record for this site, other influences must be considered, such as the use of manure and/or the aridity that characterizes the Atacama Desert. These possibilities are discussed further below.

Other than the relatively elevated  $\delta^{15}\text{N}$  values, our results are consistent with the premise that diets of the Atacama LIP communities were largely terrestrial, and that maize was an important crop (Costa, 1988). As seen in Figure 6, the Quitor 6 humans fall between the  $\delta^{13}\text{C}$  values for modern wild and domesticated camelids (Ties-

**TABLE 4.** Values for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  obtained from bone collagen in this study as compared to the values presented by Petruzzelli et al. (2012)

N°	$\delta^{13}\text{C}$		$\delta^{15}\text{N}$		$\delta^{13}\text{C}$ offset	$\delta^{15}\text{N}$ offset
	This study	Petruzzelli et al.	This study	Petruzzelli et al.		
B0415	-9.6	-8.7	14.2	15.1	0.9	0.9
B0439	-10.8	-10.4	16.2	18.0	0.4	1.8
B0448	-	-10.1	-	16.2		
B0466	-10.0	-8.7	14.2	16.5	1.3	2.3
B0468	-9.0	-8.8	21.5	23.1	0.2	1.6
B0483	-13.3	-13.0	20.3	21.4	0.3	1.1

The values obtained by Petruzzelli et al. are presented in italics.

zen and Chapman, 1992), and the archeological llamas from Quitor 6, which are relatively enriched in  $^{13}\text{C}$ . Their  $\delta^{13}\text{C}$  values suggest either grazing on  $\text{C}_4$  grasses from the surrounding areas (including the mountains) of the Atacama Oases, or foddering with maize.

In contrast Pica 8 individuals exhibit far more variability in  $\delta^{13}\text{C}_{\text{collagen}}$ ,  $\delta^{13}\text{C}_{\text{apatite}}$ , and  $\delta^{15}\text{N}$ , leading to the identification of three possible dietary groups (Figs. 2 and 3). On the basis of the high  $\delta^{13}\text{C}_{\text{collagen}}$  and  $\delta^{15}\text{N}$  values, the first group relied heavily on marine resources. Indeed, they are similar to those of modern marine fauna from northern Chile (Fig. 6). The contribution of maize is also suggested by the elevated  $\delta^{13}\text{C}_{\text{apatite}}$  values. The distribution of  $\delta^{13}\text{C}_{\text{apatite}}$  values due to marine consumption does not extend above  $-10\text{‰}$ ; thus values more enriched in  $^{13}\text{C}$  indicate the input of another more enriched carbon source. Petruzzelli et al. (2012) obtained similarly high  $\delta^{13}\text{C}_{\text{collagen}}$  and  $\delta^{15}\text{N}$  values for six individuals from Pica 8, averaging  $-9.9 \pm 1.7$  and  $18.4 \pm 3.2$ , respectively. They concluded that the diet was heavily marine-based but since they did not measure  $\delta^{13}\text{C}_{\text{apatite}}$  they were unable to detect the presence of maize. In Table 4 the values obtained by Petruzzelli et al. (2012) are compared with those obtained in this study for the same individuals (with the exception of individual B0448, not analyzed here). While there are offsets in the  $\delta^{13}\text{C}_{\text{collagen}}$  and  $\delta^{15}\text{N}$  values obtained by the two studies, they are strongly correlated, with  $r^2$  values of 0.94 and 0.97, respectively. The offset may be due to the application of a different method for collagen extraction as well as in the method of calibration and standards used. For consistency, we consider only our data in the analyses that follow.

