Journal of Archaeological Science 32 (2005) 903–913

Journal of Archaeological SCIENCE

http://www.elsevier.com/locate/jas

The origin of the Juch'uypampa Cave mummies: strontium isotope analysis of archaeological human remains from Bolivia

Kelly J. Knudson[a,*], Tiffiny A. Tung[b], Kenneth C. Nystrom[c], T. Douglas Price[a], Paul D. Fullagar[d]

[a] Laboratory for Archaeological Chemistry, Department of Anthropology, University of Wisconsin at Madison, 1180 Observatory Drive, Madison, WI 53706, USA

[b] Department of Anthropology, Vanderbilt University, VU Station B #356050, 2301 Vanderbilt Place, Nashville, TN 37235, USA

[c] Department of Anthropology, University of New Mexico, MSC01-1040, Anthropology, Albuquerque, NM 87131, USA

[d] Isotope Geochemistry Laboratory, Department of Geological Sciences, University of North Carolina, 314 Mitchell Hall, CB#3315, Chapel Hill, NC 27599, USA

Received 18 October 2004; received in revised form 4 January 2005

Abstract

Previous analyses of strontium isotopes from human bone and teeth have identified diverse patterns of residential mobility in the South Central Andes during the Middle Horizon (AD 500–1100). During this time, the large polity of Tiwanaku exerted great influence over what are now southern Peru, northern Chile, northwestern Argentina and Bolivia. Recently, five naturally-mummified individuals were discovered in the cave of Juch'uypampa in the Pulacayo region of southern Bolivia. Although these individuals were buried with a number of fine Tiwanaku-style grave goods as well as non-Tiwanaku items, the burial site is isolated and does not conform to the pattern of large Tiwanaku-affiliated cemeteries and residential sites outside of the Lake Titicaca Basin. Strontium isotope analysis was performed on enamel from two adult men and bone from a third adult male in order to test the hypotheses that one or more of the males was from either the Tiwanaku heartland in the Lake Titicaca Basin, the Chilean oasis of San Pedro de Atacama, which contains a series of cemeteries with Tiwanaku-style grave goods, or the local area in which they were buried. Results show that two individuals likely spent their childhood in the local area where they were interred, while the third man probably spent at least the last twenty years of his life in that region before being buried there. This raises interesting questions regarding the nature of Tiwanaku influence in southern Bolivia and the relationship between the Juch'uypampa mummies and the Tiwanaku polity.

Keywords: Strontium isotope analysis; South Central Andes; Bioarchaeology; Tiwanaku

1. Introduction

In the years since Ericson and Krueger [30,31,69] first proposed the application of strontium isotopes to investigate archaeological human migration, strontium isotope analysis has become an increasingly useful and popular technique. For example, strontium isotope analysis has successfully elucidated archaeological residential mobility and migration in the North American Southwest [32,94], in Bell Beaker and *Linearbandkeramik* populations in Central Europe [6–9,48,49,56,90,93], at a Norse cemetery in the Outer Hebrides [81], at a Roman fortress in Germany [100,101], and at

* Corresponding author. Tel.: +1 608 262 2866; fax: +1 608 265 4216.

E-mail address: kjknudson@wisc.edu (K.J. Knudson).

0305-4403/$ - see front matter
doi:10.1016/j.jas.2005.01.007

Teotihuacán in Mesoamerica [95]. Strontium isotope analysis also has been used to reconstruct hominid habitat utilization [55,105,106], to determine the last place of residence of Otzi, the famous Iceman [53,82], and to identify shipwrecked slaves buried in a mass grave [25].

In the Andes, strontium isotope analysis has identified diverse patterns of migration during the Middle Horizon (AD 500–1100) [60–63]. In addition, strontium isotope analysis is being used to address the origins of Wari trophy heads and victims of ritual sacrifice [114]. Building on these data, the current study investigates the life histories and origins of three of the five individuals buried in the cave of Juch'uypampa in Bolivia (Fig. 1). These individuals were buried in a remote cave in the *altiplano*, the high-altitude plain that runs between the two major Andean mountain ranges. Their mortuary textiles and other artifacts suggest ties to the Middle Horizon (AD 500–1100) Tiwanaku polity, which was centered at the site of Tiwanaku in the southeastern Lake Titicaca Basin (Fig. 1). At its height, the Tiwanaku polity exerted great influence over southern Peru, northern Chile, northwestern Argentina, and Bolivia [14,17,65–68,88,89,107,119]. Strontium isotope analysis of the three males and modern fauna from the region in which they were buried may elucidate the geographical origin of the men and provide key insights into understanding their ties to the Tiwanaku polity.

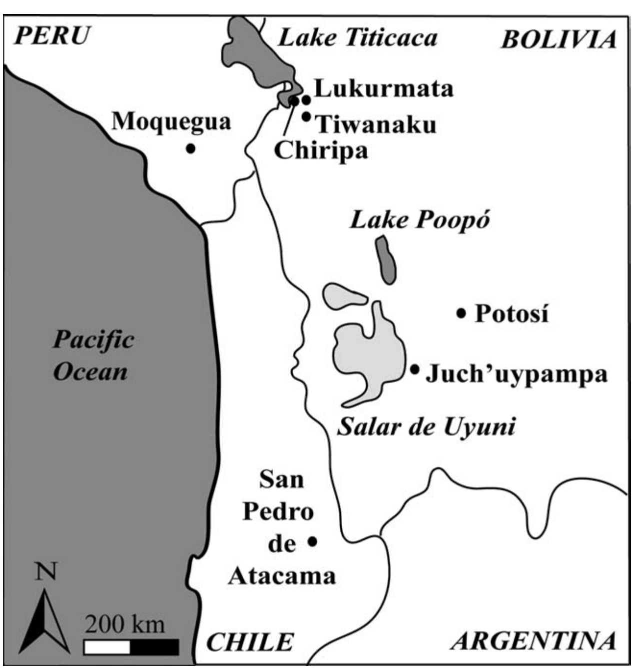

Fig. 1. Map of the study area in the South Central Andes with sites discussed in the text.

2. The Tiwanaku polity in the South Central Andes

During the Middle Horizon (AD 500–1100), the site of Tiwanaku, located in the Lake Titicaca Basin of Bolivia, was the largest and most impressive site in the South Central Andes (Fig. 1). Tiwanaku-style artifacts such as mortuary textiles, ceramics, and hallucinogenic snuff kits (*complejo de rapé*) are spread throughout the South Central Andes at this time [2,3,20,39,41,84,96,97,108,111]. In addition, a small number of Tiwanaku colonies, populated by individuals from the southeastern Lake Titicaca Basin, existed in southern Peru and possibly northern Chile [11,12,36,39–41,43,44,60–63,109,110,112].

Until now, the majority of burials of Tiwanaku-affiliated individuals outside of the Tiwanaku heartland have been found in southern Peru and northern Chile in large cemeteries such as Chen Chen and Coyo Oriental [11,12,23,37,38,42,43,45,74,84,85]. These cemeteries are often near large residential sites, and it is clear that most individuals buried in the cemeteries had been living in the area before death, though some are likely immigrants from the Lake Titicaca Basin [60–63]. Juch'uypampa is notable because it contained five individuals buried with goods with stylistic ties to the site of Tiwanaku and the Chilean oasis of San Pedro de Atacama. These artifacts do not appear to be locally-produced imitations, and were likely traded or transported from Tiwanaku and San Pedro de Atacama. However, Juch'uypampa is not a large Tiwanaku-affiliated cemetery and it is not located near a Tiwanaku-affiliated site. Who were the individuals buried there, and why were they buried with Tiwanaku-style grave goods? What was their relationship with the Tiwanaku polity? Strontium isotope analysis can help answer these questions.

