Assessing the Life History of an Andean Traveller through Biogeochemistry: Stable and Radiogenic Isotope Analyses of Archaeological Human Remains from Northern Chile

K. J. KNUDSON, W. J. PESTLE, C. TORRES-ROUFF, AND G. PIMENTEL

ABSTRACT

Bioarchaeology and biogeochemistry can elucidate aspects of individual life histories that are often lost in the archaeological record. Here, we use stable and radiogenic isotope analyses of enamel, bone and hair to reconstruct paleodiet and paleomobility in an adult male interred along a pre-Columbian route connecting the northern Chilean coast to the inland Loa River Valley. Although this well-preserved burial included mortuary goods typical of coastal cultures, it was discovered in a vast, uninhabited part of northern Chile’s hyper-arid Atacama Desert. Variation in carbon and nitrogen isotopes reflects dietary differences, while strontium and oxygen isotopes vary geologically and geographically. We use these data to examine paleodiet and paleomobility and to assess whether this was a coastal traveller seeking provisions from the interior or vice versa. Enamel stable isotope analysis is consistent with the consumption of a mixture of terrestrial and marine resources during the first years of life. Bone stable isotope analyses indicate habitual consumption of marine foodstuffs over the last 10–30 years of this individual’s life. Interestingly, stable isotope analysis of hair samples provides more fine-grained information on this individual, suggesting movements between the coast and highlands in the months before his death. Radiogenic strontium isotope data are consistent with residence on the coast or in the Atacama Desert, but are lower than strontium isotope values from higher altitudes. These dietary and geological patterns are reconcilable with coastal residency; the isotopic data are consistent with foodstuffs and textiles found with the burial. Therefore, we argue that this individual was regularly moving from the coast to inland areas, crossing the hyper-arid Atacama Desert by following strategic interzonal routes that provided access to particular resources. Copyright © 2010 John Wiley & Sons, Ltd.

Key words: Atacama Desert; carbon isotopes; Late Formative Period; nitrogen isotopes; oxygen isotopes; strontium isotopes

Introduction

An important strength of bioarchaeological research is its ability to elucidate the lives of individuals who lived in the past. By combining biogeochemistry and bioarchaeology, scholars can examine the different events of an individual’s life history, including paleodiet and paleomobility. Here, we use stable and radiogenic isotope data from enamel, bone and hair to reconstruct paleodiet and paleomobility in an adult male interred along a Late Formative Period (AD 1–500) route connecting the northern Chilean coast to the Loa River Valley (Figure 1). This well-preserved burial was found in a vast and uninhabited part of the hyper-arid Atacama Desert of northern Chile. Given the
extremely isolated location of this interment, a
determination of the individual's geographic origins
will help reconstruct not only the movements made
over his lifetime but also provide some insight into the
use of interzonal routes across the Atacama.

Here, we first introduce the archaeological and
bioarchaeological context of this individual and the
interzonal routes of the Chilean Atacama. This is
followed by a brief discussion of the role of the
individual in bioarchaeological research and the use of
biogeochemistry to reconstruct individual life
histories. We then present our sampling strategy,
laboratory methods and results from stable and
radiogenic isotopic analyses of archaeological human
enamel, bone and hair samples and discuss our
interpretations of these data, addressing diagenetic
contamination as identified through trace element
concentrations, C:N values and elemental yields. We
then put forward our interpretations of paleodiet and
diagenetic contamination as identified through trace element
paleomobility in more detail. Finally, we conclude with
a discussion of this individual's movements and assess
the way that a life history perspective not only serves to
elucidate the life of a single person, but also helps to
explore the nature of population movement in the Late
Formative Period.

**Trade routes of the ancient Atacama
Desert**

Exploring an individual's history will allow us a more
nuanced view into the life of a pre-Columbian Andean
traveller who died and was buried in a vast expanse of
desert as he moved between the coast and the interior
of the Chilean Atacama Desert. The pervasive notion
of Andean llama caravans, large trade networks and
transhumance has been a staple in the archaeology of
this region for decades (e.g. Murra, 1972; Murra, 1985;
Núñez & Dillehay, 1995; Van Buren, 1996). However,
we argue here that this traditional model does not
account for all of the ways in which ancient Andean
peoples moved across the landscape. The Late
Formative Period in the south central Andes is
characterised by a variety of different types of human
mobility (Pimentel *et al.*, 2010a, 2010b) including, we
argue, at least two distinct, albeit occasionally
simultaneous, modalities. More specifically, one type
of mobility focused on large llama caravans that
brought caravaneers from large oases in the interior to
the coast; the main goal of individuals engaged in this
Caravan Mode of mobility was trade and exchange. In
contrast, a second type of movement that existed
during the Late Formative Period in Chile focused on
small-scale mobility conducted by people living on the
coast; in this Coastal Mode of mobility, individuals
travelled to the interior without beasts of burden to
obtain resources and raw materials not available on the
coast, including high quality material for stone tools or
particular plants such as *algarrobo* (*Prosopis* spp.). In
other words, the use of Coastal Mode logistical routes
would not preclude trade and exchange; however, their
defining feature was provisioning individuals and
groups with specific goods that were unobtainable in
the home region (Pimentel *et al.*, 2010a, 2010b). While
common in many parts of the world, models of seasonal mobility or transhumance where groups moved between different residential bases are not supported by the archaeological survey data.

The individual considered here (A299) was found along one of these interzonal Coastal Mode routes (Figures 1 and 2), in an area of desert along the lines of what Nielsen (2006) has defined as an internodal space, an area between larger nuclei in a network of interaction. Excavations were conducted in 2006 as part of an environmental impact assessment in the Region of Antofagasta, northern Chile. Survey of a 225 km$^2$ area documented a series of pre-Columbian routes, waystations, lithic scatters and other archaeological sites in the Depresión Intermedia, an area of expansive desert between the Loa River and the coast. Among these finds was an isolated burial in the open desert (Cases et al., 2008; Pimentel et al., 2010b). This individual was laid in an extended position in a shallow depression near one of the interzonal routes and covered with stones. Bioarchaeological analyses conducted by Christina Torres-Rouff demonstrated that this individual was a young adult male, approximately 28–35 years old at the time of his death. The nearly complete skeletal remains ranged from very well preserved to bleached and fragmented depending on the degree of exposure. He was buried with a series of camelid and vegetable fibre textiles including small bags, a fishhook, the partial remains of dried or smoked fish, as well as algarrobo seeds and feathers (Cases et al., 2008: p. 55). Radiocarbon dates from textiles found with the burial yielded dates of 1890 ± 40 BP and 1870 ± 40 BP (Cases et al., 2008: p. 59). Once calibrated (SHCAL04), these dates have two-sigma ranges of AD 73–321 and AD 84–330 showing remarkable consistency and placing individual A299 squarely in the Late Formative Period.

