Refining Oxygen Isotope Analysis in the Nasca Region of Peru: An Investigation of Water Sources and Archaeological Samples

M. R. BUZON, a* C. A. CONLEE b AND G. J. BOWEN c

a Department of Anthropology, Purdue University, West Lafayette, IN, USA
b Department of Anthropology, Texas State University, San Marcos, TX, USA
c Department of Earth and Atmospheric Sciences and Purdue Climate Change Research Center, Purdue University, West Lafayette, IN, USA

ABSTRACT The development of complex societies, irrigation agriculture and sociopolitical transitions are of interest to researchers working in the Nasca region on the south coast of Peru. Occupied for thousands of years, many questions regarding the circumstances of these changes in the area are being investigated. Oxygen isotope analysis provides a method for exploring residential mobility of past peoples during these transitions. This study presents new δ18O data from water sources that would have been used by the ancient inhabitants, providing important information regarding the oxygen isotope variability in the region and the necessary baseline data for migration studies in this region. Our results suggest that the isotopic composition of water sources in the Nasca region is not highly variable. In addition, archaeological human tooth enamel samples from the sites of La Tiza and Pajonal Alto are analysed. The δ18Oc results of the human enamel samples confirm the local nature of the burial population, as suggested by previous strontium isotope analysis (87Sr/86Sr).

Introduction

The ancient inhabitants of the Nasca region of Peru first settled the area during the Archaic (9000–1800 BC) and over the next several thousand years developed complex societies, irrigation agriculture and interacted with foreign states and peoples. Through the excavation and analysis of settlements and cemeteries, researchers are continually expanding our understanding of how these changes occurred. Isotope analysis of human bone and tooth tissue has proven to be a productive method for investigating population movement during these times of sociopolitical transitions in various regions of the Andes (Knudson et al., 2004; Knudson & Price, 2007; Knudson, 2008; Tung & Knudson, 2008; Andrushko et al., 2009; Slovak et al., 2009; Turner et al., 2009). In the Nasca region strontium isotope analysis (87Sr/86Sr) has provided useful data for examining residential mobility, including the local nature of the trophy head-taking (Conlee, 2007; Knudson et al., 2009; Conlee et al., 2009).

This study uses oxygen isotope analysis (δ18O) as a complimentary method for determining the presence of nonlocal individuals in Nasca. The human samples used in this study come from the sites of La Tiza and Pajonal Alto in the southern Nasca drainage and date from the Early Intermediate through the Late Intermediate Period (AD 1–1476). Through the study of local Nasca area drinking water sources, in addition to archaeological human samples, we are able to refine our understanding of oxygen isotope variability in this region. Carbon isotope analysis is used in this study to understand dietary influences on δ18O values.