3. Strontium isotope analysis: an introduction

The element strontium (Sr) is present in varying concentrations in bedrock, groundwater, soil, plants and animals in any given ecosystem. Although the concentration of strontium in an organism varies according to trophic level, the amounts of different isotopes of strontium do not [5,13,21,33,34,52]. Strontium is composed of four naturally-occurring isotopes (^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr) that vary in an ecosystem based on the underlying geology [34]. More specifically, some of the ^{87}Sr is radiogenic and is formed over time by the radioactive decay of rubidium (^{87}Rb, $t_{1/2} = 4.88 \times 10^{10}$ years) [34]. Therefore, the amount of rubidium in a rock and its age partially determine the amount of ^{87}Sr in bedrock, as well as the soil, groundwater, plants and animals in that geologic zone. These factors ensure that the ^{87}Sr/^{86}Sr ratios at the earth's surface are highly variable. For example, very old rocks with very high Rb/Sr ratios, such as shales and granites, will have the highest $^{87}Sr/^{86}Sr$ such as $^{87}Sr/^{86}Sr = 0.717$ [113]. On the other hand, geologically young rocks with low Rb/Sr ratios typically have $^{87}Sr/^{86}Sr$ ratios of less than $^{87}Sr/^{86}Sr = 0.706$ [99].

Strontium geochemistry is useful for bioarchaeologists because strontium substitutes for calcium in hydroxyapatite, and the strontium isotope ratios in human tooth enamel and bone reflect the strontium isotope ratios in the food consumed during life [30,31,69,94,102]. For individuals who consumed locally-grown food from and lived in one geologic region, the strontium isotope ratios found in their dental and skeletal elements will reflect where they were living when that tooth enamel or bone was formed. Tooth enamel does not take up elements from the body or the environment after it has formed during childhood [50,51]. Therefore, the strontium isotope ratios in tooth enamel reflect place of residence during childhood, if local foods were consumed [94]. In contrast, bone continually regenerates and incorporates strontium from the body [87]. The strontium isotope ratios in bone, therefore, reflect place of residence if local foods are consumed during the last years of life [92].

4. Geology of the South Central Andes and strontium isotope signatures

The broadly-defined geologic zones of the South Central Andes are well-suited to the application of strontium isotope analysis. The Tiwanaku heartland, located in the southern Lake Titicaca Basin, is distinct from other regions within the Tiwanaku sphere of influence. Specifically, the Tiwanaku and Katari River Basins, where the site of Tiwanaku is located, are bordered by two mountain ranges, the Cordillera Blanca and the Cordillera Real [4,10,71,98]. These two mountain ranges are composed of Paleozoic andesites, red mudstones and sandstones [4,10,71,98]. In the Tiwanaku and Katari River Basins themselves, the bedrock is composed of igneous basalts and andesites and is overlain by up to 10–20 m of Quaternary fluvial and lacustrine sediments [4,10,71,98]. Strontium isotope ratios from surface water from Lake Titicaca itself are $^{87}Sr/^{86}Sr = 0.7082–0.7085$ ($n = 3$) and 20 samples from four sediment cores taken from Lake Titicaca were characterized by $^{87}Sr/^{86}Sr = 0.7083–0.7087$ [47]. These values are slightly lower than the strontium isotope ratios observed in modern guinea pig (*Cavia porcellus*, commonly called *cuy*) bones from the southern Lake Titicaca Basin. For two modern *cuy* from the Tiwanaku River Basin archaeological sites of Tiwanaku and Chiripa, $^{87}Sr/^{86}Sr = 0.7093–0.7094$ (Fig. 1, Table 1) [60,63]. One modern *cuy* from Lukurmata, an archaeological site in the Katari River Basin just northeast of the Tiwanaku River Basin, exhibited $^{87}Sr/^{86}Sr = 0.7106$ (Fig. 1, Table 1) [60,63]. Taking the mean of all three *cuy* values plus or minus two standard deviations gives $^{87}Sr/^{86}Sr = 0.7083–0.7112$; this encompasses the surface water and sediment core values from Lake Titicaca and provides an estimate of the local strontium isotope signature of the entire southern Lake Titicaca Basin (Fig. 2). However, there are parts of the northern Lake Titicaca Basin with higher strontium isotope ratios. For example, surface water from the Río Suches in the northeastern Lake Titicaca Basin has strontium isotope ratios of $^{87}Sr/^{86}Sr = 0.7120–0.7135$ ($n = 2$) [47].

The geology changes and the strontium isotope ratios increase as one travels south through the *altiplano* from the Lake Titicaca Basin [47,59,79]. The Pulacayo region on the edge of the Salar de Uyuni is located in an area of tertiary volcanics including andesite as well as a large silver-rich polymetallic deposit that was mined from 1833 until 1958 (Fig. 1) [26,58]. Despite the extraction of 5000 metric tons of silver from Pulacayo [26], these mining activities should not affect the biologically available strontium isotope ratios in the region. Since mining activities were focused on the Tajo vein, a 2.7-km-long blind vein that was 1–6 m in diameter [26], the removal of ore should not affect the strontium isotope ratios of the surrounding area. In addition, the main source of metals in the ores is the surrounding

Table 1
Strontium isotope ratios for modern *cuy* bone and archaeological fauna from the South Central Andes [60,63]

LARCH number	Sample number	Site	Region	Sample	Corrected $^{87}Sr/^{86}Sr$
F1024	Ch1A	Chiripa	Lake Titicaca Basin	*cuy* (modern)	0.709291
F1026	T1A	Tiwanaku	Lake Titicaca Basin	*cuy* (modern)	0.709368
F1025	L2A	Lukurmata	Lake Titicaca Basin	*cuy* (modern)	0.710561
F1635	QT6-18	Quitor-6	San Pedro de Atacama	mouse (archaeological)	0.707659
F1636	QT6-33	Quitor-6	San Pedro de Atacama	dog (archaeological)	0.707762
F1714	SPA1	San Pedro	San Pedro de Atacama	*cuy* (modern)	0.707511
F1027	M5A	Chen Chen	Moquegua	*cuy* (modern)	0.706184
F1028	M9A	Chen Chen	Moquegua	*cuy* (modern)	0.706452
F1029	M14A	Chen Chen	Moquegua	*cuy* (modern)	0.706121

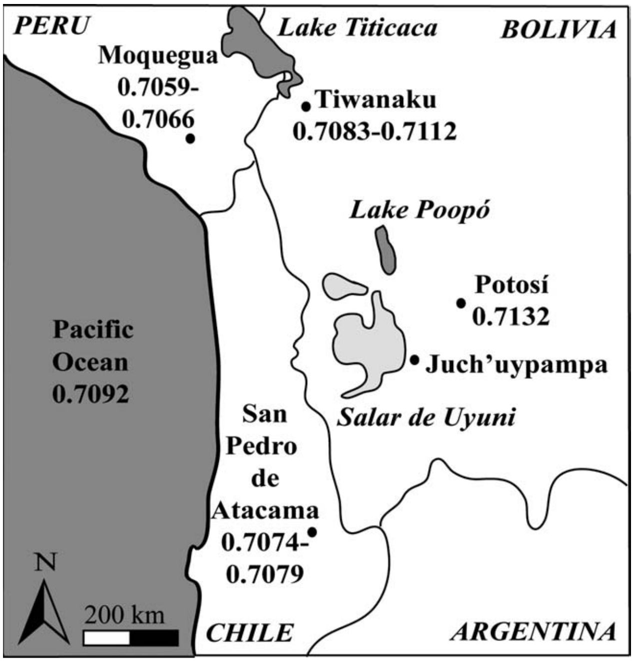

Fig. 2. Map of the South Central Andes with observed strontium isotope values.

igneous rock [26,58]. Strontium isotope ratios from surface water from the major rivers flowing into the Salar de Uyuni and the Salar itself are $^{87}Sr/^{86}Sr = 0.7074-0.7097$ ($n = 7$) [47]. Slightly higher values ($^{87}Sr/^{86}Sr = 0.7101-0.7114$, $n = 3$) are found in surface waters in rivers just east of the Salar [47]. However, even higher strontium isotope ratios ($^{87}Sr/^{86}Sr = 0.7164$-0.7178, $n = 3$) are found in the surface waters of rivers than drain from Lake Poopó (Fig. 1) [47].