The discovery of this individual in the midst of the Atacama raised questions about traffic and information flows in the Late Formative Period. Archaeological research demonstrated a mix of artefacts from coastal and interior regions. For example, the construction of a vegetable fibre, loop-stitch bag with accompanying miniaturised version suggests a coastal origin (Cases et al., 2008: p. 60), while ceramics found in the same area of the route are from the interior Loa River Valley (Cases et al., 2008: p. 65). While this solidified interpretations of this individual as a traveller, it did not clearly situate him as originating in either domain. Tying these data together with other evidence, Cases et al. (2008) argue that A299 likely had a coastal origin along with strong ties to the interior. Through our biogeochemical analyses, we hope to contribute to ongoing conversations about interzonal routes, specialised traffic, and the origins and motives of individuals found in internodal spaces.

A bioarchaeology of the individual

While much contemporary bioarchaeological research is focused on populations, analyses at the level of the individual move beyond generalisations about people to understand the life, death and surroundings of the persons that comprised a group. Stodder & Palkovich (2007: p. 226) argue for the necessity of 'complementing population studies with the contextualised interpretation of the lives of specific people in prehistory'. Following recent archaeological theory (e.g. Hodder, 2000; Fowler, 2004), a focus on the person allows for interpretations that more fully consider the role of individual agency in prehistory. Consideration of events over the course of life (e.g. Gilchrist, 2000) can also elucidate the varied experiences of an individual life and in the moments surrounding their death and burial. Clark & Wilkie (2006: p. 333), for example, state that 'one way to construct multidimensional archaeological interpretations is to create archaeologies that recognise finer grains of social difference', and they call these constructions an ‘archaeology of personhood’, which considers the individual and the lived experience.

Here we employ biogeochemical research to provide a view across the life of one individual. The insight provided through these analyses should allow us to address broader questions such as place of origin, but also provide a more detailed consideration of mobility and diet more generally, as well as near the end of life. This analysis at the small-scale considers the actions of an individual and their relationship not only to narrow factors in their immediate surroundings at a given moment, but also the role and responses of an
Life history analysis through biogeochemistry

Paleodiet and paleomobility through biogeochemistry

Stable and radiogenic isotope analysis can be used to reconstruct both paleodiet and paleomobility over the course of an individual’s lifetime. For paleodietary analysis, stable isotopes of carbon and nitrogen are the most widely used isotopic systems. Briefly, stable carbon isotopes in plants vary according to photosynthetic pathway. Most terrestrial plants (including most cereals, legumes, vegetables, nuts, and fruits) use a C₃, or Calvin, photosynthetic pathway, while tropical grasses like maize (Zea mays) use the C₄, or Hatch-Slack, photosynthetic pathway, and cacti and succulents use the CAM (Crassulacean Acid Metabolism) pathway (Calvin & Benson, 1948; Ranson & Thomas, 1960; Kortshack et al., 1965; Hatch & Slack, 1966; Hatch et al., 1967). Carbon isotope values also differ significantly between organisms from marine versus terrestrial ecosystems as a consequence of dramatic differences in the carbon sources of these two reservoirs (Chisholm et al., 1982; Schoeninger & DeNiro, 1984). Stable nitrogen isotopes vary in a fairly predictable manner according to trophic level and are particularly useful for identifying marine food consumption given clear differences in marine and terrestrial organisms’ nitrogen isotope values (DeNiro & Epstein, 1981; Schoeninger et al., 1983; Minagawa & Wada, 1984; Schoeninger & DeNiro, 1984), although there are also climatic factors that affect nitrogen isotope values (Ambrose & DeNiro, 1987; Ambrose, 1991). While the carbon isotope values in hydroxyapatite reflect the carbon sources in the whole diet, carbon and nitrogen isotopes in bone collagen overwhelmingly reflect the carbon in dietary protein sources (Ambrose & Norr, 1993; Jim et al., 2004; Kellner & Schoeninger, 2007). Stable carbon and nitrogen isotopes in hair keratin also primarily reflect the isotopic values of the carbon and nitrogen sources in the protein portion of the diet (Macko et al., 1999; O’Connell & Hedges, 1999a, 1999b; O’Connell et al., 2001).

Stable and radiogenic isotopes of oxygen and strontium are widely used for paleomobility (see overviews in Bentley, 2006; Price, 2008; Knudson, 2009). Briefly, stable oxygen isotope analysis relies on the variability of oxygen isotopes caused by environmental differences because water molecules that contain ¹⁶O will evaporate more readily than water molecules that contain the heavier isotope of oxygen, ¹⁸O (Fry, 2007; Sharp, 2007). This ensures that oxygen isotope values in precipitation (δ¹⁸Oᵥw) increases with decrease in altitude, decrease in distance from the coast, decrease in latitude and increase in temperature (Epstein & Mayeda, 1953; Craig, 1961a; Dansgaard, 1964; Gat, 1996; Koch, 1998; Bowen & Wilkinson, 2002). In contrast, radiogenic strontium isotopes vary according to bedrock age and initial composition (Faure, 1986), and do not fractionate appreciably as the strontium moves through an ecosystem to plants and their consumers’ tissues (e.g. Blum et al., 2000), unlike the mass-dependent fractionation seen in the stable strontium isotope system (Knudson et al., 2010). If an individual consumed the majority of the strontium in her or his diet from local sources, the radiogenic strontium isotope value (³⁸Sr/³⁶Sr) in her or his hydroxyapatite will reflect the radiogenic strontium isotope value in the plants, animals and water that she or he consumed, which in turns reflects the radiogenic strontium isotope value of the bedrock in that region (Ericson, 1985; Price et al., 1994; Bentley, 2006).

