

Utility of Multiple Chemical Techniques in Archaeological Residential Mobility Studies: Case Studies From Tiwanaku- and Chiribaya-Affiliated Sites in the Andes

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ABSTRACT In the south central Andes, archaeologists have long debated the extent of Tiwanaku colonization during the Middle Horizon (AD 500–1000). We tested the hypotheses regarding the nature of Tiwanaku influence using strontium isotope, trace element concentration, and oxygen isotope data from archaeological human tooth enamel and bone from Tiwanaku- and Chiribaya-affiliated sites in the south central Andes. Strontium isotope analysis of 25 individuals buried at the Tiwanaku-affiliated Moquegua Valley site of Chen Chen demonstrates that it was likely a Tiwanaku colony. In contrast, no immigrants from the Lake Titicaca Basin were present in 27 individuals analyzed from the San Pedro de Atacama cemeteries of Coyo Oriental, Coyo-3, and Solcor-3; it is likely that these sites represent economic and religious alliances, but not colonies. However, strontium isotope analysis alone cannot distinguish movement between the Tiwanaku- and Chiribaya-

affiliated sites in the Moquegua and Ilo Valleys of southern Peru. Analyzing oxygen isotope and trace element concentration data and comparing it with strontium isotope data from the same individuals provides a more detailed picture of residential mobility in the Tiwanaku and Chiribaya polities. In addition to monitoring diagenetic contamination, trace element concentration data identified movement during adulthood for certain individuals. However, these data could not distinguish movement between the Moquegua and Ilo Valleys. While oxygen isotope data could clearly distinguish the high-altitude sites from others, more data is needed to characterize the local oxygen isotope ratios of these regions. These data demonstrate the potential for archaeological reconstruction of residential mobility through multiple lines of evidence. *Am J Phys Anthropol* 132:25–39, 2007. © 2006 Wiley-Liss, Inc.

Powerful techniques for identifying archaeological residential mobility are important for elucidating the role of migration in polity formation and organization in the Andes and beyond. Although using one technique to identify archaeological residential mobility can be informative, using a combination of techniques that can identify movement between different types of geologic and environmental zones can provide a more nuanced view of archaeological population movements. Here, we present strontium isotope, trace element concentration, and oxygen isotope data from individuals buried at 12 Andean cemeteries that date from AD 500–1100. These data are used to evaluate the highly contested nature of the Tiwanaku and Chiribaya polities as well as the utility of multiple chemical approaches to identify archaeological residential mobility. We test the hypotheses that the individuals buried in the Tiwanaku-affiliated sites of Chen Chen in southern Peru and Coyo Oriental, Coyo-3, and Solcor-3 in northern Chile were first-generation migrants from the Lake Titicaca Basin. Similarly, we test the hypothesis that the individuals buried in the southern Peruvian Chiribaya-affiliated cemeteries of Chiribaya Alta, Chiribaya Baja, San Gerónimo, and El Yaral were first-generation migrants from the mid-valley zone, where Tiwanaku-affiliated sites are located. First, residential mobility through bone chemistry is discussed. We then introduce the application to the Tiwanaku and Chiribaya polities and expected local isotopic and elemental signatures for the regions included in this study, followed by the results of strontium isotope, trace element concentration,

and oxygen isotope analysis from 12 Tiwanaku- and Chiribaya-affiliated sites, and our interpretations of these data.

BONE CHEMISTRY AND RESIDENTIAL MOBILITY

Most archaeological strontium isotope analyses address human residential mobility (Price et al., 1994; Sealy et al., 1995; Sillen et al., 1995; Grupe et al., 1997; Montgomery et al., 2005; Wright, 2005). Strontium substitutes for calcium in hydroxyapatite during the development of teeth and bones (Carr et al., 1962). Strontium isotope ratios in an individual's bone and teeth directly reflect

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the isotopic ratios found in the plants, animals, and water that she or he consumed, which reflect the isotope ratios found in the soil and bedrock of that geologic region. Differences in strontium isotope ratios in tooth enamel, which does not regenerate, and bone can be used to identify the geologic origins of first-generation migrants (Ericson, 1985).