Further east, the late Cenozoic volcanics of the South Central Andes are characterized by lower strontium isotope ratios. For example, geologic samples from the San Pedro de Atacama oasis in northern Chile are $^{87}Sr/^{86}Sr = 0.7062-0.7068$ ($n = 8$) [99] and range from $^{87}Sr/^{86}Sr = 0.7069-0.7079$ ($n = 10$) near Cerro Chascon and $^{87}Sr/^{86}Sr = 0.7081-7095$ ($n = 17$) near Cerro Purico, approximately 30 km east of the oasis of San Pedro de Atacama [99]. Analysis of modern and archaeological fauna support these data; $^{87}Sr/^{86}Sr = 0.7075-0.7078$ ($n = 3$) for faunal samples from the oasis (Fig. 2, Table 1) [60,63].

The strontium isotope ratios of the late Cenozoic volcanics continue to decrease as one travels north. For example, the Barroso volcanics of the Upper Osmore Drainage exhibit $^{87}Sr/^{86}Sr = 0.7054-0.7067$ ($n = 7$) [57]. Similarly, for modern *cuy*, or guinea pig, from near the town of Moquegua in the Upper Osmore Drainage, $^{87}Sr/^{86}Sr = 0.7062-0.7064$ ($n = 3$) [60,63].

Finally, the strontium isotope signature of seawater is $^{87}Sr/^{86}Sr = 0.7092$ [115]. Seawater mixing ensures that this signature does not change depending on deep-sea sediments or location, and has been stable for the period of time covered by this study [27,86]. Individuals who consumed large amounts of marine products would have this strontium isotope signature in their tooth enamel and bone.

5. Laboratory methods: TIMS analysis of tooth enamel and bone

Initial sample preparation was performed at the Laboratory for Archaeological Chemistry at the University of Wisconsin at Madison by K.J. Knudson. Modern fauna samples from the South Central Andes were not treated for diagenetic contamination, as they had not been in contact with possible contaminants. All modern faunal bone samples were placed in a crucible and ashed at approximately 800 °C for 10 hours. The bone samples were then crushed in an agate mortar and pestle.

In contrast, archaeological tooth enamel samples were mechanically cleaned by abrasion with a Patterson NC-350 dental drill equipped with an inverted-cone carbide burr (White burrs HP-59 type 2 class 2) to remove any adhering organic matter or contaminants. The mechanical cleaning also removed the outermost layers of tooth enamel, which are most susceptible to diagenetic contamination [18,80,116–118]. Then, 5–10 mg of tooth enamel was removed with a Patterson NC-350 dental drill equipped with a carbide burr.

Because of the potential for diagenetic contamination, archaeological bone samples were mechanically and chemically cleaned before analysis. Mechanical cleaning with the Patterson NC-350 dental drill equipped with a carbide burr removed adhering soft tissue, all traces of trabecular bone, and the outermost layers of cortical bone that are most susceptible to diagenetic contamination. The bone sample was then cut with the Patterson NC-350 dental drill equipped with a diamond disc saw and chemically cleaned in an ultrasonic bath. The samples were sonicated in distilled water for 30 minutes and then rinsed with distilled water; this step was repeated three times. The bone samples were then rinsed and sonicated in 5% acetic acid for 15 minutes, and finally rinsed and sonicated in distilled water for 15 minutes [83,91,94,104]. The bone samples were then ashed at approximately 800 °C for 10 hours.

Strontium isotope ratios of powdered tooth enamel and bone ash were obtained at the Isotope Geochemistry Laboratory in the Department of Geological Sciences at the University of North Carolina at Chapel Hill by P. D. Fullagar. Three to six milligrams of bone ash or powdered tooth enamel were dissolved in 15 mL Savillex PFA vials using 500 μL of twice distilled 5N HNO_3 in a class 100 filtered air environmental hood. Then, the samples were evaporated and redissolved in 250 μL of 5N HNO_3. The strontium was separated from the sample matrix using EiChrom SrSpec resin, a crown-ether Sr-selective resin (50–100 μm diameter) loaded into the tip of a 10 mL BioRad polypropylene column. Total resin volume was approximately 50 μL. The SrSpec resin was pre-soaked and flushed with H_2O to remove strontium present from the resin manufacturing process. The resin was further cleaned in the column with repeated washes of deionized H_2O and conditioned with 5N HNO_3. Resin was used once for sample elution and discarded. The dissolved sample was loaded and washed in 750 μL of 5N HNO_3, and then strontium was eluted with 1 mL of H_2O. Total procedural blanks for strontium are typically 100–200 picograms. The sample was then evaporated, dissolved in 2 μL of 0.1 M H_3PO_4 and 2 μL of $TaCl_5$, and loaded onto degassed rhenium (Re) filaments. Isotopic ratios were measured on a VG Sector 54 thermal ionization mass spectrometer at the University of North Carolina-Chapel Hill in quintuple-collector dynamic mode, using the internal ratio $^{86}Sr/^{88}Sr = 0.1194$ to correct for mass fractionation. Recent $^{87}Sr/^{86}Sr$ analyses ($n = 52$) of strontium carbonate standard SRM 987 yield a value of 0.710260 ± 10 (2σ). Long term analyses over approximately 24 months of SRM 987 yield an average $^{87}Sr/^{86}Sr$ value of 0.710242. Internal precision for strontium carbonate runs is typically 0.0006 to 0.0009% standard error based on 100 dynamic cycles of data collection.

6. Results and discussion

6.1. Strontium isotope ratios from Juch'uypampa and Potosí, Bolivia

As discussed above, strontium isotope ratios from the Pulacayo area were initially determined based on geologic analyses of surface water in the region [47]. To substantiate these values, modern fauna were also collected in order to determine the biologically available strontium in the region, and to serve as proxies of the strontium isotope signatures of humans who lived in the region during tooth enamel and bone formation [9,92]. Modern guinea pigs, or *cuy*, were collected from Potosí, Bolivia. Like the Pulacayo region, Potosí is located in an area of tertiary volcanic rocks and should have a similar strontium isotope signature (Fig. 2) [58]. Although informants specified during interviews that the *cuy* ate only locally-grown food, the strontium isotope signatures in femoral bone from each *cuy* were very different (Fig. 3 and Table 2). One *cuy*, POT-1, exhibited strontium isotope ratios close to the expected range (POT-1, $^{87}Sr/^{86}Sr = 0.713233$). However, POT-2 exhibited strontium isotope ratios that were much higher than the expected values (POT-2, $^{87}Sr/^{86}Sr = 0.720503$). As will be discussed below, the human strontium isotope ratios were more similar to the lower strontium isotope ratio exhibited in POT-1. Therefore, it is most likely that the

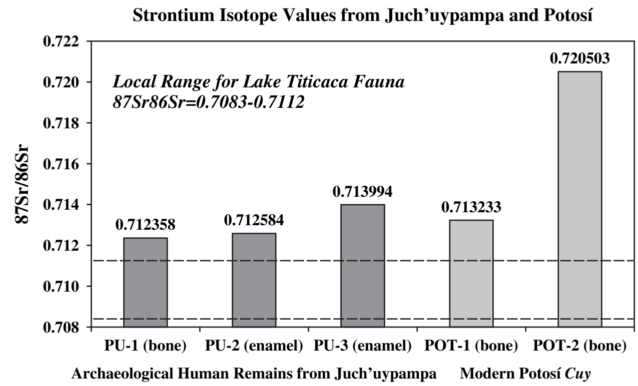

Fig. 3. Strontium isotope ratios from archaeological human remains from Juch'uypampa and modern *cuy* from Potosí.

high value of POT-2 does not accurately reflect the local signature of the Pulacayo region. It is possible that the anomalously high value in POT-2 reflects contamination from fertilizers, or that this *cuy* was in fact eating food from a different geologic zone.