Oxygen and carbon isotopes in the Nasca valley

The composition of consumed water sources is reflected in oxygen isotope ratios of human body tissues (Longinelli, 1984), expressed as δ18O. Hydrological,
geographical and climatological factors affect water δ¹⁸O values (Dansgaard, 1964; Gat, 1996; Bowen et al., 2007). This study uses tooth enamel carbonate, which has shown to be useful in tracking residential mobility via oxygen isotope analysis in the Andean region, especially in combination with strontium isotope analysis (Tomczak, 2001; Turner et al., 2006; Knudson & Price, 2007; Slovak, 2007; Turner et al., 2009; Knudson, 2009; Knudson et al., 2009). In the southern Nasca drainage, the established local strontium isotope (⁸⁷Sr/⁸⁶ Sr) range based on archaeological and modern faunal materials is 0.70559–0.70727 (Conlee et al., 2009). Using this range, researchers determined that Nasca region burials were composed primarily of local individuals, including trophy heads (Knudson et al., 2009) and decapitated bodies. Two exceptions include individuals from La Tiza and Pajonal Alto that date to the Middle Horizon, a time of great change in Nasca society. Some portions of the southern valleys are devoid of surface water for the entire year. The rivers are called ‘influent streams’ because they flow partially on the surface as well as drop completely subsurface to the mid-altitude yunga. The chala is located below 500 meters above sea level (m.a.s.l.) and receives little to no rainfall. The yunga is located between 500–2300 m.a.s.l. Reference data for the isotopic composition of precipitation water in these regions are sparse. The observed average δ¹⁸O of meteoric water (δ¹⁸Oₘₗₑₜ) all meteoric water values are reported relative to V-SMOW) value for La Serena, Chile located some 1400 km to the south of Nasca at an elevation of 146 m, is −4.6‰, and similar values are found 400 km further to the south at the coastal site of Valparaiso, Chile average −4.0‰ (all data from IAEA/WMO, 2009). 1400 km to the north of Nasca, in southern Ecuador, sites within the chala elevation range have slightly higher values of −1.4‰ (Machala, 4 m elevation) to −3.9‰ (Uzhcurrumi, 290 m). The Ecuadorian sites receive much more precipitation, however, and are probably poorer analogues for conditions in the Nasca region. Within the yunga elevation zone, Santiago, Chile (520 m elevation, 1400 km south of Nasca) represents the only reasonably analogous collection site and has an average δ¹⁸Oₘₚₑₜ value of −4.5‰. Short-term (~1–3 year) precipitation monitoring data exists for approximately 40 high-elevation (2700–4550 m) sites in the western Andes within ~350–1000 km of Nasca (Aravena et al., 1999; IAEA/WMO, 2009), and show significantly lower δ¹⁸Oₘₚₑₜ values at most sites (~4.5 to ~23.2‰). These data are consistent in suggesting relatively high values, close to −4‰, for rainwater in the chala and lower yunga zones in which our study sites lie, with values likely decreasing steadily with altitude to very low values (< −10‰) in the high Andes. Previous work in northern Chile has attributed this variation with altitude to a decrease in the effect of Pacific-derived moisture on rainfall with increasing elevation and distance from the coast (Aravena et al., 1999).

Reconstructions of the paleoenvironment in the Nazca-Palpa region suggest changing conditions over time (Eitel et al., 2005). At the time of the earliest settlements in the region during the Archaic, the area experienced humid conditions. Aridification set in just...
before the Paracas Culture (800–200 BC). Increasing aridity by the Middle Nasca Period (after AD 250) may have contributed to the collapse of the Nasca civilisation. More humid conditions returned in the Late Intermediate Period (AD 1000–1400). Present arid conditions began subsequently in the 14th and 15th centuries (Eitel et al., 2005). This variable aridity must be kept in mind when using modern water samples to examine mobility of past humans. In particular for this study, samples dating to the Late Intermediate Period will reflect conditions that differ from those represented by the other ancient and modern samples and should be interpreted in relation to the modern water samples with caution. The potential effects of climatic change on the isotopic values during this interval could include decreases in the degree of evaporation of surface waters, leading to lower δ18O values, or increases in the amount of Pacific-sourced moisture, leading to higher δ18O values (although this effect remains controversial, e.g. Eitel et al., 2005; Magilligan et al., 2008).

Carbon isotope ratios of tooth enamel apatite reflect the isotope composition of whole dietary carbon sources (Ambrose & Norr, 1993; Tieszen & Fagre, 1993) and are expressed as δ13C values relative to the V-PDB standard. Carbon is assimilated by plants through one of three photosynthetic pathways (C₄, C₃, CAM), and tissues in plants using different pathways have distinct δ13C values. C₄ plants have higher δ13C values and C₃ plants have lower δ13C values (CAM plants are intermediate between C₄ and C₃; Bender, 1971; Smith & Epstein, 1971). For this study, carbon isotopes are used to investigate the local or non-local nature of an individual’s diet. An isotopic study of the local Nasca diet using bone collagen (Kellner and Schoeninger, 2008) reveals a wide range of food items, including maize (C₄ plant) with little incorporation of marine resources. The ingestion of chicha, maize beer, was likely an integral and endemic cultural practice for the Nasca people (Kellner & Schoeninger, 2008). The analysis of botanical remains from the Nasca area site of Pajonal Alto suggests that maize, followed by the lima bean, were the most common cultivated plants. Additional plant foods included other types of beans, peppers, huarango and fruit, such as pacay. Squash, tubers, yucca and sweet potato were also cultivated (Conlee, 2000).