In contrast, because of biopurification of calcium, the amount of strontium or barium relative to calcium decreases as one moves up the food chain (Burton et al., 1999). Archaeologists have determined the amounts of plant and animal material in an individual's diet, and, in the case of barium to calcium ratios (Ba/Ca), marine food consumption (Schoeninger, 1979; Burton, 1996). However, researchers have identified limitations of trace element concentrations to determine paleodiet (Sillen et al., 1989; Burton and Wright, 1995; Burton and Price, 2000; Sandford and Weaver, 2000). Since the strontium and barium concentrations in different geologic zones vary widely, these concentrations in bone from different geologic zones also vary widely (Turekian and Kulp, 1956a,b). Although this complicates paleodietary trace element analysis, it may be useful for migration studies (Burton et al., 2003).

Finally, analysis of oxygen isotopes in hydroxyapatite phosphate and carbonate elucidates paleoclimate and paleoecology (Longinelli, 1984; Fricke and O'Neil, 1996; Stuart-Williams and Schwarcz, 1997; Fricke et al., 1998). The oxygen isotopic signature of meteoric water ($\delta^{18}\text{O}_w$) is determined by environmental and climatic factors such as temperature, elevation, humidity, distance from the ocean, and latitude (Craig, 1961; Poage and Chamberlin, 2001). This oxygen isotope signature is deposited in hydroxyapatite carbonate ($\delta^{18}\text{O}_{sc}$) and phosphate ($\delta^{18}\text{O}_p$) in tooth enamel and bone, since body water and body phosphate and carbonate are in equilibrium when body temperature is constant (Longinelli, 1984; Luz et al., 1984). Provided that most oxygen came from local water sources, oxygen isotope analysis of hydroxyapatite carbonate and phosphate indicates the environment in which an individual was living while her or his tooth enamel and bone was forming. Recent oxygen isotope analyses have identified archaeological human migration in Mesoamerica and beyond (White et al., 2004).

For all of these techniques, it is necessary to ensure that the bone or tooth enamel was not changed by post-depositional contamination. Numerous studies have shown that bone is susceptible to diagenetic contamination from the burial environment, although tooth enamel is less so (Nelson et al., 1986; Sillen, 1989; Montgomery et al., 1999; Nielsen-Marsh and Hedges, 2000a). Mechanical and chemical cleaning of archaeological tooth enamel and bone can eliminate much of the diagenetic contamination that occurs, and monitoring the ratio of calcium to phosphorus (Ca/P) and uranium concentrations can identify contaminated samples (Lambert et al., 1991; Sillen and Sealy, 1995; Nielsen-Marsh and Hedges, 2000b).

In addition, nonlocal food sources can have a variable effect on an individual's isotopic signature. For example, if an individual eats large quantities of food from a region with a very similar strontium isotope signature, her or his strontium isotope signature may not change appreciably. However, relatively small quantities of high-calcium, and hence high-strontium, foodstuffs imported from a region with a dramatically different strontium isotope ratio may change the strontium isotope signature in an individual's tooth enamel and bone. This is also the case for trace element concentrations from various

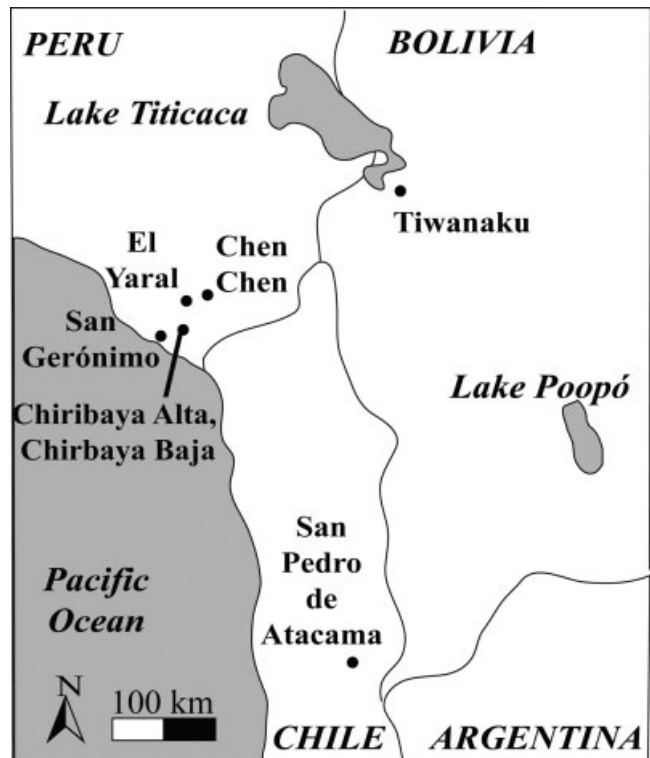


Fig. 1. Map of the south central Andes with Tiwanaku-affiliated sites of Tiwanaku, Chen Chen, and San Pedro de Atacama and Chiribaya-affiliated sites of El Yaral, San Gerónimo, Chiribaya Alta, and Chiribaya Baja.