The second group shows relatively high  $\delta^{13}\text{C}$  values, especially for bone and tooth apatite, but lower values for  $\delta^{15}\text{N}$ ; this combination suggests the greater importance of maize for these individuals with lower use of coastal resources. While  $\delta^{15}\text{N}$  values remain high (around  $14\text{‰}$ ), factors other than marine resources may also play a role, including the use of animal manure on fields, the aridity effect, and others, as discussed below. The third group corresponds to individuals B0420, B0427, B0492, and B0453, whose isotopic composition suggests a largely  $\text{C}_3$ -based terrestrial diet. Individual B0453, however, only shows this pattern during early youth (third molar), as the isotopic composition shifts strongly by adulthood to a diet comprising both marine resources and maize, and falling within the first group. Apart from the three abovementioned groups, a single individual (B0424) shows a very high  $\delta^{15}\text{N}$  value ( $+24.4\text{‰}$ ) combined with relatively low  $\delta^{13}\text{C}_{\text{apatite}}$  values for both bone ( $-10.5\text{‰}$ ) and tooth enamel ( $-8.5\text{‰}$ ). This



suggests a very high component of marine foods and a low component of maize. All the individuals from the third group, and this last individual, exhibit  $\delta^{18}\text{O}$  values differing from the others at Pica 8, a point to which we return below.

Our results for Pica 8 are consistent with the importance of both maize and marine resources in the Pica-Tarapacá culture (Moragas, 1995; Uribe, 2006). Considerable evidence of maize has been found at Pica 8, with textile bags still completely full of maize grains (Núñez, 1984). Contacts with the coast are recorded by the presence of dried fish, feathers of coastal birds, fish bones, and shellfish (Núñez, 1984; Zlatar, 1984).

The greater isotopic variability in Pica 8 is seen particularly in the distribution of  $\delta^{15}\text{N}$ , which points to the existence of three distinct isotopic, and hence dietary, groups at the former site. As noted above, gender does not appear to be a significant factor. Rather, these groups can be largely—though not entirely—related to the sectors, which were identified above as highly relevant in structuring the observed isotopic variability. Despite our inability, in the absence of a site plan, to place the location of the individual burials and the cemetery sectors in relation to one another, it is interesting to note that the group with the consistently highest  $\delta^{15}\text{N}$  values, indicative of a high contribution of marine dietary protein, is found in Sector I. Sector I also contains most of the archeological evidence related to the coast, in contrast to sectors G and B that show sparser marine evidence (Núñez, 1984). Of the six individuals attributed to sector G included in the study, only one exhibits an elevated  $\delta^{15}\text{N}$  value ( $20.3\text{‰}$ ), on par with those seen in sector I (averaging  $21.7 \pm 2.0\text{‰}$ ) as compared to an average of  $13.3 \pm 0.5\text{‰}$  for the remaining five individuals in sector G. Other sectors of the cemetery present evidence related to the *altiplano* such as *chuño* (potato flour), quinoa, and llama burials (sectors B and E) as well as marine resources. Still others (A, B, D, and E) also show evidence associated with the eastern side of the Andes such as tropical birds (*Ara ararauna*) and plants (*Ormosia coccinea*). Excluding sector I with its isotope and zooarcheological evidence for a strong coastal influence, the average  $\delta^{15}\text{N}$  for all remaining sectors is  $15.1 \pm 2.9\text{‰}$  ( $n = 16$ ); this is further reduced to  $13.9 \pm 1.5\text{‰}$  when three outliers with elevated values are removed.

Having established the importance of the sectors at Pica 8, it remains to explain why this should be the case. The first point to consider is whether the observed isotopic (and hence dietary) differences are synchronic or diachronic. As noted above, most of the few available radiocarbon dates are problematic. Even if assignment to the LIP is accepted, the possibility remains that the sectors relate to different phases within this period. As noted above, the earlier Pica-Tarapacá phase appears to have stronger coastal links than the subsequent Camiña phase. Nevertheless, the ceramic typologies (Pica Charcollo and Pica Chiza types) observed for many of the burials analyzed in this study, together with the radiocarbon date (cal AD 902–1270) on a textile obtained by Núñez (1976), suggest that the cemetery was in use during the first half of the LIP (Tarapacá phase) (Uribe et al., 2007). At least eight out of the 30 burials (B0420, B0426, B0428, B0430, B0441, B0447, B0467, and B0468) analyzed in this study—from different sectors and  $\delta^{15}\text{N}$  values ranging from  $10.9\text{‰}$  to  $23.3\text{‰}$ —are associated with pottery types indicative of the first half of the LIP in Tarapacá (Pica Charcollo, Pica Chiza, and Pica Gris

Alisado) (Uribe et al., 2007). In contrast, no pottery of later or earlier periods, has been identified in any of the graves included in this study that have information regarding their offerings.