One goal of this study is to begin to build the baseline δ18O data in the region with the inclusion of water samples from various sources in the Nasca area that would have been used by ancient inhabitants. These additional human samples and new water source data will allow for a preliminary interpretation of the possible presence of foreigners in the human samples in relation to the local δ18O water values and will provide important reference data for future studies. Another goal is to examine the evidence for past human mobility in the Nasca region by analysing human samples from the sites of La Tiza and Pajonal Alto in conjunction with published data. Based on previous isotope analyses (Conlee et al., 2009; Knudson, 2009; Knudson et al., 2009), we expect that the majority of human samples examined will not differ from the local isotopic signature.

### Materials and methods

Table 1 provides the sample number, material (including tooth type), location, date, sex and age for the samples used in this study. The samples analysed for this study include seven human tooth enamel samples from La Tiza and one human tooth enamel sample from Pajonal Alto. The size of this sample of human individuals is admittedly small. However, the sample represents all of the securely dated individuals for which we have tooth enamel at La Tiza and Pajonal Alto. The analysis of this group of individuals along with published data from other samples analysed in the region provides an indication of the variability at various sites in the Nasca area. In addition, eight modern water sources from the Nasca valley were sampled: Orcona puquio, Orcona pozo 1, Orcona pozo 2, Cahauchi river, Cahauchi pozo, Nasca modern irrigation ditch, Bisambra puquio (Nasca) and Cantal-loq puquio. As mentioned above, a puquio is an ancient horizontal well that taps subterranean river water. A pozo is a modern well that taps underground water. The analysis of these eight water samples is an important first step in understanding the variability in water sources in the Nasca region. Undoubtedly, future research will need to include additional water samples collected during various seasons and years in order to confirm our preliminary findings presented here.

La Tiza is located where the Aja and Tierras Blancas river valleys merge into the Nasca drainage (Figure 1). Human occupation at this site began in the Middle Archaic (ca. 3500 BC) and was inhabited intermittently until the Spanish conquest in AD 1532. La Tiza contains several domestic areas and cemeteries. The individuals included in this study were excavated in 2004, 2005 and 2006 and were located in a variety of contexts (Table 1). Sample 2 (Middle Horizon) was buried in a pit inside of a domestic structure with one intact ceramic vessel. Samples 3, 4 and 6 were all found in one large domestic structure (Late Intermediate Period), while sample 7 was buried in a pit in a structure...
Table 1. Oxygen, carbon and strontium isotope values for human tooth enamel and water samples