geologic regions. For oxygen isotope analysis, the majority of oxygen in the body is from ingested water, so demonstrating local water consumption is necessary. For the populations included in this study, the lines of evidence used to determine the sources of the food and water consumed will be discussed later. In conclusion, these three techniques measure archaeological migration between different kinds of geologic or environmental zones and, together, provide a more complete picture of archaeological migration.

THE TIWANAKU AND CHIRIBAYA POLITIES OF THE SOUTH CENTRAL ANDES

Based in the Lake Titicaca Basin, the Tiwanaku polity exerted great political, economic, and religious influence over what are now southern Peru, northern Chile, and Bolivia. Despite the clear importance of the Tiwanaku polity between AD 500 and 1000, the exact nature of Tiwanaku influence has been controversial. Some scholars have argued that Tiwanaku established colonies in southern Peru and northern Chile at sites such as Chen Chen and San Pedro de Atacama (Fig. 1) (Ponce Sanginés, 1972; Goldstein, 1992; Oakland Rodman, 1992; Kolata, 1993), while Goldstein (2005) utilized a bottom-up perspective that focuses on the pluralistic nature of the Tiwanaku diaspora. Others argue that Tiwanaku influence involved economic and religious relationships that relied on llama caravans, but not on direct colonization (Lynch, 1983; Mujica et al., 1983; Browman, 1984; Dillehay and Núñez A., 1988).

The Tiwanaku-affiliated site of Chen Chen is located in the same drainage as the Chiribaya-affiliated sites of

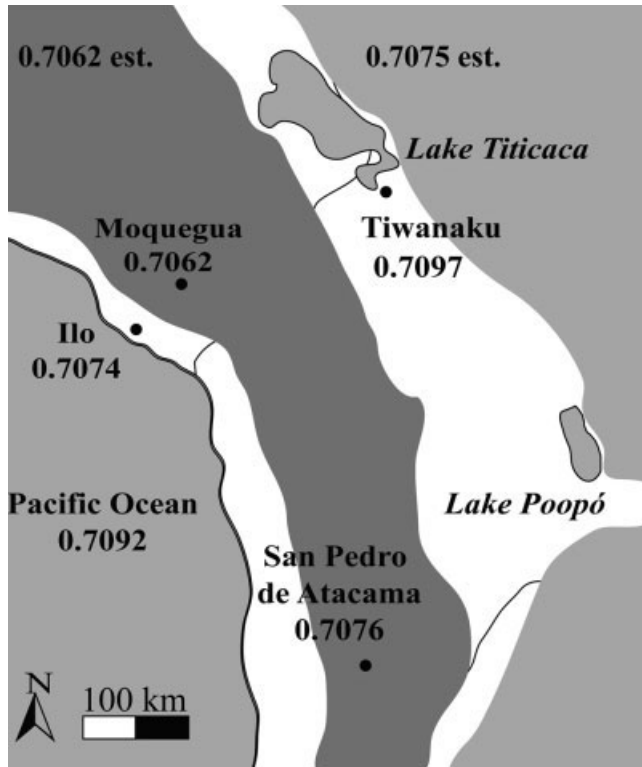


Fig. 2. Map of $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios in the south central Andes, including estimated averages for Cenozoic volcanics and volcanic-derived sediments (dark grey), Paleozoic marine sedimentary rocks (light grey), and seawater (Hawkesworth et al., 1982; James, 1982; Rogers and Hawkesworth, 1989). Values for the Moquegua and Ilo Valleys, San Pedro de Atacama, and Tiwanaku are based on analysis of modern fauna.

Chiribaya Alta, Chiribaya Baja, San Gerónimo, and El Yarál. Research on Chiribaya residential mobility has focused on the origins of the polity on the coast or in the highlands (Sutter, 2000; Lozada Cerna and Buikstra, 2002; Buikstra et al., 2005).