A life history approach to paleodiet and paleomobility

Biological tissues that formed at different times will reflect the isotopic values of the foods consumed and water imbibed at various times in an individual’s life, enabling scholars to examine paleodiet and paleomobility throughout an individual’s lifetime using isotopic data in different biological tissues (Sealy et al., 1995). Enamel begins to form in utero, with the mineralisation of the first molar (Gleiser & Hunt, 1955; Hillson, 1996). Enamel formation continues until the third molar mineralises approximately 15–25 years after birth, although third molar formation times are highly variable (Hillson, 1996; Olze et al., 2006; Harris, 2007). Most studies that utilise human enamel use bulk samples that reflect a few years of enamel formation...
While enamel reflects the first years of life, bone isotopic values reflect the years preceding an individual’s death since bone remodels. Bone remodelling rates also can vary widely based on the skeletal element, type of bone and age, sex and activity levels (e.g. Mulhern & Van Gerven, 1997; Courteix et al., 1999, Mulhern, 2000; Cho et al., 2006). Analysing samples from bones with different remodelling rates can provide paleodiary and paleomobility data from different periods in an individual’s life (Sealy et al., 1995, Katzenberg, 2000).

Since human hair grows an average of 1 cm per month (Valkovic, 1988; Randall & Ebling, 1991), hair samples can provide very fine-grained data on paleodiet and paleomobility in the weeks before death. Modern hair studies have investigated turnover rates and the correlation between hair and dietary composition (e.g. Fuller et al., 2005; Williams, 2007). In archaeology, isotopic analyses of human hair have been used in paleodiary studies (e.g. Roy et al., 2005; Knudson et al., 2007; Richards et al., 2007). While archaeological paleodiary studies of one individual (White et al., 2009b) are less common, modern human hair is increasingly used to investigate mobility (e.g. O’Brien & Wooller, 2007; Ehleringer et al., 2008).

Lack of preservation, funds or time can make reconstructing individual life histories through biogeochemistry difficult. However, when possible, reconstructions of individual life histories in the archaeological record can provide valuable information. Although rare compared to larger studies of mortuary populations using bulk analyses of bone or enamel, isotopic analyses of multiple biological tissues from one individual have been successfully utilised in different regions (e.g. Sealy et al., 1995; Torres-Rouff & Knudson, 2007; Wilson et al., 2007; White et al., 2009a).

**Paleodiet and paleomobility in the Andes: Baseline isotopic data**

The Andes are an ideal region for reconstruction of paleodiary and paleomobility because of the geologic and geographic variability. Both C₃ and C₄ plants were regularly consumed in the Andes, and the isotopic values of these plants and the dietary consequences of their consumption have been elucidated in a number of Andean regions (e.g. Hastorf, 1990; Tykot & Staller, 2002, Falabella et al., 2008; Kellner & Schoeninger, 2008; Finucane, 2009; White et al., 2009b). The most commonly consumed C₄ plant in the Andes, maize (Zea mays), exhibits a δ¹³C(V-PDB) of between −10 and −14‰ in both modern and archaeological samples (DeNiro & Hastorf, 1985; Tieszen & Chapman, 1992; Horn et al., 2009). Commonly consumed C₃ plants in the Andes include beans (Phaseolus spp.), squash (Cucurbita spp.) and potatoes (Solanum spp.); these C₃ plants exhibit much more depleted carbon isotope values of δ¹³C(V-PDB) of −22 to −29 ‰ (DeNiro & Hastorf, 1985; Tieszen & Chapman, 1992; Horn et al., 2009). In the Andean Atacama Desert, terrestrial mammals such as llamas (Lama glama) and alpacas (Lama pacos) averaged a δ¹³C(V-PDB) of −22‰ (Tieszen & Chapman, 1992); similar δ¹³C(V-PDB) values were obtained from modern camelids in central Peru (Schoeninger & DeNiro, 1984). However, some archaeological camelid populations consumed more C₄ or even marine resources (see examples in Burger & van der Merwe, 1990, Finucane et al., 2006; Izeta et al., 2009). Finally, marine resources in the Andean region exhibit carbon isotope values that are between the values seen for C₃ and C₄ plants, averaging δ¹³C(V-PDB) of −15.02‰ (Tieszen & Chapman, 1992).

In contrast, as a consequence of both enriched δ¹⁵N(AIR) values at the basal end of the food chain and the generally longer trophic chains seen among marine organisms, marine species and individuals that eat marine foods tend to exhibit more enriched δ¹⁵N(AIR) values than do their terrestrial counterparts (Schoeninger et al., 1983; Minagawa & Wada, 1984; Schoeninger & DeNiro, 1984). However, hot, arid environments can also exhibit enriched δ¹⁵N(AIR) values (Ambrose & DeNiro, 1987; Ambrose, 1991). For this reason, it is particularly important to use data from the arid Chilean Atacama and surrounding coast as baseline nitrogen isotope data. For example, marine organisms from the Pacific Ocean off of northern Chile exhibit elevated δ¹⁵N(AIR) values of +17.9‰ in invertebrates, +18.0‰ in vertebrates, and +19.2‰ in fish, all of which far exceed any of the δ¹⁵N(AIR) values seen for regional terrestrial species (Tieszen & Chapman, 1992). Similar trends in marine δ¹⁵N(AIR) enrichment are also apparent in the central Chilean coast (Hückstädt et al., 2007). Given the richness and diversity of marine resources off the northern Chilean coast, marine resources may have been an important part of the diet, as in other coastal regions (e.g. Tomczak, 2003; Knudson et al., 2007; Horn et al., 2009; White et al., 2009b). While terrestrial resources in the arid coast and highlands are expected to be enriched, analyses of terrestrial mammals demonstrate that the terrestrial resources are significantly depleted compared to the marine resources, and δ¹⁵N(AIR) values

Copyright © 2010 John Wiley & Sons, Ltd.
range from +4.7‰ to +5.7‰ (Tieszen & Chapman, 1992).

Extreme distances in altitude and hydrologic systems ensure that oxygen isotope values in precipitation vary widely in the Andes, although the movement of surface water throughout the Andes as well as human consumption patterns can complicate its use in archaeological paleomobility studies (Knudson, 2009). However, there are large differences in elevation, amounts of precipitation and amounts of glacial ice when comparing the coast, Atacama Desert, and the highlands of the altiplano (Messerli et al., 1993; Wolfe et al., 2001; Núñez et al., 2002; Houston, 2006).