Accepting for the present the greater likelihood that the spatially structured isotopic/dietary variability seen in the cemetery is largely synchronic, perhaps it can be related to the various “ethnic”<sup>2</sup> origins and ongoing subsistence orientation of the different sectors of the community using the Pica 8 cemetery. Unfortunately, there is no information about burial offerings for almost half of the graves analyzed here (Table 1), so it is difficult to discuss their possible ethnic relationships or social status from this perspective (although further research to make use of the textiles accompanying many of the graves is underway). However, the spatial separation of burials has long been noted as a dimension of mortuary practice that is strongly linked with social affiliation (Binford, 1971). The implications of this are that, even though the Pica-Tarapacá culture consisted of communities with wide-ranging contacts, these contacts may have been maintained over many generations by distinct social groups within individual communities, and not led to widespread sharing with those using different sectors of same cemetery for burial. Thus, for example, sector I would represent a subset of the Pica 8 community with privileged access to coastal resources that were not distributed more widely within the community, or at least were not shared equally. This recalls the *allyu* organization known ethnohistorically from other areas in the Atacama region, in which cultural groups are related through kin relationships and reciprocity (Cock, 1981).

Also noteworthy is the presence of nonlocal pottery in the cemetery (corresponding to ca. 6% of the ceramic assemblage), which provides some possible directions for future studies on ethnicity and other forms of identity at Pica 8. These ‘foreign’ ceramics are associated with the LIP of the Atacama Oases, (Aiquina and Dupont pottery) and the Arica culture to the north (San Miguel pottery), while other vessels are related to styles known from the *altiplano* (Catalán, 2006). This presents a rich field for future studies, combining multi-isotope approaches with a consideration of burial location and grave offerings. A more robust and precise chronology will be crucial for its interpretation.

Oxygen isotope values obtained for Quito 6 are consistent with results obtained in northern Chile (cf. Knudson, 2009). No outliers were observed in the sample. Even though the Atacama oases are about 200 km away from the coast, and located at a relatively high altitude (2450 masl),  $\delta^{18}\text{O}$  values are moderately positive. Quito is located in an area with two rivers (the San Pedro and Vilama) whose waters are exposed and thus subject to prolonged evaporation and enrichment in  $^{18}\text{O}$  (Aravena, 1995). On the other hand, Pica 8 shows surprisingly low  $\delta^{18}\text{O}_{\text{apatite}}$  values as compared to Quito 6, even though Quito is at a higher altitude than Pica (1250 masl) and more distant from the coast. Pica is, however, located in an area with a complex groundwater system (*Pampa del Tamarugal*) whose waters derive mainly from high altitude precipitation and snow-melt (Magaritz et al., 1990). Thus the springs of Pica are likely fed directly from the Andes via underground aquifers, mitigating the enrichment effect of evaporation.

<sup>2</sup>We accept that the term is not unproblematic.

Our results for Pica 8 are entirely consistent with  $\delta^{18}\text{O}$  analyses of such water sources in the Atacama Desert (Aravena, 1995).

Four individuals at Pica 8 have bone apatite and enamel  $\delta^{18}\text{O}$  values sufficiently distinct to be considered as outliers. These outliers are most clearly distinguishable in enamel, with individuals B0420, B0427, and B0453 having values below  $-10\text{‰}$ , similar to those observed by Knudson (2009) for groups living in the *altiplano* of Bolivia at high altitudes (above 3500 masl). These individuals also show more depleted in  $^{13}\text{C}$  values for bone apatite, indicating a diet based on  $\text{C}_3$  resources. Thus they may have subsisted on *altiplano* crops such as *quinoa* and potatoes in infancy (between 3 and 10-years-old) or youth (between 10- and 18-years-old) depending on the tooth analyzed. Individual B0424 on the other hand shows the highest  $\delta^{18}\text{O}$  ( $\delta^{18}\text{O}_{\text{enamel}} -3.7\text{‰}$ ;  $\delta^{18}\text{O}_{\text{apatite}} -5.7\text{‰}$ ) value, while relatively low  $\delta^{13}\text{C}_{\text{apatite}}$  ( $\delta^{13}\text{C}_{\text{enamel}} -8.5\text{‰}$ ;  $\delta^{13}\text{C}_{\text{apatite}} -10.5\text{‰}$ ) and high  $\delta^{15}\text{N}$  values (24.4‰, the highest in the present study), suggest a strong focus on marine resources. Thus the  $^{18}\text{O}$ -enrichment might reflect the influence of freshwater sources at or near the coast where evaporation of  $\text{H}_2\text{O}$  is high. As far as we are aware, there are no  $\delta^{18}\text{O}$  data for individuals demonstrably living at the coast, so we cannot ascribe the observed high value to coastal conditions with any degree of certainty, though we suspect this is the case. Contacts between the coast and inlanders have been evidenced in campsites associated with llama caravan routes close to Pica (Briones et al., 2005), the village of Caserones (Uribe, 2006), and the Eastern Cemetery of Quillagua (Latham, 1933; Núñez, 1984) where similar isotopic values to those observed at Pica 8 were found (Santana, 2011).