By identifying residential mobility in the individuals moving, instead of through their artifacts, isotope and trace element concentration analyses can examine the nature of Tiwanaku influence, Chiribaya origins, and the relationship between the Chiribaya- and Tiwanaku-affiliated sites. More specifically, we test the hypotheses that the individuals buried in the Tiwanaku-affiliated sites of Chen Chen in southern Peru and Coyo Oriental, Coyo-3, and Solcor-3 in northern Chile were, in part, first-generation migrants from the Lake Titicaca Basin. Similarly, we test the hypothesis that the individuals buried in the southern Peruvian Chiribaya-affiliated cemeteries of Chiribaya Alta, Chiribaya Baja, San Gerónimo, and El Yarál were first-generation migrants from the mid-valley zone where Tiwanaku-affiliated sites are located.

ANDEAN GEOLOGIC AND ENVIRONMENTAL CHEMICAL SIGNATURES

As shown in Figure 2, strontium isotope signatures for the Cenozoic volcanics of the Andes, where Chen Chen and San Pedro de Atacama are located, are lower than those found in seawater and in the dense alluvial deposits of the Lake Titicaca Basin. The Tiwanaku heartland is located on

the southeast edge of Lake Titicaca and is bordered by mountain ranges composed of Paleozoic andesites, sandstones, and red mudstones (Argollo et al., 1996). In the Tiwanaku River Basin where the site of Tiwanaku is located, the bedrock is composed of igneous basalts and andesites overlain by up to 10–20 m of Quaternary fluvial and lacustrine sediments (Argollo et al., 1996). Surface water from Lake Titicaca is characterized by $^{87}\text{Sr}/^{86}\text{Sr} = 0.7082\text{--}0.7085$, and four Lake Titicaca sediment cores had $^{87}\text{Sr}/^{86}\text{Sr} = 0.7083\text{--}0.7087$ ($n = 20$) (Grove et al., 2003).

Geologic analyses of the late Cenozoic volcanics of the south central Andes show that exposed bedrock samples from the San Pedro de Atacama region have $^{87}\text{Sr}/^{86}\text{Sr} = 0.7062\text{--}0.7068$ (Fig. 2) (Rogers and Hawkesworth, 1989). This geologic zone also includes the Moquegua and Ilo Valleys where both Tiwanaku- and Chiribaya-affiliated sites are located; here, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in exposed bedrock range from 0.7055 to 0.7068 (Hawkesworth et al., 1982; James, 1982; Rogers and Hawkesworth, 1989). Although the Moquegua and Ilo Valleys are not geologically distinct, we hypothesized that Chiribaya marine food consumption (Tomczak, 2003) would elevate strontium isotope ratios to the seawater signature, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7092$ (Veizer, 1989).

In addition, the geologic variability in our study area led us to hypothesize that these regions would also exhibit different Sr/Ca and Ba/Ca ratios. As discussed in more detail later, we tested this hypothesis using trace element concentration data from modern and archaeological guinea pig, or *cuy*, bone samples and one mouse bone from the south central Andes.

The south central Andes are also well suited for oxygen isotope analysis. We hypothesized that the differences in elevation, temperature, and precipitation patterns between the arid Ilo Valley, the fertile Moquegua Valley, and the high-altitude Lake Titicaca Basin would cause different oxygen isotope ($\delta^{18}\text{O}$) signatures. Oxygen isotope ratios in precipitation and local surface water support these hypotheses. Mean $\delta^{18}\text{O}_{\text{sc}} = -13.31$ to -10.76 relative to the Vienna standard mean ocean water (VSMOW) standard for precipitation measured in the Bolivian capital of La Paz between 1996 and 2001, and oxygen isotopes in groundwater and surface water in the Lake Titicaca Basin show a range of $\delta^{18}\text{O}_{\text{sc}} = -17.6$ to -12.6 relative to the VSMOW standard (IAEA/WMO, 2004). In contrast, mean $\delta^{18}\text{O}_{\text{sc}}$ from lower altitudes in southern Peru and northern Chile are expected to be higher than the altiplano samples (Wolfe et al., 2001).