For example, precipitation, or meteoric water, collected between 1998 and 2002 in coastal La Serena, Chile, exhibited $\delta^{18}O_{\text{mw(VSMOW)}} = -5.6 \pm 2.3\%$ (1σ, n = 16) (IAEA/WMO, 2006). In contrast, precipitation collected between 2001 and 2002 in altiplano Puno, Peru exhibited $\delta^{18}O_{\text{mw(VSMOW)}} = -13.3 \pm 5.3\%$ (1σ, n = 20) (IAEA/WMO, 2006). Oxygen isotope signatures in ground water from the Salar de Atacama and the altiplano are also quite different (Boschetti et al., 2007; Nester et al., 2007, see also Quade et al., 2000). Finally, there is no evidence of significant differences between current climatic conditions in these regions and the paleoclimate approximately two thousand years ago (Messerli et al., 1993; Núñez & Grosjean, 1994, Betancourt et al., 2000; Bobst et al., 2001; Núñez et al., 2002).

Radiogenic strontium isotope values vary geologically (Faure, 1986). The Atacama Desert is located in a geologic zone composed largely of late Cenozoic volcanic rocks like andesites (Hawkesworth et al., 1982; James, 1982, O’Callaghan & Francis, 1986; Rogers & Hawkesworth, 1989). Exposed bedrock samples from the region exhibit mean $^{87}\text{Sr}/^{86}\text{Sr} = 0.70646 \pm 0.00020$ (1σ, n = 8) (Rogers & Hawkesworth, 1989) and $^{87}\text{Sr}/^{86}\text{Sr} = 0.70653 \pm 0.00036$ (1σ, n = 16) (Francis et al., 1977); similar values are present in groundwater from the Salar de Atacama (Boschetti et al., 2007). Biologically available strontium isotope values in the San Pedro de Atacama region were determined from modern and archaeological small mammal samples, which exhibit mean $^{87}\text{Sr}/^{86}\text{Sr} = 0.70764 \pm 0.00013$ (1σ, n = 3) (Knudson & Price, 2007). In contrast, $^{87}\text{Sr}/^{86}\text{Sr}$ values are much higher in the neighbouring altiplano (Grove et al., 2003). For example, biologically-available radiogenic strontium isotope values in faunal samples from the Tiwanaku Valley of Bolivia’s Lake Titicaca Basin exhibit mean $^{87}\text{Sr}/^{86}\text{Sr} = 0.70963 \pm 0.00028$ (1σ, n = 8) (Knudson & Price, 2007). On the northern and central Chilean coast, radiogenic strontium isotope data show that values are similar to data from the Atacama Desert (Parada et al., 1999, Kramer et al., 2005). However, coastal radiogenic strontium isotope values may be influenced by seawater, in which $^{87}\text{Sr}/^{86}\text{Sr} = 0.7092$ (Veizer, 1989), either through the consumption of marine resources or through sea spray (Whipkey et al., 2000).

## Laboratory methods

### Sampling strategy

Samples were collected in order to provide as much information about paleodiet and paleomobility throughout this individual’s lifetime (Tables 1 and 2). Enamel samples were collected in order to understand paleomobility during the first years of this individual’s life, since permanent tooth enamel begins to form in utero and continues through the childhood, depending of the tooth in question (see Hillson, 1996). Unfortunately, the enamel fragments excavated and used for analysis could not be definitively identified as to tooth type; while the tooth enamel formed earlier than the bone samples collected, there may be some overlap between the periods during which the enamel formed and the life span of this individual.

### Table 1. Isotopic data from archaeological human hair samples

<table>
<thead>
<tr>
<th>Laboratory Number</th>
<th>Distance from scalp (cm)</th>
<th>Wt % C</th>
<th>Wt % N</th>
<th>Atomic C:N</th>
<th>$\delta^{13}\text{C}_{\text{ker}(V-PDB)}$ (%)</th>
<th>$\delta^{15}\text{N}_{\text{ker}(AIR)}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-58-1</td>
<td>0-2</td>
<td>45.3</td>
<td>14.6</td>
<td>3.6</td>
<td>-13.1</td>
<td>24.0</td>
</tr>
<tr>
<td>F-58-2</td>
<td>2-4</td>
<td>45.1</td>
<td>14.5</td>
<td>3.6</td>
<td>-12.3</td>
<td>24.2</td>
</tr>
<tr>
<td>F-58-3</td>
<td>4-6</td>
<td>45.6</td>
<td>14.7</td>
<td>3.6</td>
<td>-13.1</td>
<td>24.1</td>
</tr>
<tr>
<td>F-58-4</td>
<td>6-8</td>
<td>44.9</td>
<td>14.3</td>
<td>3.7</td>
<td>-15.8</td>
<td>24.6</td>
</tr>
<tr>
<td>F-58-5</td>
<td>8-10</td>
<td>44.4</td>
<td>14.1</td>
<td>3.7</td>
<td>-16.3</td>
<td>22.2</td>
</tr>
<tr>
<td>F-58-6</td>
<td>10-12</td>
<td>44.2</td>
<td>13.8</td>
<td>3.7</td>
<td>-16.0</td>
<td>18.4</td>
</tr>
<tr>
<td>F-58-7</td>
<td>12-14</td>
<td>44.8</td>
<td>14.2</td>
<td>3.7</td>
<td>-16.5</td>
<td>17.1</td>
</tr>
<tr>
<td>F-58-8</td>
<td>14-16</td>
<td>44.8</td>
<td>14.2</td>
<td>3.7</td>
<td>-16.0</td>
<td>19.9</td>
</tr>
<tr>
<td>F-58-9</td>
<td>16-18</td>
<td>44.2</td>
<td>14.2</td>
<td>3.6</td>
<td>-14.8</td>
<td>23.7</td>
</tr>
<tr>
<td>F-58-10</td>
<td>18-20</td>
<td>44.3</td>
<td>14.3</td>
<td>3.6</td>
<td>-15.4</td>
<td>23.4</td>
</tr>
</tbody>
</table>
and bone formed. Bone collagen was collected from a tibia fragment in order to understand paleodiet during the last year before death. Femoral collagen turnover is approximately 1.5–3.0% per year for adult males (Hedges et al., 2007); similar turnover rates would be expected for the tibia. Bone hydroxyapatite samples were collected from a tibia and a rib, which will provide paleodiet and paleomobility information from the last years of life. Cortical bone turnover rates are approximately 2% per year in the tibia and approximately 4% per year in ribs (Carr et al., 1962; Kulp & Schulert, 1962; Parfitt, 1983; Mulhern, 2000). In addition, hair samples were collected in order to determine paleodiet during the last months before death (see Sandford & Kissling, 1993; Macko et al., 1999). Finally, modern plants (Schinus molle, Acacia sp.) were collected from the inland Atacama Desert region and burial site to provide baseline data on the radiogenic strontium isotopic values in the region (Table 2); these data will be augmented with published isotopic data from the Atacama Desert.