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Material</th>
<th>Location (date)</th>
<th>Age (years)</th>
<th>Sex</th>
<th>Latitude/longitude</th>
<th>Elevation(m)</th>
<th>δ18Oc(VPDB)</th>
<th>δ18Omw(VSMOW)</th>
<th>δ18Odw</th>
<th>δ13C(VPDB)</th>
<th>δ87Sr/86Sr</th>
<th>δ13CVPDB</th>
<th>87Sr/86Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>P4 (2–7)</td>
<td>La Tiza (MH)</td>
<td>30–40</td>
<td>M</td>
<td>-14.810631</td>
<td>700</td>
<td>-6.8</td>
<td>-10.0</td>
<td>-4.1</td>
<td>0.70640</td>
<td>74.901056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>P4 (2–7)</td>
<td>La Tiza (LIP)</td>
<td>25–35</td>
<td>F?</td>
<td></td>
<td></td>
<td>-5.0</td>
<td>-7.6</td>
<td>-7.2</td>
<td>0.70612</td>
<td>74.901056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>I1 (0–4)</td>
<td>La Tiza (LIP)</td>
<td>12–18 months</td>
<td>J</td>
<td></td>
<td></td>
<td>-6.5</td>
<td>-9.6</td>
<td>-7.0</td>
<td>0.70682</td>
<td>74.901056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>P4 (2–7)</td>
<td>La Tiza (LIP)</td>
<td>18 months</td>
<td>J</td>
<td></td>
<td></td>
<td>-6.4</td>
<td>-9.5</td>
<td>-6.8</td>
<td>0.70643</td>
<td>74.901056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>C (0–6)</td>
<td>La Tiza (EN)</td>
<td>45+</td>
<td>F</td>
<td></td>
<td></td>
<td>-7.1</td>
<td>-10.4</td>
<td>-6.7</td>
<td>0.70655</td>
<td>74.901056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>c (iu-1)</td>
<td>La Tiza (EN)</td>
<td>9–10</td>
<td>J</td>
<td></td>
<td></td>
<td>-7.6</td>
<td>-11.0</td>
<td>-8.0</td>
<td>0.70677</td>
<td>74.901056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>M1 (0–2.5)</td>
<td>La Tiza (MH)</td>
<td>25–35</td>
<td>F</td>
<td></td>
<td></td>
<td>-5.9</td>
<td>-8.8</td>
<td>-8.4</td>
<td>0.70747f</td>
<td>74.901056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>m2 (iu-1)</td>
<td>Pajonal Alto (MH)</td>
<td>3–5</td>
<td>J</td>
<td>-14.916733</td>
<td>565</td>
<td>-7.2</td>
<td>-10.5</td>
<td>-5.6</td>
<td>0.70770f</td>
<td>74.945303</td>
<td>74.916733</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Water</td>
<td>Orcona puquio</td>
<td>3–5</td>
<td>J</td>
<td>-14.810582</td>
<td>694</td>
<td>-11.1</td>
<td></td>
<td></td>
<td></td>
<td>74.892764</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Water</td>
<td>Orcona pozo 1</td>
<td>3–5</td>
<td>J</td>
<td>-14.808723</td>
<td>700</td>
<td>-11.5</td>
<td></td>
<td></td>
<td></td>
<td>74.89124</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Water</td>
<td>Orcona pozo 2</td>
<td>3–5</td>
<td>J</td>
<td>-14.811915</td>
<td>695</td>
<td>-12.3</td>
<td></td>
<td></td>
<td></td>
<td>74.89199</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Water</td>
<td>Cahauchi river</td>
<td>3–5</td>
<td>J</td>
<td>-14.769166</td>
<td>372</td>
<td>-11.5</td>
<td></td>
<td></td>
<td></td>
<td>75.12263</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Water</td>
<td>Cahauchi pozo</td>
<td>3–5</td>
<td>J</td>
<td>-14.816143</td>
<td>370</td>
<td>-12.1</td>
<td></td>
<td></td>
<td></td>
<td>75.11491</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Water</td>
<td>Nasca irrigation ditch</td>
<td>3–5</td>
<td>J</td>
<td>-14.8189945</td>
<td>598</td>
<td>-12.3</td>
<td></td>
<td></td>
<td></td>
<td>74.941315</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Water</td>
<td>Bisambra puquio</td>
<td>3–5</td>
<td>J</td>
<td>-14.82598</td>
<td>621</td>
<td>-12.0</td>
<td></td>
<td></td>
<td></td>
<td>74.929</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Water</td>
<td>Cantalop puquio</td>
<td>3–5</td>
<td>J</td>
<td>-14.826589</td>
<td>654</td>
<td>-12.6</td>
<td></td>
<td></td>
<td></td>
<td>74.91034</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Tooth type and position is indicated; upper case = permanent teeth, lower case = deciduous teeth; the parentheses indicated the time period of enamel crown development in years; iu = in utero.

b MH = Middle Horizon, LIP = Late Intermediate Period, EN = Early Nasca.

c M = Male, F = Female, F? = Possible Female, J = Juvenile, no sex determination.

d These values have not been corrected for the effects of breast milk consumed during the development of the teeth used.