METHODS

Tooth and bone samples were mechanically and chemically cleaned in the Laboratory for Archaeological Chemistry at the University of Wisconsin at Madison by K.J. Knudson, as described elsewhere (Knudson et al., 2004, 2005). Strontium isotope ratios 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 and K.J. Knudson, under the direction of P.D. Fullagar. Samples were prepared as reported elsewhere (Knudson et al., 2004, 2005), and 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 $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ to correct for mass fractionation. Long-term analyses over ~24 months of SRM 987 yield an average $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.710242. Internal precision for Sr carbonate runs is typ-

TABLE 1. Strontium isotope, trace element concentration, and oxygen isotope data for archaeological human samples

Site (sector)	Lab number	Specimen number	Age	Sex	Dental and skeletal material	Corrected $^{87}\text{Sr}/^{86}\text{Sr}$	Log (Ba/Ca)	Log (Sr/Ca)	$\delta^{18}\text{O}_{\text{sc}}$
Chen Chen (B)	F1015	M1-0681	50-80	M	LRC	0.706786	NA	NA	NA
Chen Chen (B)	F1700	M1-0681	50-80	M	Femur	0.706985	-4.05	-2.95	NA
Chen Chen (C)	F1016	M1-1600	40-45	M	LLM1	0.706932	NA	NA	-6.53
Chen Chen (C)	F1701	M1-1600	40-45	M	Femur	0.708850	-4.24	-3.10	NA
Chen Chen (L)	F1017	M1-3660-1	30-44	F	LRM1	0.706726	NA	NA	NA
Chen Chen (L)	F1702	M1-3660-1	30-44	F	Rib	0.707004	-3.93	-2.98	NA
Chen Chen (L)	F1018	M1-3718	50-80	F	LRC	0.706992	NA	NA	NA
Chen Chen (L)	F1703	M1-3718	50-80	F	Rib	0.706861	NA	NA	NA
Chen Chen (L)	F1019	M1-3840	35-39	F	LLM1	0.708843	NA	NA	-5.84
Chen Chen (L)	F1704	M1-3840	35-39	F	R ulna	0.707004	-3.83	-2.74	NA
Chen Chen (B)	F1020	M1-S/NB092	25-35	F	LRM1	0.709995	NA	NA	-6.78
Chen Chen (B)	F1705	M1-S/NB092	25-35	F	Rib	0.707165	-3.95	-3.10	NA
Chen Chen (A)	F1201	M1-0016	50-70	F	LLM1	0.706562	NA	NA	NA
Chen Chen (A)	F1205	M1-2947	50-80	F	LRM1	0.719211	NA	NA	-2.93
Chen Chen (I)	F1204	M1-2947	50-80	F	Rib	0.707688	-4.31	-3.20	NA
Chen Chen (I)	F1207	M1-3154	40-59	M	LRM1	0.706921	NA	NA	NA
Chen Chen (I)	F1206	M1-3154	40-59	M	Rib	0.706642	-4.51	-3.29	NA
Chen Chen (K)	F1209	M1-S/NK380	40-50	F	LLM1	0.707422	NA	NA	-7.04
Chen Chen (K)	F1208	M1-S/NK380	40-50	F	Rib	0.707109	-4.14	-3.00	NA
Chen Chen (D)	F1203	M1-2115	35-49	F	M1	0.707128	NA	NA	NA
Chen Chen (I)	F1966	M1-2622-1	30-70	M	LLM1	0.707362	NA	NA	NA
Chen Chen (K)	F1968	M1-3472	19-24	M	URM1	0.707031	NA	NA	-6.50
Chen Chen (K)	F1970	M1-3527	15-18	SA	LLM1	0.706702	NA	NA	NA
Chen Chen (A)	F1972	M1-0036	40-50	F	LLM1	0.714404	NA	NA	-4.21
Chen Chen (I)	F1974	M1-2762	19-21	PF	LLM1	0.708186	NA	NA	NA
Chen Chen (D)	F1976	M1-2068	18-21	F	LLM1	0.707136	NA	NA	NA
Chen Chen (E)	F1978	M1-2296	40-50	M	LLM1	0.707810	NA	NA	NA
Chen Chen (C)	F1980	M1-1370	35-45	M	LRM1	0.706785	NA	NA	NA
Chen Chen (L)	F1982	M1-3833	30-35	M	M1	0.707048	NA	NA	NA
Chen Chen (L)	F1984	M1-3768	20-34	F	ULM1	0.707191	NA	NA	NA
Chen Chen (K)	F1986	M1-3536	19-22	PF	LRM1	0.706700	NA	NA	NA
Chen Chen (L)	F1988	M1-3747	12-17	SA	LRM1	0.706844	NA	NA	-6.28
Chen Chen (A)	F1990	M1-0086	40-60	F	URM1	0.706887	NA	NA	NA
Chen Chen (L)	F1998	M1-0572	35-39	F	URM1	0.707087	NA	NA	NA
Chiribaya Alta (3)	F0683	CHA-1173	55-60	M	UM1	0.707335	NA	NA	NA
Chiribaya Alta (3)	F0685	CHA-1173	55-60	M	Femur	0.707475	-3.93	-3.22	NA
Chiribaya Alta (4)	F0700	CHA-3907	30-40	M	Lm1	0.708617	NA	NA	NA
Chiribaya Alta (4)	F0697	CHA-3907	30-40	M	Rib	0.707424	-4.45	-3.14	NA
Chiribaya Alta (7)	F0723	CHA-2375	35-45	F	Lm1	0.707162	NA	NA	NA
Chiribaya Alta (7)	F0724	CHA-2375	35-45	F	Femur	0.707347	-4.31	-3.06	NA
Chiribaya Alta (3)	F0679	CHA-3763	32-35	F	UM1	0.708861	NA	NA	-9.93
Chiribaya Alta (3)	F0681	CHA-3763	32-35	F	Femur	0.708675	-4.34	-3.14	NA
Chiribaya Alta (3)	F0687	CHA-1144	40-45	M	UM1	0.708847	NA	NA	NA
Chiribaya Alta (3)	F0688	CHA-1144	40-45	M	Femur	0.707430	-4.42	-3.38	NA
Chiribaya Alta (4)	F0702	CHA-3704	45+	M	Lm1	0.707693	NA	NA	NA
Chiribaya Alta (4)	F0704	CHA-3704	45+	M	Femur	0.707469	-4.38	-3.22	NA
Chiribaya Alta (7)	F0714	CHA-1475	30-40	F	Lm1	0.717065	NA	NA	-4.77
Chiribaya Alta (7)	F0716	CHA-1475	30-40	F	Rib	0.710031	-4.48	-3.13	NA
Chiribaya Alta (3)	F0691	CHA-3494	30-40	F	UM1	0.708053	NA	NA	NA
Chiribaya Alta (3)	F0692	CHA-3494	30-40	F	Rib	NA	-4.41	-3.15	NA
Chiribaya Alta (4)	F0694	CHA-1219	25-35	F	UM1	0.707707	NA	NA	-5.76