Stable carbon, nitrogen and oxygen isotope analysis

At the Field Museum of Natural History (FMNH) and at Arizona State University (ASU), bone samples were mechanically cleaned of any visible surface discoloration, soft tissue, adherent soil and cancellous bone by abrasion using drills equipped with cylindrical high-speed burrs. Mechanical cleaning removed the outermost layers of bone which are most likely to contain diagenetic contaminants and the more chemically active cancellous or porous bone (Waldron, 1981; Ambrose, 1993). Rotational speed was kept as low as possible in order to minimise the heat produced by friction and any consequent denaturation of proteins. At the FMNH, tibia bone collagen was extracted and purified using a protocol first established by Longin (1971) and modified by Ambrose (1990). The bone sample was hand ground using an acid-washed porcelain mortar and pestle and passed through a series of geological screens. Approximately 0.75 g of coarse-ground (0.5–1.0 mm) bone was placed in a coarse-sintered glass frit filter funnel, demineralised for 48 h in 0.1 M HCl, treated for lipids and humics with 0.0625 M NaOH for 20 h, gelatinised at 90°C in 10⁻³ M HCl, condensed and freeze-dried.

At the FMNH and the ACL, bone and enamel hydroxyapatite was prepared according to established methodologies (Lee-Thorp et al., 1989; Koch et al., 1997). Approximately 10 mg of tooth enamel powder or 0.5 g of bone power was treated with 2% NaOCl to remove organic materials. Samples were then treated with 0.1 M CH₃COOH to remove labile carbonates. Pretreatment of hair samples also took place at the FMNH. An approximately 20 cm long section of approximately 30 hairs, with scalp ends aligned, was immersed in a 2:1 methanol and chloroform solution for two hours after which it was rinsed twice with ASTM Type I water; this removes any endogenous lipids leaving only pure keratin (O’Connell & Hedges, 1999b; O’Connell et al., 2001). After cleaning, the hair sample was manually straightened using dissecting needles and fine tweezers, wrapped in aluminium foil, and cut into 2 cm sections which were then dried for 24 h at 50°C and then finely diced using a razor blade and stored in individual annealed 20 ml scintillation vials.

Carbon and nitrogen isotope analysis of bone collagen (δ¹³C, δ¹⁵N) and hair keratin (δ¹³C, δ¹⁵N), as well as carbon isotope analysis of bone hydroxyapatite (δ¹³C), were performed at the University of Illinois at Chicago using a Thermo-Finnigan Delta+XL stable isotope ratio mass spectrometer equipped with a Costech Analytical ECS 4010 Elemental Analyser coupled to the mass spectrometer via a Thermo-Finnigan ConFlo III or, for hydroxyapatite carbonate analyses, equipped with a
Thermo-Finnigan GasBench II. For collagen analyses, replicate analyses of acetalnide (the laboratory secondary standard), and working standards (thiourea and hydroxyproline) resulted in reproducibility of ±0.1‰ for δ¹³C and ±0.2‰ for δ¹⁵N. For hydroxyapatite carbonate analyses, replicate analyses of BaCO₃ and CaCO₃ resulted in reproducibility of ±0.1‰ for δ¹³C. Carbon isotope ratios are reported relative to the V-PDB (Vienna PeeDee belemnite) carbonate standard and are expressed in parts per mil (%o) using the following standard formula: δ¹³C = (((¹³C/¹²C)Sample)/(¹³C/¹²C)Standard) - 1) × 1000 (Craig, 1961b). Nitrogen isotope ratios are reported relative to the AIR (atmospheric nitrogen) standard and are expressed in parts per mil (%o) using the following formula: δ¹⁵N = (((¹⁵N/¹⁴N)Sample)/(¹⁵N/¹⁴N)Standard) - 1) × 1000 (Mariotti, 1983).

At ASU, oxygen and carbon isotope analysis of archaeological hydroxyapatite carbonate (δ¹⁸Oap, δ¹³Cap) was performed using the Thermo-Finnigan MAT 253 stable isotope mass spectrometer equipped with a Thermo-Finnigan GasBench II. Carbonate isotopic analyses were performed on a Finnigan MAT 253 mass spectrometer and replicates of NBS-19 resulted in a reproducibility of ±0.2‰ for δ¹⁸O and ±0.2‰ for δ¹³C. Oxygen and carbon isotope ratios (δ¹⁸Oap, δ¹³Cap) are reported relative to the V-PDB (Vienna PeeDee belemnite) carbonate standard and are expressed in per mil (%o) using the following standard formula: δ¹⁸O = (((¹⁸O/¹⁶O)Sample)/(¹⁸O/¹⁶O)Standard) - 1) × 1000 (Copleen, 1994; Craig, 1961b).

Trace element concentration analysis

In order to better understand the extent of diagenetic contamination in the enamel and bone samples, concentrations of major, minor, and trace elements were also generated. At ASU, samples were photographed, cast and then mechanically cleaned by abrasion with a Dremel 3956-02 Variable Speed MultiPro drill equipped with an engraving cutter to remove any adhering as well as the outermost layers of tooth, which are most susceptible to diagenetic contamination (Waldron et al., 1979; Waldron, 1981; Waldron, 1983; Montgomery et al., 1999; Budd et al., 2000). Approximately 20 mg of tooth enamel was then removed with a Dremel 3956-02 Variable Speed MultiPro drill equipped with an engraving cutter.

Ten milligrams of tooth enamel powder was then dissolved in 0.64 ml of 5 M HNO₃, and diluted with 9.36 ml of Millipore H₂O. Samples were analysed on the quadrupole inductively coupled plasma mass spectrometer (Q-ICP-MS) at ASU. Trace element concentrations are reported as ratios with the exception of strontium (Table 2).