Interestingly, while they begin to approach the mean for Pica 8, the bone apatite  $\delta^{18}\text{O}$  results for three of the outlying individuals (as defined by their enamel values) remain more negative. Given that bone is a dynamic tissue, it would seem that the isotopic composition of these individuals was still “equilibrating” with the Pica 8 environment. Another possible explanation is that diagenesis affected the isotopic values of bone apatite, although the strong correlation observed between  $\delta^{13}\text{C}_{\text{collagen}}$  and  $\delta^{13}\text{C}_{\text{apatite}}$  argues against this. The outliers show negative  $\delta^{13}\text{C}_{\text{collagen}}$  values as well as low values for carbon and oxygen isotopes in both bone and enamel apatite.

It is remarkable that the  $\delta^{18}\text{O}$  outliers observed for tooth and bone apatite (including individual B0492 for whom no tooth sample was available), are also outliers for their  $\delta^{13}\text{C}_{\text{collagen}}$ ,  $\delta^{13}\text{C}_{\text{apatite}}$ , and  $\delta^{15}\text{N}$  values. Individuals B0420 and B0492 exhibit very low  $\delta^{13}\text{C}_{\text{collagen}}$  and  $\delta^{15}\text{N}$  values, suggesting a largely  $\text{C}_3$ -based terrestrial diet during infancy as well as adulthood. This combination is consistent with origins in the *altiplano*. Even though they probably died in Pica and likely lived there during their last years, there is little evidence for the typical seafood and maize diet of others in the same cemetery. Possibly they continued to consume an *altiplano* diet, since the availability of these foods is attested by the presence of potato and *quinoa* at Pica 8. Unfortunately, individual B0427 had poor collagen preservation but the  $\delta^{13}\text{C}_{\text{apatite}}$  value indicates a diet based on  $\text{C}_3$  resources with no detectable consumption of maize. In contrast to those outliers, a coastal origin is suggested for individual B0424, a male with the most positive  $\delta^{18}\text{O}$  value (for bone and enamel apatite) and highest  $\delta^{15}\text{N}$  value. It would seem that this individual

maintained his dietary habits while in Pica as there is little evidence for maize consumption during the last years of his life.

The Atacama of northern Chile is the driest desert in the world, with almost no precipitation in most years (Ericksen, 1983; Latorre et al., 2005). The level of  $^{15}\text{N}$  enrichment—to up 24.4‰—at Pica 8 is nevertheless remarkably high for an inland site. Similar but variable results have been reported for other sites in the coast of northern Chile and southern Peru (Tieszen et al., 1992; Aufderheide et al., 1994; Tomczak, 2003; Santana et al., 2012; Torres-Rouff et al., 2012) with the most  $^{15}\text{N}$ -enriched values generally found in coastal sites. For example, individuals at the coastal sites of Cañamo and Chinchorro have  $\delta^{15}\text{N}$  values of up to 26‰ (Tieszen et al., 1992; Santana et al., 2012). That said, the highest values from Pica 8 and other sites in northern Chile are well beyond what would be expected from aridity or ‘normal’ marine inputs. Other factors must be at play.