In addition to the *cuy* samples from Potosí, samples from three adults buried in the cave of Juch'uypampa were analyzed in order to determine their origin. The cave of Juch'uypampa contained the remains of five naturally-mummified individuals, including three adult males, one 7- to 9-year-old child and one 6- to 8-year-old child. To determine the origin of the adults from Juch'uypampa, dental samples were analyzed from two adult males (PU-2, PU-3). Due to concerns over the conservation of the specimens, only one bone sample from the third adult male was collected and analyzed (PU-1). A detailed bioarchaeological examination of these burials, including the mortuary textiles and other grave goods, is forthcoming from the Fundación ASUR (Fundación para la Investigación Antropológica y el Etnodesarrollo "Antropólogos del Surandino").

Tooth enamel samples from two of the adults exhibit very similar strontium isotope ratios (PU-2, $^{87}Sr/^{86}Sr = 0.712584$ and PU-3, $^{87}Sr/^{86}Sr = 0.713994$) (Fig. 3 and Table 2). In addition, strontium isotope ratios from the left navicular bone of one other individual are also similar (PU-1, $^{87}Sr/^{86}Sr = 0.712358$) (Fig. 3 and Table 2). It is highly unlikely that these results reflect diagenetic contamination. First of all, tooth enamel is resistant to diagenetic contamination because of the large size of its phosphate crystals and the small amount of pore space in the enamel [51,64,103]. Numerous studies have demonstrated the resistance of the inner layers of tooth enamel to diagenetic contamination [18,19,22,48,54,73,80,94]. Bone, unfortunately, is much more susceptible to diagenetic contamination than tooth enamel. Removing the outermost layers of bone [70,91,116–118] and washing the remaining bone sample with weak acid [83,91,94,104] removes primary areas of contamination and eliminates calcite that can

Table 2
Strontium isotope ratios for modern *cuy* bone from Potosí, Bolivia and archaeological human tooth enamel and bone from Juch'uypampa, Bolivia

LARCH number	Sample number	Site	Sample	Age	Sex	Sample type	Corrected $^{87}Sr/^{86}Sr$
F2780	PU-1	Juch'uypampa	human	30–40 years	M	L navicular	0.712358
F2782	PU-2	Juch'uypampa	human	45–55 years	M	ULI2	0.712584
F2784	PU-3	Juch'uypampa	human	young to mid adult	M	ULM2	0.713994
F2778	POT-1	Potosí	*cuy*	adult	NA	R femur	0.713233
F2779	POT-2	Potosí	*cuy*	adult	NA	R femur	0.720503

accumulate in bone while buried. Both of these techniques were utilized in this study to minimize any diagenetic contamination. Additionally, because the individuals were placed in a fairly dry cave and naturally mummified rather than being buried underground, contact with potential contaminants in groundwater was minimal.

Since diagenetic contamination from the burial environment cannot explain the similar strontium isotope values found in the three men, it is reasonable to suggest that these three men consumed food from the same geologic zone, or from different geologic zones with the same strontium isotope signature. However, because we sampled teeth from two males and bone from another, our data reflect strontium uptake at different stages of their lives. Since the left navicular was analyzed from individual PU-1, the strontium isotope signature reflects much of his adult life. The average rate of bone regeneration is commonly cited as 7–11 years. However, the actual rate of turnover varies according to the skeletal element involved, and average turnover rates of 3% per year in cortical bone and 26% per year in trabecular bone have been estimated [46]. The navicular, one of the tarsal bones of the foot, is a poorly-vascularized and slowly-remodeling bone [24,35,72] that should provide strontium isotope ratios from at least the last 20 years of life.

In contrast, the strontium isotope ratios observed in the tooth enamel of the other two males reflects strontium uptake during childhood. For example, the upper left second incisor from individual PU-2 was included in this study. Because the enamel in the permanent second incisor begins to form 3–4 months after birth and continues for 4–5 years [51], the strontium isotope ratios in this tooth represent the biologically available strontium in this individual's diet before 4–5 years of age. For individual PU-3, the upper second molar was used in this study. Crown formation of permanent second molars occurs between 3 and 7 years of age while root formation occurs between 8 to 12 years [1,28,51,75]. Therefore, strontium isotope ratios from individual PU-3 represent strontium ingestion between ages 3 and 7 years.

6.2. General discussion of results

The strontium isotope signatures from the three men are very similar, suggesting that each man consumed food from the same geologic region at least for some time during their lives. Because the strontium isotope values presented here reflect childhood diet for PU-2 and PU-3 and adult diet for PU-1, it is likely that the first two males grew up in a similar geologic zone from which they obtained their food, while the third male likely lived in the same geologic region during adulthood. This could also mean that each man consumed a similar diet of imported foods.

In most residential mobility studies that utilize strontium isotope analysis, individuals are identified as local or non-local to the study area based on comparison with modern and/or archaeological fauna, and the local range is identified as the mean of the faunal strontium isotope ratios plus or minus two standard deviations [7–9,60,63,92–95]. According to this methodology, the local range for the region around the cave of Juch'uypampa is the mean of the two *cuy* samples plus or minus two standard deviations and is $^{87}Sr/^{86}Sr = 0.7066–0.7272$. This is so large it encompasses most of the geologic zones of the South Central Andes; as such, it is a meaningless definition of "local". Clearly, more *cuy* samples from Pulacayo and Potosí are necessary to characterize a local range according to the most common methodology. Alternatively, individuals may be identified as local based on comparison with a known local archaeological population; unfortunately, no comparison populations have been identified in the Pulacayo region.

When modern and archaeological fauna are unavailable or contaminated, it is still possible to make meaningful interpretations based on archaeological tooth enamel and uncontaminated bone [8,9]. It is possible, then, to match the observed archaeological human strontium isotope ratios with known strontium isotope signatures in order to test hypotheses about the origin and life history of these three individuals. First of all, because these individuals were buried with Tiwanaku-style goods such as textiles, we hypothesized that they were from the site of Tiwanaku itself or from the Tiwanaku heartland in the southeastern Lake Titicaca Basin. However, strontium isotope analysis of modern *cuy* from three sites in the southeastern Lake Titicaca Basin shows a local range of $^{87}Sr/^{86}Sr = 0.7083–7112$, based on the mean of the *cuy* strontium isotope ratios plus or minus two standard deviations (Fig. 2) [60,63]. In addition, strontium isotope analysis of 16 individuals buried at Tiwanaku and the surrounding sites of Kirawi, Iwawe and Tilata show that the majority exhibit strontium isotope signatures within this range [60,63]. Because none of the individuals analyzed here exhibit enamel or bone strontium isotope ratios that are within this Lake Titicaca Basin range, it is unlikely that PU-2 or PU-3 lived in the southeastern Lake Titicaca Basin during enamel formation. Similarly, the strontium isotope data show that PU-1 did not live in the southeastern Lake Titicaca Basin during adulthood. However, his place of residence during childhood is unknown.

However, Tiwanaku-style artifacts are found at a number of other sites in the South Central Andes. Therefore, it is possible that these individuals were not from the site of Tiwanaku itself but instead from a provincial Tiwanaku site. For example, the largest sites with Tiwanaku artifacts near the cave of Juch'uypampa are found in the San Pedro de Atacama oasis of northern Chile. However, strontium isotope analysis of modern and archaeological fauna from the oasis show that the local range is $^{87}Sr/^{86}Sr = 0.7074-7079$ (Fig. 2) [60,63], which is much lower than the Juch'uypampa strontium isotope ratios. Similarly, although it is farther from Juch'uypampa, the Upper Osmore Drainage in southern Peru contains three large Tiwanaku-affiliated site complexes near the modern town of Moquegua and has a local strontium isotope signature of $^{87}Sr/^{86}Sr = 0.7059-7066$ as determined by modern fauna (Fig. 2) [60,63]. Again, this strontium isotope signature is much lower than the Juch'uypampa samples.

Finally, none of these data match the strontium isotope signatures of seawater, in which $^{87}Sr/^{86}Sr = 0.7092$ [115]. Therefore, it is unlikely that these individuals lived on the coast or consumed enough calcium, and therefore strontium, from marine products in quantities large enough to change their strontium isotope signatures.