Radiogenic strontium isotope analysis

In the ACL, eight milligrams of tooth enamel powder was dissolved in 0.50 ml of 5 M HNO₃. The strontium was separated from the sample matrix using Eichrom SrSpec resin, a crown-ether strontium-selective resin (100–15 μm diameter) loaded into the tip of a glass column. Resin was used once for sample elution and discarded. The SrSpec resin was pre-soaked and flushed with H₂O to remove strontium present from the resin manufacturing process. The resin was further cleaned in the column with repeated washes of deionised H₂O and conditioned with 750 μl of HNO₃. The dissolved sample was loaded in 250 μl of 5 M HNO₃, washed in 500 μl of 5 M HNO₃, and then the strontium was eluted with 1000 μl of H₂O.

The enamel samples were analysed using a Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) at ASU. Recent ⁸⁷Sr/⁸⁶Sr analyses of strontium carbonate standard SRM-987 yield a value of ⁸⁷Sr/⁸⁶Sr = 0.710261 ± 0.000002 (2σ), which is in agreement with analyses of SRM-987 using a thermal ionisation mass spectrometer (TIMS), where ⁸⁷Sr/⁸⁶Sr = 0.710263 ± 0.000016 (2σ) (Stein et al., 1997), and analyses of SRM-987 using an identical MC-ICP-MS, where ⁸⁷Sr/⁸⁶Sr = 0.710251 ± 0.000006 (2σ) (Balcaen et al., 2005).

Results

Archaeological human collagen samples exhibited δ¹³Ccol(V-PDB) = −12.7‰ and δ¹⁵Ncol(V-PDB) = 21.6‰, while archaeological human hair samples ranged from δ¹³Cker(V-PDB) = −16.5‰ to δ¹³Cker(V-PDB) = −12.3‰ and from δ¹⁵Nker(AIR) = 17.1‰ to δ¹⁵Nker(AIR) = 24.6‰ (Tables 1 and 2). Archaeological human enamel hydroxyapatite exhibited δ¹³Cap(V-PDB) = −7.4‰ while archaeological human bone hydroxyapatite exhibited δ¹³Cap(V-PDB) = −8.6‰, δ¹³Cap(V-PDB) = −9.2‰ and δ¹³Cap(V-PDB) = −10.6‰ (Table 2). Archaeological human enamel hydroxyapatite exhibited δ¹⁸Oap(V-PDB) = −4.2‰, while archaeological human bone hydroxyapatite exhibited δ¹⁸Oap(V-PDB) = −6.5‰ and δ¹⁸Oap(V-PDB) = −8.1‰ (Table 2). In the archaeological human bone and enamel samples analysed, Ca/P = 2.1–2.2 and U/Ca ranged from U/Ca = 4.2 × 10⁻⁸ to U/Ca = 4.2 × 10⁻⁸.
Ca = 4.4 × 10⁻⁶ (Table 2). Strontium concentrations ranged from Sr = 166 ppm to Sr = 439 ppm. Enamel and bone values range from ⁸⁷Sr/⁸⁶Sr = 0.70745 to ⁸⁷Sr/⁸⁶Sr = 0.70883 while modern plant values were ⁸⁷Sr/⁸⁶Sr = 0.70700 and ⁸⁷Sr/⁸⁶Sr = 0.71031 (Table 2).

Diagenetic contamination

When using archaeological materials that have been subjected to various post-depositional processes, documenting diagenetic contamination is imperative (see overviews in Sillen, 1989; Tuross et al., 1989; Price et al., 1992; Kohn et al., 1999; Hedges, 2002; Lee-Thorp & Sponheimer, 2003; Lee-Thorp, 2008). The degree of diagenetic contamination and alteration in the collagen and keratin samples was examined using collagen yield, atomic C:N ratios and weight percent carbon and nitrogen (Ambrose, 1990). For the sole bone collagen sample, the collagen yield was 1.3 wt%, (or roughly 6.1 wt% of the bone’s original collagen content) the atomic C:N ratio was 3.6, with 9.3 wt% carbon yield and 3.1 wt% nitrogen yield. The collagen yield and elemental values for this sample are undeniably low, indicating a significant amount of collagen degradation, and the possibility of at least some diagenetic contamination. However, all three values are above the typically cited minimums for isotope analysis of collagen, and the atomic C:N ratio is within the widely recognised range of 2.9–3.6 (Ambrose, 1990; van Klinken, 1999). On the whole, while this sample would appear to have lost some significant amount of collagen (and the elemental constituents thereof), the collagen that remains is still consistent with generally accepted standards for analysis. The proximity of the isotopic values of the bone collagen sample to those of the diagenetically more robust hair sample, as discussed below, provides further reassurance as to the quality of its preservation (Lubecz et al., 1987; Macko et al., 1999; Roy et al., 2005). For hair keratin samples, atomic C:N values were well within acceptable limits, ranging from C:N = 3.6–3.7 (Table 1). In addition, the yields of carbon and nitrogen from the archaeological hair samples were close to the expected values in hair, which are 44–46 wt% carbon and 13–14 wt% nitrogen (e.g. Roy et al., 2005). These data imply that little post-mortal loss of hair keratin or diagenetic contamination occurred (e.g. Ambrose, 1990; Lee-Thorp, 2008).

Trace element concentration data was analysed for two archaeological human bone samples and one archaeological human enamel sample as a proxy for diagenetic alteration in hydroxyapatite. In human bone, biogenic Ca/P = 2.1 (Sillen & LeGros, 1991). As shown in Table 2, Ca/P = 2.1–2.2 in these samples, indicating biogenic enamel and bone values. The Ca/P values are low, suggesting little diagenetic contamination (Table 2) (see Price et al., 1992; Price et al., 2002). However, the strontium concentrations were Sr = 166 ppm in the enamel fragments, Sr = 216 ppm in the rib samples and Sr = 439 ppm in the tibia sample. Most human populations exhibit strontium concentrations in the range of Sr = 50–300 ppm (e.g. Elias, 1980; Hancock et al., 1989; Hancock et al., 1993; Budd et al., 1998; Montgomery et al., 1999; Montgomery et al., 2007). The range of strontium concentrations indicates that the bone samples may have included both biogenic and diagenetic strontium from the burial environment. However, particularly high strontium concentrations of Sr = 555 pm have been identified in archaeological human populations identified as exhibiting biogenic strontium concentration values (Montgomery et al., 2007). We also note that strontium concentrations can vary geologically (Burton et al., 2003), and that the variability in strontium concentrations in this region is not well known.