e Determined to be non-local using strontium isotope analysis, Conlee et al., 2009.
with typical Nasca culture burial goods (Early Nasca), and sample 8 was a child placed in a wall (Early Nasca) with a fragment of a large polychrome ceramic vessel. These are all local burial types that have been documented throughout the Nasca region. In contrast, sample 9 was located in a looted above ground tomb that contained multiple individuals including a partial mummy bundle, and rich grave goods. This type of elite burial is new in the Middle Horizon and a large number of these tombs have been identified at La Tiza (Conlee, 2010; in review). Pajonal Alto is a small village located in the Taruga valley, the valley south of La Tiza. It was first occupied in the early Middle Horizon (AD 600) and then again in the Late Intermediate Period (AD 1300). Sample 10 is a child dated to the Middle Horizon, found underneath a midden that dated to the Late Intermediate and Late Horizon. Additional site and burial information is detailed in Conlee et al. (2009).

Tooth enamel is generally less susceptible to contamination than bone or dentine and is considered a dead tissue because it is not penetrated by any organic structures (Steele & Bramblett, 1988). Therefore, tooth enamel will reflect the isotope composition of the environment in which a person lived while the tooth was forming. Minerals may be taken up by the surface of the tooth during life or after burial, though these materials seldom penetrate deep into the enamel (Budd et al., 2000; Price et al., 2004; Wright, 2005). However, as a precaution, the teeth were mechanically cleaned and the surface abraded to remove contamination. These techniques have been shown to reduce some diagenetic contamination (Nielsen-March & Hedges, 2000). These samples were also assessed for contamination by measuring uranium concentrations (see results in Conlee et al., 2009). Uranium, which can reflect the uptake of groundwater (Hedges and Millard, 1995), is not normally found in skeletal tissues and should be below the equipment detection limit (i.e. 0.003 ppm—ICP-MS).

All stable isotope analyses were conducted using established protocols at the Purdue Stable Isotope Facility, Department of Earth and Atmospheric Sciences, Purdue University. For the oxygen and carbon isotope analysis, a tooth enamel sample was cut from the crown and pulp and dentine were removed. The human tooth enamel samples were lightly ground, treated with 5%NaOCl solution for 24 h, rinsed and freeze-dried prior to analysis (Vennemann et al., 2001). The oxygen and carbon isotope composition of hydroxyapatite carbonate was analysed using a ThermoFinnigan Delta V Isotope Ratio Mass Spectrometer (IRMS) following reaction with orthophosphoric acid and chromatographic isolation of CO₂ on a GasBench automated preparation device. Multiple analyses of a pure calcite reference material gave a reproducibility of ±0.04% for δ¹³C and ±0.06% for δ¹⁸O. Water samples were placed in GC vials and 0.3 µl aliquots were auto-injected into a Thermochemical Elemental Analyser (ThermoFinnigan). The injected water was pyrolysed under reducing conditions at 1400°C to produce H₂ and CO gases. These were separated chromatographically in a helium carrier gas stream and introduced sequentially into the ion source of a Delta V IRMS for isotope ratio determination (Gehre et al., 2004). Multiple sequential injections (5 or 6) were made for each sample and the reported values represent the average of the final 3–4 injections. All data obtained by either method were normalised to the VSMOW-SLAP scale through repeated analysis of 2 laboratory reference waters calibrated relative to VSMOW and SLAP (Coplen, 1996). The average analytical precision was approximately 0.3‰ for δ¹⁸O (1σ) based on the repeated analysis of a third reference water.

The oxygen isotope data are expressed in parts per thousand (‰) using the standard formula:

\[ \delta = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \times 1000 \]

Oxygen isotope ratios in bones and teeth can be measured in minerals, carbonate and phosphate. Phosphate is considered by some to be less affected.
by diaganesis (Luz & Kolodny, 1989), though more studies use carbonate. The following equation provides the relationship between phosphate and carbonate:

$$\delta^{18}O_{c,\text{VSMOW}} = (8.50\% + \delta^{18}O_{p,\text{VSMOW}})/0.98$$

(Jacumin et al., 1996).

Observed meteoric water (mw) samples are presented relative to V-SMOW. The oxygen isotope data from enamel are presented relative to V-PDB. The relationship between V-SMOW and V-PDB is demonstrated in the following equation:

$$\delta^{18}O_{c,\text{VSMOW}} = (1.03092 \times \delta^{18}O_{c,\text{VPDB}}) + 30.92\%$$

(Sharp, 2007).