Although the archaeological human strontium isotope values do not match the strontium isotope signatures in areas with known Tiwanaku-affiliated sites, it is clear that four of the five strontium isotope ratios presented here are very similar, and that the one *cuy* bone value is anomalous. The mean of these four samples (POT-1, PU-1, PU-2 and PU-3) is $^{87}Sr/^{86}Sr = 0.713042 \pm 0.000735$ (1σ). This is within the range of values seen in other populations identified as "local" to a particular region [8,9,60]. Instead of being displaced Tiwanaku travelers, the Juch'uypampa burials may have been individuals who lived in the Pulacayo and Potosí region during adulthood, in the case of PU-1, and in the first few years of life, in the case of individuals PU-2 and PU-3. There are no known large Tiwanaku-affiliated residential sites or Middle Horizon residential sites in the area, which had previously been understood as a well-traveled but sparsely-populated region of caravan networks [15,16,29,76,112]. This complicates our understanding of the relationship between the Tiwanaku polity and the southern *altiplano*, and raises new questions. For example, why was a small group of individuals, identified as local by their strontium isotope signatures, buried with a number of high-quality Tiwanaku-style goods?

However, the enamel strontium isotope ratio of PU-3 (PU-3, $^{87}Sr/^{86}Sr = 0.713994$) is higher than the other enamel and bone values. It is possible that this individual would be considered non-local to the Pulacayo region with a local range determined by additional *cuy* samples. If this is the case, this group of individuals may represent at least two different regions. This would support our understanding of Tiwanaku as a diverse, heterogeneous polity with a great deal of fluidity between various regions under Tiwanaku influence.

Finally, strontium isotope ratios of $^{87}Sr/^{86}Sr = 0.7120-0.7135$ ($n = 2$) have been measured in surface water in Río Suches in the northeastern Lake Titicaca Basin [47]. Therefore, it is possible that these men lived in the northeastern Lake Titicaca Basin and only coincidentally match the Potosí *cuy* strontium isotope ratio. As will be discussed below, the use of other isotopes in addition to strontium may be used to test this hypothesis.

7. Conclusion and suggestions for further research

Strontium isotope analysis has been used here to test the hypothesis that individuals buried with Tiwanaku-style artifacts in Juch'uypampa are from the site of Tiwanaku itself, from the Tiwanaku-affiliated San Pedro de Atacama region, or from the local area in which they were buried. Based on strontium isotope ratios from enamel or bone, two of the three men did not spend their childhood in either Tiwanaku or San Pedro, and one man did not spend the last two decades of his life in either locale. Instead, it appears that all three spent considerable time in southern Bolivia in the Pulacayo region, or at least consumed foods from that region or one with a similar strontium value. These data contradict the material culture data from the burial goods, and raise new questions regarding the nature of Tiwanaku influence in the southern Bolivian *altiplano*.

Although strontium isotope analysis of the individuals buried in Juch'uypampa has demonstrated that these individuals are not from near the site of Tiwanaku or from the San Pedro de Atacama region, more research remains to be done. As previously discussed, more modern and archaeological fauna from the southern *altiplano* will help augment the strontium isotope data from the Lake Titicaca Basin and lower-altitude sites like San Pedro. In addition, expanding this study to include samples from the two juveniles buried in the cave of Juch'uypampa as well as additional tooth enamel and bone samples from the three adult men in the cave will continue to identify their life histories. Finally, the forthcoming analysis of the grave goods included with these individuals will continue to elucidate the relationship these individuals had with the Tiwanaku polity.

In addition, lead isotope analysis shows much promise for residential mobility studies in this region. The South Central Andes are divided into discrete lead isotope provinces [58,77,78]. Because lead isotopes are dependent on the age of a geologic formation and uranium and thorium decay, not rubidium decay, lead isotope analysis gives complementary data when used with strontium isotope analysis. Therefore, lead isotope analysis of archaeological human bone and tooth enamel samples from individuals buried in the cave of Juch'uypampa may help identify the specific *altiplano* origin of these individuals.

Acknowledgements

This research could not have been conducted without logistical and financial assistance from the Discovery Channel, Atlantic Productions and the "Mummy Autopsy" crew, the Laboratory for Archaeological Chemistry at the University of Wisconsin at Madison, and the Isotope Geochemistry Laboratory at the University of North Carolina at Chapel Hill. The authors would like to thank Sra. Verónica Cereceda and her colleagues at the Fundación ASUR (Fundación para la Investigación Antropológica y el Etnodesarrollo "Antropólogos del Surandino") in Sucre, Bolivia and as well as DINAAR (Dirección Nacional de Arqueología y Antropología) of Bolivia for generously granting access to the individuals sampled in this study. The authors are also grateful to Dra. María Antonietta Costa Junquiera for her bioarchaeological analysis of the individuals buried at Juch'uypampa and her close reading of a preliminary draft of this manuscript. Finally, this manuscript was strengthened by the constructive comments of Dr. William Middleton and three anonymous reviewers.

References

[1] D.L. Anderson, G.W. Thompson, F. Popovich, Age of attainment of mineralization stages of the permanent dentition, Journal of Forensic Sciences (1975) 191–200.

[2] K. Anderson, Tiwanaku Political Economy: The View from Cochabamba, Paper presented at the Annual Meeting of the Society for American Archaeology, Chicago, IL, 1999.

[3] K. Anderson, R. Cespedes Paz, R. Sanzetenea, The Late Formative to Middle Horizon Transition in Cochabamba, Bolivia, Paper presented at the Annual Meeting of the Society for American Archaeology, Seattle, Washington, 1998.

[4] J. Argollo, L. Ticcla, A.L. Kolata, O. Rivera, Geology, geomorphology, and soils of the Tiwanaku and Catari River Basins, in: A.L. Kolata (Ed.), Tiwanaku and Its Hinterland: Archaeology and Paleoecology of an Andean Civilization, vol. 1, Smithsonian Institution Press, Washington, DC, 1996, pp. 57–88.

[5] V. Balter, Allometric constraints on Sr/Ca and Ba/Ca partitioning in terrestrial mammalian trophic chains, Ecosystem Ecology 139 (2004) 83–88.

[6] R.A. Bentley, Human Migration in Early Neolithic Europe: A Study by Strontium and Lead Isotope Analysis of Archaeological Skeletons, Doctoral dissertation, Department of Anthropology, University of Wisconsin at Madison, 2001.

[7] R.A. Bentley, R. Krause, T.D. Price, B. Kaufmann, Human mobility at the early Neolithic settlement of Vaihingen, Germany: evidence from strontium isotope analysis, Archaeometry 45 (2003) 471–487.

[8] R.A. Bentley, T.D. Price, J. Luning, D. Gronenbron, J. Wahl, P.D. Fullagar, Prehistoric migration in Europe: strontium isotope analysis of early Neolithic skeletons, Current Anthropology 34 (2002) 799–804.

[9] R.A. Bentley, T.D. Price, E. Stephan, Determining the "local" 87Sr/86Sr range for archaeological skeletons: a case study from Neolithic Europe, Journal of Archaeological Science 31 (2004) 365–375.

[10] M.W. Binford, A.L. Kolata, The natural and human setting, in: A.L. Kolata (Ed.), Tiwanaku and Its Hinterland: Archaeology and Paleoecology of an Andean Civilization, vol. 1, Smithsonian Institution Press, Washington, DC, 1996, pp. 23–56.

[11] D.E. Blom, Tiwanaku Regional Interaction and Social Identity: A Bioarchaeological Approach, Doctoral dissertation, Department of Anthropology, University of Chicago, 1999.

[12] D.E. Blom, B. Hallgrimsson, L. Keng, M.C. Lozada Cerna, J.E. Buikstra, Tiwanaku 'colonization': bioarchaeological implications for migration in the Moquegua Valley, Peru, World Archaeology 30 (1998) 238–261.