One peculiarity of the northern Chile coastal system is that many marine fauna show values strongly enriched in  $^{15}\text{N}$ , regardless, apparently, of their position in the trophic system. This differs from the marine isotope values from other parts of the coast such as in Central Chile (Falabella et al., 2007), or in other upwelling systems. In an attempt to explain large numbers of marine animal  $\delta^{15}\text{N}$  values above +20‰, Tieszen and Chapman (1992, p. 413) suggested that “Our inability to document trophic level differences in this system may simply reflect the complex nature of the trophic transfers or substantial variation in a seemingly small sample area.” The lack of trophic level distinction is shown in Figure 6, in which fish, unusually, have higher average  $\delta^{15}\text{N}$  values than sea mammals. Thus, in this part of the eastern Pacific upwelling system, it is not necessary for humans to consume large amounts of high-trophic marine mammals, since marine fish alone would suffice to induce high  $\delta^{15}\text{N}$ .

Terrestrial influences must also be considered in relation to the prevalence of relatively high  $\delta^{15}\text{N}$  values at Pica 8 and Quitor 6 (disregarding the very high  $\delta^{15}\text{N}$  ‘marine consumers’ in Sector I, Pica 8 for the moment). Evidence for a positive correlation between  $\delta^{15}\text{N}$  values in plants and aridity has been identified in many contexts around the world (Heaton et al., 1986; Heaton, 1987; Murphy and Bowman, 2009; Hartman and Danin, 2010), although aridity is but one factor contributing to the variability (Craine et al., 2009). Studies of modern plants in northern Chile indicate  $\delta^{15}\text{N}$  values averaging about 11‰ in the coastal locality of Paposo (Evans and Ehleringer, 1994), while values of up to 14‰ have been reported for *kiwicha* (*Amaranthus caudatus*), a crop that played an important role in Inkan diet, as well as in earlier Peruvian cultures (Turner et al., 2010). Seeds of the genus *Amaranthus* have been found in Pica-Tarapacá contexts but they have yet to be fully documented (Uribe, own observations), or analysed for their isotopic composition.

It has also been shown that variation in  $\delta^{15}\text{N}$  in animal tissues may also be due to variation in gut physiology. Sponheimer et al. (2003), in an experimental feeding study, showed that alpacas gave the highest diet-consumer tissue difference ( $\Delta^{15}\text{N}$ ) as compared to llamas, horses, cattle, goat, and rabbits. The isotopic composition of herbivores from northern Chile is still poorly known, but  $\delta^{15}\text{N}$  values for Llama (*Lama glama*) average about 6‰, well within the range expected for

terrestrial herbivores (Tieszen and Chapman, 1992) (shown in Fig. 6). However,  $\delta^{15}\text{N}$  obtained for llamas from the Formative Period (Tulán 54) in the Atacama oases indicate higher values—ranging from +9.8‰ to 13‰ (López et al., 2013). This may suggest that conditions favoring high soil  $^{15}\text{N}$  pertained in the oases.

Recently, the isotopic effects of manuring as part of an intensive horticultural regime have been widely considered, as indeed one might expect in an oasis context. The use of animal waste as manure has been shown to have a considerable impact on the  $\delta^{15}\text{N}$  values of plants (e.g., Finucane, 2007; Bogaard et al., 2007; Fraser et al., 2011; Szpak et al., 2012). An experimental study carried out by Szpak et al. (2012) showed that application of llama dung and/or seabird guano has a strong  $^{15}\text{N}$ -enrichment effect on soil and plants, resulting in high  $\delta^{15}\text{N}$  values for maize of up to  $+13.9 \pm 0.6\text{‰}$  and  $+38.1 \pm 0.6\text{‰}$ , respectively. Thus it has been suggested that high  $\delta^{15}\text{N}$  for archeological plants is because of application of seabird guano (Poulson et al., 2013) rather than to diagenesis of plant tissues as earlier suggested by others (DeNiro and Hastorf, 1985; Aufderheide et al., 1994; Schwarcz et al., 1999).