Interpretations

Paleodiet

Bone collagen isotope values largely reflect the isotopic makeup of dietary protein although, due to complex patterns of fractionation, the direct comparison of consumer and source isotope values is generally impossible (DeNiro & Epstein, 1978; Ambrose & Norr, 1993; Kellner & Schoeninger, 2007). Stable carbon isotopic data from bone collagen from this individual (δ¹³C_col[V.PDB] = −12.7‰) is consistent with a mixture of C₃ and C₄ protein with the likely inclusion of a substantial amount of marine resources. Highly enriched bone collagen nitrogen isotope data (δ¹⁵N_coll[AIR] = +21.6‰) indicates that he habitually consumed marine foodstuffs, particularly high-trophic level marine protein, over the last 10–30 years of his life. While the δ¹³C(V.PDB) values of collagen and keratin cannot be directly compared, the δ¹⁵N(AIR) values of these two biomolecules are comparable (McCullagh et al., 2005). The fact that the δ¹⁵N_coll[AIR] value for this individual is intermediate to the extremes seen in the δ¹⁵N_ker[AIR] values (δ¹⁵N_ker[AIR] = +17.1 to +24.6‰) implies that this individual habitually switched between higher and lower trophic-level resources, likely as a result of frequent trips to and from the coast.
On average, bone and enamel hydroxyapatite carbonate will reflect the carbon isotope values of all plants and animals consumed, plus 9.4% (Ambrose & Norr, 1993). Bone hydroxyapatite carbonate in this individual exhibited \( \delta^{13}C_{ap(V-PDB)} = -8.6 \) to \(-10.6\)%o, which is consistent with the consumption of a mixture of C\(_3\) and C\(_4\) plant and animal and/or marine resources. Enamel hydroxyapatite carbonate in this individual exhibited \( \delta^{13}C_{ap(V-PDB)} = -7.4\)%o, which is also consistent with the consumption of a mixture of C\(_3\), C\(_4\), and marine resources during the first years of life. Because the enamel fragments could not be identified as to dental element, we assume that breast milk may have also been consumed during enamel formation.

Isotopic data from bone provides a long-term average of food consumption over the last 10–30 years of life, whereas hair isotopic data provides complementary short-term information on food consumption in the last months before death. Unfortunately, due to the complexity of fractionation of carbon isotopes between diet and bone collagen (Ambrose & Norr, 1993), the results of \( \delta^{13}C \) analysis of keratin and collagen are not directly comparable, whereas \( \delta^{15}N \) appears to increase by 2–4% between dietary protein and both bone collagen and hair keratin (Schoeninger, 1985; McGullagh et al., 2005). Carbon isotope data from hair keratin is variable, and ranges from \( \delta^{13}C_{ker(V-PDB)} = -16.5\)%o to \( \delta^{13}C_{ker(V-PDB)} = -12.3\)%o. Similarly, nitrogen isotope data from hair keratin are variable, and ranges from \( \delta^{15}N_{ker(AIR)} = +17.1\)%o to \( \delta^{15}N_{ker(AIR)} = +24.6\)%o. That the plots for \( \delta^{13}C_{ker(V-PDB)} \) and \( \delta^{15}N_{ker(AIR)} \) do not move in complete lockstep is surely the result of complex combinations of dietary resources which are nonetheless drawn from clearly distinct reservoirs. Hair grows approximately 1 cm per month (Valkovic, 1988; Randall & Ebling, 1991) allowing us to interpret paleodiet on a month-by-month timeframe. Based on these data we argue that he travelled extensively in the last 20 months of his life. He likely spent the 6–8-month period preceding his death eating a marine-focused diet and living on the coast (Figure 3). Before this period, it is probable that he spent 8–12 months eating a largely terrestrial diet and living in an inland location. A brief visit to the coast where he ate marine resources for 2–4 months occurred before this period. Finally, the isotopic values in the most distal portions of the hair imply that this individual likely lived inland and consumed terrestrial resources during this time of his life. While seasonal variation in resource availability in one location might be a suitable alternate explanation for the observed isotopic differences in a more temperate region, the unyielding aridity of the region in question, its general stability in temperature and the general lack of seasonally migratory faunal resources, makes such an explanation

![Figure 3. Carbon and nitrogen isotope data from bone collagen and hair keratin from an individual buried in the hyper-arid Atacama Desert. Note that while \( \delta^{15}N_{ker(AIR)} \) values of hair keratin and bone collagen can be directly compared, differences in fractionation of carbon isotopes in the two biomolecules of keratin and collagen make direct comparison of \( \delta^{13}C_{ker(V-PDB)} \) impossible. This figure is available in colour at wileyonlinelibrary.com.](wileyonlinelibrary.com)
unlikely in the present case. It would seem instead that this individual was moving long distances between areas with different foods, rather than staying in one place and having different foods come into season around him or making the sort of short distance excursions typical of transhumance.

Since hair keratin is enriched by 1–2‰ compared to bone collagen (McCullagh et al., 2005; Knudson et al., 2007), we compare our data to archaeological hair data from other Andean regions rather than compare keratin and collagen data. In the Peruvian and Chilean Andes, nitrogen isotope data from later Inka-period *capacocha* sacrifices are much lower than the enriched nitrogen isotope data generated here (Wilson et al., 2007), and further support high amounts of marine protein consumption in individual A299. In fact, our data are more similar to archaeological hair data from Chinchorro sites on the coast of northern Chile (Macko et al., 1999) and from Chiribaya sites on the coast of southern Peru (Knudson et al., 2007); data from Chinchorro and Chiribaya sites indicate that large amounts of marine protein were consumed by these individuals.