[13] J.D. Blum, E.H. Taliaferro, M.T. Weisse, R.T. Holmes, Changes in Sr/Ca, Ba/Ca, and 87Sr/86Sr ratios between trophic levels in two forest ecosystems in the Northeastern USA, Biogeochemistry 49 (2000) 87–101.

[14] D.L. Browman, Towards the development of the Tihuanaco (Tiwanaku) State, in: D.L. Browman (Ed.), Advances in Andean Archaeology, Mouton, The Hague, 1978, pp. 327–349.

[15] D.L. Browman, Tiwanaku expansion and altiplano economic patterns, Estudios Arquelógicos 5 (1980) 107–120.

[16] D.L. Browman, Tiwanaku: development of interzonal trade and economic expansion in the Altiplano, in: D.L. Browman, R.L. Burger, M.A. Rivera (Eds.), Social and Economic Organization in the Prehispanic Andes, BAR International Series 194, London, 1984, pp. 117–142.

[17] D.L. Browman, Political institutional factors contributing to the integration of the Tiwanaku state, in: L. Manzanilla (Ed.), Emergence and Change in Early Urban Societies, Plenum Press, New York, 1997, pp. 229–243.

[18] P. Budd, J. Montgomery, B. Barreiro, R.G. Thomas, Differential diagenesis of strontium in archaeological human dental tissues, Applied Geochemistry 15 (2000) 687–694.

[19] P. Budd, J. Montgomery, A. Cox, P. Krause, B. Barreiro, R.G. Thomas, The distribution of lead within ancient and modern human teeth: implications for long-term and historical exposure modeling, The Science of the Total Environment 220 (1998) 121–136.

[20] G.B. Caballero, El Tiwanaku en Cochabamba, Arqueologia Boliviana 1 (1984) 67–72.

[21] R.C. Capo, B.W. Stewart, O.A. Chadwick, Strontium isotopes as tracers of ecosystems processes: theory and methods, Geoderma 82 (1998) 197–225.

[22] M. Chiaradia, A. Gallay, W. Todt, Different contamination styles of prehistoric human teeth at a Swiss Necropolis (Sion, Valais) inferred from lead and strontium isotopes, Applied Geochemistry 18 (2003) 353–370.
[23] J.A. Cocilovo, M.V. Zavattieri, Biología del Grupo Prehistórico de Coyo Oriental (San Pedro de Atacama, Norte de Chile): Ii Deformación Craneana Artificial, Estudios Atacameños 11 (1994) 135–143.
[24] E. Coris, J. Lombardo, Tarsal navicular stress fractures, American Family Physician 67 (2003) 85–90.
[25] G. Cox, J. Sealy, Investigating identity and life histories: isotopic analysis and historical documentation of slave skeletons found on the Cape Town foreshore, South Africa, International Journal of Historical Archaeology 1 (1997) 207–224.
[26] C.G. Cunningham, J. McNamee, J.P. Vasquez, G.E. Ericksen, A model of volcanic dome-hosted precious metal deposits in Bolivia, Economic Geology 86 (1991) 415–421.
[27] E.J. Dasch, Strontium isotopes in weathering profiles, deep-sea sediments and sedimentary rocks, Geochimica et Cosmochimica Acta 33 (1969) 1521–1552.
[28] M.C. Dean, A.D. Beynon, Histological reconstruction of crown formation times and initial root formation times in a modern human child, American Journal of Physical Anthropology 86 (1991) 215–228.
[29] T.D. Dillehay, L. Núñez, A Camelids, caravans, and complex societies in the South-Central Andes, in: N. Sanders, O. de Montmollin (Eds.), Recent Studies in Precolumbian Archaeology, BAR Series, Oxford, 1988, pp. 603–634.
[30] J.E. Ericson, Strontium isotope characterization in the study of prehistoric human ecology, Journal of Human Evolution 14 (1985) 503–514.
[31] J.E. Ericson, Some problems and of strontium isotope analysis for human and animal ecology, in: R.W. Rundel, J.R. Ehleringer, K.A. Nagy (Eds.), Stable Isotopes in Ecological Research, Springer-Verlag, New York, 1989, pp. 254–269.
[32] J.A. Ezzo, C.M. Johnson, T.D. Price, Analytical perspectives on prehistoric migration: a case study from East-Central Arizona, Journal of Archaeological Science 24 (1997) 447–466.
[33] G. Faure, Principles of Isotope Geology, John Wiley, New York, 1986.
[34] G. Faure, J.L. Powell, Strontium Isotope Geology, Springer-Verlag, New York, 1972.
[35] P. Golano, O. Farinas, I. Saenz, The anatomy of the navicular and periarticular structures, Foot and Ankle Clinics 9 (2004) 1–23.
[36] P.S. Goldstein, Omo, a Tiwanaku Provincial Center in Moquegua, Peru, Doctoral dissertation, Department of Anthropology, University of Chicago, 1989.
[37] P.S. Goldstein, La Cultura Tiwanaku y la Relación de Sus Fases Cerámicos en Moquegua, Trabajos arqueológicos en Moquegua, Peru 2 (1990) 31–58.
[38] P.S. Goldstein, La Ocupación Tiwanaku en Moquegua, Gaceta Arqueológica Andina V (1990) 75–104.
[39] P.S. Goldstein, Tiwanaku temples and state expansion, Latin American Antiquity 4 (1992) 22–47.
[40] P.S. Goldstein, Community and state in the earliest Tiwanaku colony: domestic patterns and state integration at Omo M12, Moquegua, in: M.S. Aldenderfer (Ed.), Domestic Architecture, Ethnicity, and Complementarity in the South Central-andes, University of Iowa Press, Iowa City, 1993, pp. 25–41.
[41] P.S. Goldstein, Tiwanaku settlement patterns of the Azapa Valley, Chile: new data, and the legacy of Percy Dauelsberg, Dialogo Andino 14/15 1996 (1995) 57–73.
[42] P.S. Goldstein, Moquegua y el Imperio Tiwanaku, in: K. Wise (Ed.), Moquegua: Los Primeros Doce Mil Años, Policrom, Arequipa, Peru, 1998, pp. 45–58.
[43] P.S. Goldstein, Communities without borders: the vertical archipelago and diaspora communities in the southern Andes, in: M.A. Canuto, J. Yaeger (Eds.), The Archaeology of Communities: A New World Perspective, Routledge, London, 2000, pp. 182–209.
[44] P.S. Goldstein, From stew-eaters to maize-drinkers: the Chicha economy and the Tiwanuku expansion, in: T.L. Bray (Ed.), The Archaeology and Politics of Food and Feasting in Early States and Empires, Kluwer Academic/Plenum Publishers, New York, 2003, pp. 143–172.
[45] P.S. Goldstein, B. Owen, Tiwanaku En Moquegua: Las Colonias Altiplánicas, in: P. Kaulicke, W.H. Isbell (Eds.), Boletin De Arqueología Pucp No. 5, Huari Y Tiwanaku: Modelos Vs. Evidencias, Segunda Parte, Pontifica Universidad Católica del Perú, 2001, pp. 139–168.
[46] J.K. Gong, E. Burgess, P. Bacalao, Accretion and exchange of strontium 85 in trabecular bone, Radiation Research 28 (1966) 753–768.
[47] M.J. Grove, P.A. Baker, S.L. Cross, C.A. Rigsby, G.O. Seltzer, Application of strontium isotopes to understanding the hydrology and paleohydrology of the Altiplano, Bolivia-Peru, Paleogeography, Paleoclimatology, Paleoecology 194 (2003) 281–297.
[48] G. Grupe, T.D. Price, P. Schroter, F. Sollner, C.M. Johnson, B.L. Beard, Mobility of Bell Beaker people revealed by strontium isotope ratios of tooth and bone: a study of Southern Bavarian skeletal remains, Applied Geochemistry 12 (1997) 517–525.
[49] G. Grupe, T.D. Price, F. Sollner, Mobility of Bell Beaker people revealed by strontium isotope ratios of tooth and bone: a study of Southern Bavarian skeletal remains: a reply to the comment by Peter Horn and Dieter Muller-Sohnius, Applied Geochemistry 14 (1999) 271–275.
[50] S. Hillson, Teeth, Cambridge University Press, Cambridge, 1986.
[51] S. Hillson, Dental Anthropology, Cambridge University Press, Cambridge, 1996.
[52] D.A. Hodell, R.L. Quinn, M. Brenner, G. Kamenov, Spatial variation of strontium isotopes (87Sr/86Sr) in the Maya region: a tool for tracking ancient human migration, Journal of Archaeological Science 31 (2004) 585–601.
[53] J. Hoogewerff, W. Papesch, M. Kralik, M. Berner, P. Vroon, H. Miesbauer, O. Gaber, K.-H. Kunzel, J. Kleinjans, The last domicile of the Iceman from Hauslabjoch: a geochemical approach using Sr, C and O isotopes and trace element signatures, Journal of Archaeological Science 28 (2001) 983–989.
[54] K.A. Hoppe, P.L. Koch, T.T. Furutani, Assessing the preservation of biogenic strontium in fossil bones and tooth enamel, International Journal of Osteoarchaeology 13 (2003) 20–28.
[55] P. Horn, S. Holzl, D. Storzer, Habitat determination on a fossil stag's mandible from the site of *Homo erectus heidelbergensis* at Mauer by use of 87Sr/86Sr, Naturwissenschaften 81 (1994) 360–362.
[56] P. Horn, D. Muller-Sohnius, Comment on 'mobility of Bell Beaker people revealed by strontium isotope ratios of tooth and bone: a study of southern Bavarian skeletal remains' by Gisela Grupe, T. Douglas Price, Peter Schroter, Frank Sollner, Clark M. Johnson, and Brian L. Beard, Applied Geochemistry 14 (1999) 263–269.
[57] D.E. James, A combined O, Sr, Nd, and Pb isotopic and trace element study of crustal contamination in central Andean Lavas, I. Local geochemical variations, Earth and Planetary Science Letters 57 (1982) 47–62.
[58] G. Kamenov, A.W. Macfarlane, L. Riciputi, Sources of lead in the San Cristobal, Pulacayo, and Potosi mining districts, Bolivia, and a reevaluation of regional ore lead isotope provinces, Economic Geology 97 (2002) 573–592.
[59] J. Klerkx, S. Deutsch, H. Pichler, W. Zeil, Strontium isotopic composition and trace element data bearing on the origin of Cenozoic volcanic rocks of the Central and Southern Andes,