It is highly likely that the ancient populations of northern Chile used animal manure, given the existence of intensive agricultural systems over many centuries. Early historical records mention that the use of seabird guano extended from southern Peru (Arequipa) to northern Chile (Tarapacá) (Ericksen, 1983). We do not know, however, whether the populations used animal manure in the same way, or in similarly large quantities, so it is difficult at this stage to estimate the full impact of manuring in particular archeological cultures and communities. Given the strong  $^{15}\text{N}$ -enrichment in plants due to manuring, one could envisage that the consumption of terrestrial foods under such circumstances could be confused with marine foods. Further research is clearly needed on the isotopic composition of archeological and modern soils and plants, and the effects of seabird guano or llama dung in the arid zones and oases of northern Chile and southern Peru.

Notwithstanding the variety of factors that might influence the isotopic composition of past populations, we can make some firm inferences from the isotope data about the Pica 8 and Quito 6 individuals. Both the archeological record and the isotopic data at Pica 8 show strong evidence for the consumption of marine resources, with a maximum  $\delta^{15}\text{N}$  value of 24.4‰. Most of these  $^{15}\text{N}$ -enriched individuals come from just one Sector (I) in the cemetery. At the same time there are individuals from other sectors with values between 11‰ and 15‰, where  $^{15}\text{N}$ -enrichment may be ascribed to consumption of plants, including maize, enriched in  $^{15}\text{N}$  due to manuring or to aridity effects. Differences in  $^{15}\text{N}$ -enrichment are unlikely to have been caused by the consumption of marine resources at different trophic levels, since the Pacific upwelling affects the entire food web (Tieszen and Chapman, 1992). Llama dung manuring very likely featured in field management practices at Quito 6, considering the community's strong emphasis on pastoralism and agriculture, but it is not clear that there was a strong effect on the  $\delta^{15}\text{N}$  composition of Quito 6 individuals, which are only moderately elevated compared to humans in less arid zones.

The high  $\delta^{15}\text{N}$  values frequently observed in this study clearly require further investigation and further documentation of the modern isotopic ecology of the

desert and its oases; to date the only information on isotope distributions in modern flora and fauna is from Tieszen and Chapman (1992).

## CONCLUSIONS

Archeological characterizations propose a reliance on terrestrial diets including maize for the Atacama oases, and for the Pica-Tarapacá culture, greater use of imported marine alongside terrestrial sources, including maize. The  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  data on human bone collagen and bone apatite from Quito 6 and Pica 8 presented here independently confirm this scenario, and supply additional detail concerning its extent and the not-inconsiderable variability, seen particularly at Pica 8. At Quito 6 the isotopic evidence is uniformly consistent with a diet based mainly on the consumption of terrestrial resources and considerable quantities of maize. While we have not formally assessed the relationship between diet and social status here, given that the burials at Quito 6 have very similar grave offerings (Costa, 1988), it is unlikely that the low isotopic variability observed between individuals can be related in any recognizable way to differences in social status. The homogeneity observed in the dietary patterns of Quito 6 could be instead reflecting a closed social group with a strict internal order in terms of ethnicity and identity that would discourage the presence of nonlocal individuals.

The high variability observed in the isotopic values for Pica 8 appears to relate to location within the cemetery, although whether this represents different contemporary social units, or diachronic change, remains uncertain. The possibility for diachronic change further investigation, but on present evidence it seems unlikely given the cemetery's assignment to the relatively temporally restricted first phase of the Tarapacá culture. Ethnicity might have played an important role within a heterogeneous population, a scenario that concurs with the abundant evidence for broad trade contacts, the hypothesis that the Pica-Tarapacá culture integrated different environmental zones, and the presence of nonlocal individuals indicated by the isotopic data for at least five individuals. On the basis of both hydrology and diet, this group has diverse origins both in the *altiplano* and the coast. In contrast to Quito 6, Pica 8 reflects a more open social organization that allowed the interaction and coexistence of nonlocals. Yet, at the same time, different sections of the community appear to have maintained distinct and separate subsistence practices, seen most clearly in the high marine contribution in the diets of those buried in sector I. Rather than a 'melting pot', this sustained cultural diversity may have defined the Pica-Tarapacá culture. Thus, in these two cemeteries it is possible to see very different ways of organising Andean society during the Late Intermediate Period. The results obtained here support the archeological hypotheses (Núñez, 1984) of a period of intense mobility and complex social relationships between different cultural groups.

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