Drinking water (dw) values were calculated from the enamel samples. The following equation was used:

$$\delta^{18}O_{dw} = (\delta^{18}O_{p,\text{VSMOW}} - 22.70)/0.78$$

(Luz et al., 1984).

Results and discussion

Oxygen isotope analysis

The results of the oxygen and carbon isotope analysis of archaeological human tooth enamel samples from La Tiza and Pajonal Alto and the water samples are provided in Table 1. The mean $\delta^{18}O_c$ value for the human enamel samples is $-6.6\%$ with values ranging from $-5.0\%$ to $-7.6\%$. The average $\delta^{18}O_{mw}$ value for the Nasca region samples is $-11.9\%$ with values ranging from $-11.1\%$ to $-12.6\%$. These values show relatively little variation and are much lower than those recorded for modern precipitation at sites with similar elevation. They are similar to values for modern precipitation within the western Peruvian Andes and are consistent with all surface and ground water samples being derived in part or in whole from higher-elevation precipitation falling under climate conditions similar to modern.

Evidence of human migration

The range of $\delta^{18}O$ values for the human tooth enamel is relatively narrow in comparison with other sites thought to include a considerable presence of nonlocal individuals (e.g. White et al., 2000; Hewitt et al. 2008; Knudson et al., 2009; Slovak et al., 2009). Two individuals, samples 3 and 9, have noticeably higher $\delta^{18}O_c$ values in comparison with the other human samples (Figure 2). Of these, sample 9, a female dating to the Middle Horizon period, was also identified as nonlocal using strontium isotope analysis (Figure 3; Conlee et al., 2009). Sample 3 was considered local using strontium isotope analysis; however, it is worth noting that its $^{87}\text{Sr}/^{86}\text{Sr}$ value was lowest of all human samples, possibly suggestive of a different geological origin (Figure 3). Given the age and sex of sample 3 (25–35 year old female), this individual may have married into the community from elsewhere. Strontium isotope analysis also identified sample 10, a Middle Horizon child, as nonlocal, but the enamel $\delta^{18}O_c$ value for this sample is not as distinctive as those of samples 3 and 9.

![Figure 2](image1.png)

Figure 2. Results of carbon and oxygen isotope analyses of human tooth enamel samples. Each sample is represented by its tooth type letter (upper case = permanent tooth, lower case = deciduous tooth, italic bold font = Pajonal Alto).

![Figure 3](image2.png)

Figure 3. Results of oxygen and strontium (Conlee et al., 2009) isotope analyses of human tooth enamel samples. Each sample is represented by its tooth type letter (upper case = permanent tooth, lower case = deciduous tooth, italic bold font = Pajonal Alto).
values of this sample are similar to other human samples in our dataset. Overall, the oxygen isotope analysis in combination with the published Sr isotope data does not suggest substantial mixing of individuals from areas characterised by contrasting δ^{18}O or 86Sr/87Sr values.

Weaning

It is important to note that all of the teeth used in the study (Table 1) formed before or during the weaning process. The enamel crowns of premolars develop between about 2–7 years (Hillson, 1996), the time during which breast milk is likely being supplemented by solid foods but weaning is not complete (Wright & Schwarcz, 1998). The permanent canine crown also forms during this time (although begins development earlier); the permanent first molar, deciduous canine and deciduous second molar all develop during the time before weaning. Breast milk is generally enriched in δ^{18}O relative to drinking water (Roberts et al., 1998). Thus, the δ^{18}O values presented here are likely higher than those for teeth that developed after weaning was complete. Wright and Schwarcz (1998) found that third molars, which develop after weaning, had δ^{18}O values 0.6‰ lower, on average, than premolars.

Similarly, the equation used to estimate drinking water values from the measured δ^{18}O data is based on studies of post-weaning teeth, and δ^{18}O_{dw} estimates derived based on our samples are likely to be somewhat higher than the true values of local drinking water. It is important, however, to note that the timing, nature and rate of supplementation and weaning are highly variable within and between populations (e.g. Schurr, 1998).