Journal of Volcanology and Geothermal Research 2 (1977) 49–71.
[60] K.J. Knudson, Tiwanaku Residential Mobility in the South Central Andes: Identifying Archaeological Human Migration through Strontium Isotope Analysis, Doctoral dissertation, Department of Anthropology, University of Wisconsin at Madison, 2004.
[61] K.J. Knudson, T.D. Price, J.E. Buikstra, D.E. Blom, Tiwanaku Residential Mobility as Determined by Strontium and Lead Isotope Analysis, Paper presented at the 66th Annual Meeting of the Society for American Archaeology, April 18–22, New Orleans, LA, 2001.
[62] K.J. Knudson, T.D. Price, J.E. Buikstra and D.E. Blom, Migration in the Middle Horizon: Bone Chemistry and the Nature of the Tiwanaku Polity in the South Central Andes, Paper presented at the 69th Annual Meeting of the Society for American Archaeology, March 31–April 4, Montreal, Canada, 2004.
[63] K.J. Knudson, T.D. Price, J.E. Buikstra, D.E. Blom, The use of strontium isotope analysis to investigate Tiwanaku migration and mortuary ritual in Bolivia and Peru, Archaeometry 46 (2004) 5–18.
[64] M.J. Kohn, M.J. Schoeninger, W.W. Barker, Altered states: effects of diagenesis on fossil tooth chemistry, Geochimica et Cosmochimica Acta 63 (1999) 2737–2747.
[65] A.L. Kolata, Tiwanaku: portrait of an Andean Civilization, Field Museum of Natural History Bulletin 53 (1982) 13–18, 23–28.
[66] A.L. Kolata, The Tiwanaku: Portrait of an Andean Civilization, Blackwell, Oxford, 1993.
[67] A.L. Kolata, Tiwanaku and Its Hinterland: Archaeology and Paleoecology of an Andean Civilization, vol. 1, 1 1996.
[68] A.L. Kolata, Tiwanaku and Its Hinterland: Archaeological and Paleoecological Investigations of an Andean Civilization: vol. 2, Urban and Rural Archaeology, 2 2003.
[69] H.W. Krueger, Sr Isotopes and Sr/Ca in Bone, Poster paper presented at Biomineralization Conference, Airlie House, Warrenton, VA, April 14–17, 1985.
[70] J.B. Lambert, J.M. Weydert, S.R. Williams, J.E. Buikstra, Inorganic analysis of excavated human bone after surface removal, Journal of Archaeological Science 18 (1991) 363–383.
[71] A. Lavenu, Formación Geológica y Evolución, in: C. Dejoux, A. Iltis (Eds.), El Lago Titicaca: Síntesis Del Conocimiento Limnológico Actual, ORSTOM, La Paz, 1991, pp. 19–27.
[72] S. Lee, R. Anderson, Stress fractures of the tarsal navicular, Foot and Ankle Clinics 9 (2004) 85–104.
[73] J. Lee-Thorp, M. Sponheimer, Three case studies used to reassess the reliability of fossil bone and enamel isotope signals for paleodietary studies, Journal of Anthropological Archaeology 22 (2003) 208–216.
[74] G. LePaige, Cultura de Tiahuanaco en San Pedro de Atacama, Anales 1 (1961) 19–23.
[75] H.M. Liversidge, Crown formation times of the permanent dentition and root extension rate in humans, in: J. Moggi-Cecchi (Ed.), Aspects of Dental Biology: Paleontology, Anthropology and Evolution, Institute for the Study of Man, 1995, pp. 267–275.
[76] T.F. Lynch, Camelid pastoralism and the emergence of the Tiwanaku civilization in the South-Central Andes, World Archaeology 15 (1983) 1–14.
[77] A.W. Macfarlane, Isotopic studies of northern Andean crustal evolution and ore metal sources, in: B.J. Skinner (Ed.), Geology and Ore Deposits of the Central Andes, Society of Economic Geologists, Littleton, CO, 1999, pp. 195.
[78] A.W. Macfarlane, P. Marcet, A.P. LeHuray, U. Petersen, Lead isotope provinces of the Central Andes inferred from ores and crustal rocks, Economic Geology 85 (1990) 1857–1880.
[79] R.H. McNutt, J.H. Crockett, A.H. Clark, J.C. Caelles, E. Farrar, S.J. Haynes, M. Zentilli, Initial 87Sr/86Sr ratios of plutonic and volcanic rocks of the Central Andes between latitudes 26 and 29 degrees South, Earth and Planetary Science Letters 27 (1975) 305–313.
[80] J. Montgomery, P. Budd, A. Cox, P. Krause, R.G. Thomas, La-Icp-Ms evidence for the distribution of lead and strontium in Romano-British, medieval and modern human teeth: implications for life history and exposure reconstruction, in: S.M.M. Young, A.M. Pollard, P. Budd, R.A. Ixer (Eds.), Metals in Antiquity, BAR International Series, Oxford, 1999, pp. 290–296.
[81] J. Montgomery, P. Budd, T. Neighbour Sr., Sr isotope evidence for population movement within the Hebridean Norse community of Nw Scotland, Journal of the Geological Society 160 (2003) 649–653.
[82] W. Muller, H. Fricke, A.N. Halliday, M.T. McCulloch, J.-A. Wartho, Origin and migration of the alpine Iceman, Science 302 (2003) 862–866.
[83] C.M. Nielsen-Marsh, R.E. Hedges, Patterns of diagenesis in bone II: effects of acetic acid treatment and the removal of diagenetic CO3, Journal of Archaeological Science 27 (2000) 1151–1159.
[84] A. Oakland Rodman, Textiles and ethnicity: Tiwanaku in San Pedro de Atacama, North Chile, Latin American Antiquity 3 (1992) 316–340.
[85] B. Owen, P. Goldstein, Tiwanaku en Moquegua: Interacciones Regionales y Colapso, in: P. Kaulicke, W.H. Isbell (Eds.), Boletin De Arqueología Pucp No. 5, Huari Y Tiwanaku: Modelos Vs. Evidencias, Segunda Parte, Pontifica Universidad Católica del Perú, 2001, pp. 169–188.
[86] M.R. Palmer, H. Elderfield, Sr isotope composition of sea water over the past 75 Myr, Nature 314 (1985) 526–528.
[87] A.M. Parfitt, The physiologic and clinical significance of bone histomorphometric data, in: R.R. Recker (Ed.), Bone Histomorphometry: Techniques and Interpretation, CRC Press, Inc, Boca Raton, Florida, 1983, pp. 143–223.
[88] C. Ponce Sanginés, Tiwanaku: Espacio, Tiempo, Y Cultura, Academia Nacional de Ciencias de Bolivia, La Paz, 1972.
[89] C. Ponce Sanginés, Tiwanaku: 200 Años De Investigaciones Arqueológicas, Producciones Cima, La Paz, 1995.
[90] T.D. Price, R.A. Bentley, J. Luning, D. Gronenborn, J. Wahl, Prehistoric human migration in the *Linearbankeramik* of Central Europe, Antiquity 75 (2001) 593–603.
[91] T.D. Price, J. Blitz, J.H. Burton, J. Ezzo, Diagenesis in prehistoric human bone: problems and solutions, Journal of Archaeological Science 19 (1992) 513–529.
[92] T.D. Price, J.H. Burton, R.A. Bentley, The characterization of biologically available strontium isotope ratios for the study of prehistoric migration, Archaeometry 44 (2002) 117–136.
[93] T.D. Price, G. Grupe, P. Schroter, Migration in the Bell Beaker period of Central Europe, Antiquity 72 (1998) 405–411.
[94] T.D. Price, C.M. Johnson, J.A. Ezzo, J. Ericson, J.H. Burton, Residential mobility in the prehistoric Southwest United States: a preliminary study using strontium isotope analysis, Journal of Archaeological Science 21 (1994) 315–330.
[95] T.D. Price, W.D. Middleton, L. Manzanilla, Immigration and the ancient city of Teotihuacan in Mexico: a study using strontium isotope ratios in human bone and teeth, Journal of Archaeological Science 27 (2000) 903–913.
[96] M.A. Rivera, Alto Ramirez Y Tiwanaku, Un Caso de Interpretación Simbólica a Traves de Datos Arquelógicos en el Area de los Valles Occidentales S. Del Perú Y N. De Chile, Dialogo Andino 4 (1985) 39–58.
[97] M.A. Rivera, The prehistory of Northern Chile: a synthesis, Journal of World Prehistory 5 (1991) 1–47.
[98] L.A. Rodrigo, D. Wirrmann, Aspecto general de la sedimentación general, in: C. Dejoux, A. Iltis (Eds.), El Lago