**Paleomobility**

Archaeological human hydroxyapatite exhibited $\delta^{18}O_{\text{ap}}(V-PDB) = -4.2$‰ in early-forming enamel, while archaeological human bone hydroxyapatite values are lower in both the tibia ($\delta^{18}O_{\text{ap}}(V-PDB) = -6.5$‰) and rib ($\delta^{18}O_{\text{ap}}(V-PDB) = -8.1$) (Table 2). Given the faster turnover rate of rib remodelling, the rib oxygen isotope value likely represents the last years of life, while the tibia represents oxygen isotope consumption over a slightly longer period before this individual's death (Carr et al., 1962; Kulp & Schulert, 1962; Parfitt, 1983; Mulhern, 2000). The higher oxygen isotope value in the enamel and tibia samples are consistent with oxygen isotope data from individuals buried in the San Pedro de Atacama oasis in the neighbouring highlands (Knudson & Price, 2007; Knudson, 2009; Knudson & Torres-Rouff, 2009), with some expected enrichment from the consumption of $^{18}$O-enriched breast milk during enamel formation (Roberts et al., 1988). The lower oxygen isotope value identified in the rib sample is consistent with values from archaeological human remains buried in the Lake Titicaca Basin (Knudson & Price, 2007; Knudson, 2009; Knudson & Torres-Rouff, 2009). However, we note that the oxygen isotope values in the drinking water sources likely consumed by this individual are not well known, and that the complexities of water movement and treatment in the Andes ensure that each environmental zone has a wide range of variable oxygen isotope values (Knudson, 2009). In addition, it is possible that oxygen isotopes may be incorporated into distinct tissues differently (Warinner & Tuross, 2009), such that the period of life reflected in oxygen isotope values in different bones may not be clear.

Radiogenic strontium isotope data in early-forming enamel (ACL-2079, $^{87}$Sr/$^{86}$Sr = 0.70883) is slightly higher than the strontium isotope values in his tibia (ACL-2077, $^{87}$Sr/$^{86}$Sr = 0.70745) or rib (ACL-2078, $^{87}$Sr/$^{86}$Sr = 0.70806) (Table 2). This variability may be the result of biogenic and digenetic strontium in the bone samples, particularly the tibia sample. However, while there is some variability in enamel and bone that formed at different times in this individual’s life, this variability is quite small when compared to the range of known bioavailable radiogenic strontium isotope values from the South Central Andes (Knudson et al., 2005; Knudson & Buikstra, 2007; Knudson & Price, 2007; Knudson, 2008; Knudson & Torres-Rouff, 2009). The mean radiogenic strontium isotope value in both enamel and bone (mean $^{87}$Sr/$^{86}$Sr = 0.70811 ± 0.00069 (1σ, n = 3)) is higher than the mean radiogenic strontium isotope value in modern and archaeological faunal samples from San Pedro de Atacama (mean $^{87}$Sr/$^{86}$Sr = 0.70764 ± 0.00013 (1σ, n = 3) (Knudson, 2007; Knudson & Price, 2007). However, it is lower than radiogenic strontium isotope data from faunal and human samples from the neighbouring *altiplano* (Knudson et al., 2005; Knudson, 2008; Knudson & Torres-Rouff, 2009).

Radiogenic strontium isotope data are consistent with the consumption of strontium in sources from the geologic zones of the northern Chilean coast and the Atacama Desert. They are not consistent with the consumption of exclusively *altiplano* strontium sources, or with the consumption of exclusively marine sources of strontium, such as bones from whole small fish, which exhibit the radiogenic strontium isotope value of seawater, which is $^{87}$Sr/$^{86}$Sr = 0.7092 (Veizer, 1989). However, given the previously discussed consumption of marine resources, it is likely that this individual’s radiogenic strontium isotope values result from the consumption of both terrestrial strontium from the coast and Atacama Desert and marine strontium.

**Conclusion**

The isolated yet intentional burial of an adult male in the vast, hyper-arid and uninhabited Atacama Desert...
of northern Chile allowed us to examine paleodiet and paleomobility in one well-travelled individual in the past. We generated stable carbon and nitrogen isotopic data from bone collagen and hair keratin, stable carbon and oxygen isotopic data from enamel and bone hydroxyapatite carbonate, and radiogenic strontium isotope data from enamel and bone hydroxyapatite in order to examine paleodiet and paleomobility from birth to death and at various scales. Through these data we were able to discern this individual’s movements and interactions over his life. We argue that this individual was regularly moving from the coast to the highlands, crossing the hyper-arid Atacama Desert by following strategic interzonal routes that provided access to particular resources. As Stodder & Palkovich (2007: p. 26) argue, ‘without this complementary domain of individuals—the typical and the unique—the population paradigm constrains the contribution of bioarchaeology to contemporary studies of agency and social processes in the past’. Here, a detailed life history approach enables us to examine larger anthropological questions about complex pre-Columbian systems of trade and exchange.

Our biogeochemical and bioarchaeological approach to a Late Formative Period traveller’s life history has revealed an individual who originated from the Pacific coast of the Atacama Desert and yet engaged in significant movement across this desert over the course of his life. These data support the model of a different type of population movement for inhabitants of the coast during the Late Formative Period. He stands as evidence of patterns of human movement that are more than llama caravans from the highlands to the coast. Our data suggest that this individual’s last trip was oriented from the coast to the interior. We argue that he ultimately died as he was moving inland and others interred his body along one of these interzonal routes. Understanding the life course of this individual provided insight into the larger patterns of human mobility in the area—an idea espoused by Clark & Wilkie (2006: p. 334) who present personhood as a framework by which to investigate larger issues. Similarly, we use the experience of this individual to help argue that it was not only groups of highland peoples caravanning from inland oases to the coast, but also coastal groups that possessed their own system of multi-directional mobility including frequent trips to the interior. Our analysis suggests that the phenomenon of interzonal mobility in the Andes is versatile and diverse, involving multiple strategies, interests, and objectives.

Acknowledgements

The authors gratefully acknowledge funding from FONDECYT 1090762, Arizona State University, and the Colorado College. María Francisca Fernández (Archaeologist, Sociedad Química Minera) facilitated access, bioarchaeological analysis and sampling of individual A299’s skeletal remains. The quality of the excavation, led by Charles Rees, allowed for the detailed reconstruction provided herein, and they express their sincere gratitude for the tremendous effort put forth by the team in both the field and lab settings. Finally, they thank the directors and staff of the Archaeological Chemistry Laboratory at Arizona State University, the W.M. Keck Foundation Laboratory for Environmental Biogeochemistry at Arizona State University, the NSF Stable Isotope Preparation Laboratory at the Field Museum of Natural History, and the Stable Isotope Laboratory of the Department of Earth and Environmental Science at the University of Illinois at Chicago.

References


Blum JD, Talisaferrro EH, Weisse MT, Holmes RT. 2000. Changes in Sr/Ca, Ba/Ca, and 87Sr/86Sr ratios between trophic levels in two forest ecosystems in the northeastern USA. *Biogeochemistry* 49: 87–810.