Oxygen isotope variability in the Nasca coastal region

The human enamel δ^{18}Oc values from La Tiza and Pajonal Alto, with an average value of −6.6‰ ± 0.8‰, are similar but generally higher than values from other sites in the region (Knudson, 2009; Knudson et al., 2009). Knudson et al. (2009) reported δ^{18}Oc values for individuals from five sites in the Nasca valley (Figure 4): Cahauchi at −7.9‰ ± 1.9‰ (n = 16), Cantayo at −7.4‰ ± 2.9‰ (n = 6), Majoro Chico at −7.8‰ ± 1.9‰ (n = 5), Aja at −9.1‰ (n = 1), and Paredones at −8.5‰ (n = 1). These samples also show more variability than those in the current study. Knudson et al. (2009) attribute the variability to use of enamel samples from both pre-weaning and post-weaning teeth (in addition to
temporal and spatial differences). In comparison to Knudson et al.’s (2009) mean $\delta^{18}$O$_c$ value for the (pre-weaning) first molar ($-7.2\% _{\circ}$ ± 2.2\%), the present study’s mean $\delta^{18}$O$_c$ value is still higher and less variable. Both the samples in the current study and Knudson et al.’s (2009) include individuals from various time periods. Although we have highlighted two possible migrant individuals from La Tiza with higher $\delta^{18}$O$_c$ values, the variability in Knudson et al. (2009) study is suggestive of a higher frequency of nonlocal individuals.

The calculated mean $\delta^{18}$O drinking water value for La Tiza/Pajonal Alto is $-9.7\% _{\circ}$ ± 1.1\% , with the two possible immigrants removed, the mean $\delta^{18}$O$_{dw}$ value is $-10.1\% _{\circ}$ ± 0.6\%. Assuming a correction of $-0.6\% _{\circ}$ (Wright & Schwarcz, 1998) for the effect of breast milk on the pre-weaning $\delta^{18}$O$_c$ values, the estimated average drinking water values become $-10.3\% _{\circ}$ and $-10.7\% _{\circ}$ (all samples and possible immigrants removed, respectively). The mean $\delta^{18}$O$_{mw}$ value of our Nasca region valley water samples is $-11.9\% _{\circ}$ ± 0.5\%. The slightly higher calculated $\delta^{18}$O$_{dw}$ value in comparison to the mean $\delta^{18}$O$_{mw}$ value may be the result of a number of factors. Any above-ground storage of water in the Nasca region would have led to evaporation, resulting in an increase in $\delta^{18}$O values (Gat, 1996). Also, plant and animal foods from very arid environments, such as the Nasca region, might be $^{18}$O-enriched due to high rates of transpiration and transcutaneous water loss (West et al., 2008). In addition, bone collagen studies on regional samples (Kellner & Schoeninger, 2008) and botanical studies (Conlee, 2000) suggest that chicha was commonly consumed. The production of this maize beer includes boiling, which would result in higher $\delta^{18}$O values. The storage of this beverage during the lengthy fermentation process in open-air cisterns or other containers may also have resulted in evaporation. It has been suggested that the use of chicha increased during the Late Intermediate Period in some areas (Hastorf & Johannessen, 1993). The three LIP samples from La Tiza have higher $\delta^{18}$O$_c$ values than the others, on average, and one possible explanation for this could involve increased use of chicha with elevated $\delta^{18}$O values.

Knudson (2009) indicates that mean $\delta^{18}$O$_{dw}$ values for the Nasca tooth and bone samples are much lower than expected based on observed $\delta^{18}$O$_{mw}$ values in the chala and yunga zones. The observed $\delta^{18}$O$_{mw}$ values for the modern water sources reported by Knudson (2009), however, are outside of the Nasca valley. Using post-weaning third molars and bone, Knudson’s (2009) mean $\delta^{18}$O$_{dw}$ value is $-13.2\% _{\circ}$ ± 1.5\% (n = 6). In comparison to our water samples collected from sources likely consumed by ancient Nasca region residents ($\delta^{18}$O$_{mw}$ = $-11.9\% _{\circ}$ ± 0.8\%), Knudson’s (2009) $\delta^{18}$O$_{dw}$ values are only slightly lower. The presence of nonlocal residents may account for this lower mean $\delta^{18}$O$_{dw}$ value.