Titicaca: Síntesis Del Conocimiento Limnológico Actual, ORSTOM, La Paz, 1991, pp. 39–45.

[99] G. Rogers, C.J. Hawkesworth, A geochemical traverse across the North Chilean Andes: evidence for crust generation from the mantle wedge, Earth and Planetary Science Letters 91 (1989) 271–285.

[100] M.M. Schweissing, G. Grupe, Stable strontium isotopes in human teeth and bone: a key to migration events of the late Roman period in Bavaria, Journal of Archaeological Science 30 (2003) 1373–1383.

[101] M.M. Schweissing, G. Grupe, Tracing migration events in man and cattle by stable strontium isotope analysis of appositionally grown mineralized tissue, International Journal of Osteoarchaeology 13 (2003) 96–103.

[102] J.C. Sealy, N.J. van der Merwe, A. Sillen, F.J. Kruger, H.W. Krueger, 87Sr/86Sr as a dietary indicator in modern and archaeological bone, Journal of Archaeological Science 18 (1991) 399–416.

[103] R.P. Shellis, G.H. Dibdin, Enamel microporosity and its functional implications, in: M.F. Teaford, M.M. Smith, M.W.J. Ferguson (Eds.), Development, Function and Evolution of Teeth, Cambridge University Press, Cambridge, 2000, pp. 242–251.

[104] A. Sillen, Diagenesis of the inorganic phase of cortical bone, in: T.D. Price (Ed.), The Chemistry of Prehistoric Human Bone, Cambridge University Press, Cambridge, 1989, pp. 211–228.

[105] A. Sillen, G. Hall, R. Armstrong, Strontium-calcium ratios (Sr/Ca) and strontium isotope ratios (87Sr/86Sr) of *Australopithecus robustus* and *Homo* Sp. from Swartkrans, Journal of Human Evolution 28 (1995) 277–285.

[106] A. Sillen, G. Hall, S. Richardson, R. Armstrong, 87Sr/86Sr ratios in modern and fossil food-webs of the Sterkfontein Valley: implications for early hominid habitat preferences, Geochimica et Cosmochimica Acta 62 (1998) 2463–2473.

[107] C. Stanish, Tiwanaku political economy, in: W.H. Isbell, H. Silverman (Eds.), Andean Archaeology I: Variations in Sociopolitical Organization, Kluwer Academic/Plenum Publishers, New York, 2002, pp. 169–198.

[108] E.M. Stovel, The Importance of Being Atacameño: Political Identity and Mortuary Ceramics in Northern Chile, Doctoral dissertation, Department of Anthropology, State University of New York at Bimghampton, 2002.

[109] R.C. Sutter, Prehistoric genetic and cultural change: a bioarchaeological search for the Pre-Inka Altiplano colonies in the coastal valleys of Moquegua, Peru and Azapa, Chile, Latin American Antiquity 11 (2000) 43–70.

[110] R.C. Sutter, L. Mertz, Non-metric cranial trait variation and prehistoric biocultural change in the Azapa Valley, Chile, American Journal of Physical Anthropology 123 (2003) 130–145.

[111] C.M. Torres, The iconography of the prehispanic snuff trays from San Pedro de Atacama, Northern Chile, Andean Past 1 (1987) 191–245.

[112] C.M. Torres, W.J. Conklin, Exploring the San Pedro de Atacama/Tiwanaku relationship, in: P. Dransart (Ed.), Andean Art: Visual Expression and Its Relation to Andean Beliefs and Values, Avebury, Aldershot, 1995, pp. 78–108.

[113] A. Tricca, P. Stille, M. Steinman, B. Kiefel, J. Samuel, J. Eikenberg, Rare earth elements and Sr and Nd isotopic compositions of dissolved and suspended loads from small river systems in the Vosges Mountains (France), the River Rhine and Groundwater, Chemical Geology 160 (1998) 139–158.

[114] T. Tung, K.J. Knudson, Local Ancestors or Foreign Enemies?: The Origin of Trophy Heads from the Wari Site of Conchopata, Current Anthropology, submitted for publication.

[115] J. Veizer, Strontium isotopes in seawater through time, Annual Review of Earth and Planetary Science 1 (1989) 141–167.

[116] H.A. Waldron, Postmortem absorption of lead by the skeleton, American Journal of Physical Anthropology 55 (1981) 395–398.

[117] H.A. Waldron, On the post-mortem accumulation of lead by skeletal tissues, Journal of Archaeological Science 10 (1983) 35–40.

[118] H.A. Waldron, A. Khera, G. Walker, G. Wibberly, C.J.S. Green, Lead concentrations in bones and soil, Journal of Archaeological Science 6 (1979) 295–298.

[119] D. Wallace, Tiwanaku as a symbolic empire, Estudios Arqueológicos 5 (1980) 133–144.