**Carbon isotope analysis**

The mean $\delta^{13}$C$_c$ value for our human tooth enamel samples is $-6.7\% _{\circ}$, with a wide range of values from $-4.1\% _{\circ}$ to $-8.4\% _{\circ}$ (Figure 2). C$_4$ metabolic pathway plants demonstrate $\delta^{13}$C$_c$ values = $-9\% _{\circ}$ to $-14\% _{\circ}$, C$_3$ metabolic pathway plants demonstrate $\delta^{13}$C values = $-20\% _{\circ}$ to $-35\% _{\circ}$ (Tieszen and Chapman, 1992); the $\delta^{13}$C$_c$ values from tooth enamel reflect the carbon isotopic composition of the entire diet + 9.4\% (Ambrose & Norr, 1993). Consequently, the values from La Tiza and Pajonal Alto suggest a diet of primarily C$_4$ sources. The documented botanical remains found at Pajonal Alto (Conlee, 2000) and isotopic studies of Nasca region burials (Kellner & Schoeninger, 2008) confirm the importance of maize in the diet. The two individuals with higher $\delta^{18}$O$_c$ values (samples 3 and 9) have slightly lower $\delta^{13}$C$_c$ values. As mentioned above, the teeth used in this study likely reflect a diet before weaning was complete. Wright and Schwarcz (1998) found that, on average, enamel $\delta^{13}$C$_c$ becomes higher with increasing age, with most of the shift occurring by the age of three (in their sample from the site of Kaminaljuyu in Guatemala). Thus, the mean $\delta^{13}$C$_c$ values presented here for pre-weaned teeth may be slightly lower than the mean adult diet value for this sample. In comparison with other regional samples, the mean $\delta^{13}$C$_c$ value is lower (ranging from $-7.1\% _{\circ}$ to 8.5\%, Knudson et al., 2009). Knudson et al. (2009) use various teeth in their study, including some third molars (post-weaning), which may account for the higher values documented.

**Conclusions**

This study has explored the oxygen isotope variability in water sources as well as archaeological human tooth enamel samples in the Nasca region of Peru. The eight water samples analysed reveal relatively low variability in oxygen isotope values. The analysis of samples from human tooth enamel from La Tiza and Pajonal Alto confirm the overall local nature of the population interred at these sites. The calculated $\delta^{18}$O$_{dw}$ values for these sites are higher than the $\delta^{18}$O$_{mw}$ values of the tested water sources. This difference may be accounted for by factors such as $^{18}$O-enrichment of breast milk.
and foods from very arid environments as well the consumption and storage of chicha, a boiled beverage. Studies of other samples from the Nasca region (Knudson, 2009) show a larger range of δ18Oc values, suggesting the inclusion of non-local individuals. This analysis of drinking water sources has provided important preliminary data needed for the examination of ancient mobility in the Nasca region.

Acknowledgements

Work at La Tiza was funded by a National Science Foundation Grant BCS-0314273, the H. John Heinz III Fund Grant Program for Latin American Archaeology and the Research Enhancement Program at Texas State University. Research at Pajonal Alto was supported by a National Science Foundation Dissertation Improvement Grant, and a Humanities and Social Science Grant from the University of California, Santa Barbara. Permission to excavate at La Tiza and Pajonal Alto was granted by the Instituto Nacional de Cultura de Peru. A great deal of thanks goes to all of the participants of Proyecto La Tiza 2002–2008 and Proyecto Pajonal Alto 1997 who aided in the excavation of these burials. We appreciate the help that Aldo Noriega and Sarah Cross provided in the collection of water samples. This is Purdue Climate Change Research Center paper #0926. [Correction made here after initial online publication.]

References