TABLE 1. (Continued)

Site (sector)	Lab number	Specimen number	Age	Sex	Dental and skeletal material	Corrected ⁸⁷ Sr/ ⁸⁶ Sr	Log (Ba/Ca)	Log (Sr/Ca)	δ ¹⁸ O _{sc}
Chiribaya Alta (4)	F0693	CHA-1219	25-35	F	Femur	NA	-4.53	-3.16	NA
Chiribaya Alta (4)	F0705	CHA-3610	25-32	F	UM1	0.707830	NA	NA	-4.58
Chiribaya Alta (4)	F0708	CHA-3610	25-32	F	Rib	NA	-4.59	-3.29	NA
Chiribaya Alta (7)	F0711	CHA-2574	25-35	M	LM1	0.707874	NA	NA	-6.33
Chiribaya Alta (7)	F0709	CHA-2574	25-35	M	Rib	NA	-4.40	-3.28	NA
Chiribaya Alta (7)	F0719	CHA-3218	45-50	M	LM1	0.707448	NA	NA	NA
Chiribaya Alta (7)	F0719	CHA-3218	45-50	M	Rib	NA	-4.48	-3.47	NA
Chiribaya Baja (1)	F0753	CHB-10035	MA	PF	UI1	0.706560	NA	NA	NA
Chiribaya Baja (1)	F0751	CHB-10035	MA	PF	Femur	0.707096	-4.19	-3.10	NA
Chiribaya Baja (1)	F0755	CHB-10488	MA	PM	UI1	0.707513	NA	NA	NA
Chiribaya Baja (1)	F0754	CHB-10488	MA	PM	Rib	0.708027	-3.18	-3.18	NA
Coyo-3	F1652	CO3-1	40-44	M	URM1	0.707608	NA	NA	NA
Coyo-3	F1653	CO3-1	40-44	M	Rib	NA	-3.76	-2.71	NA
Coyo-3	F1654	CO3-5	30-34	M	URM1	0.707704	NA	NA	NA
Coyo-3	F1655	CO3-5	30-34	M	Rib	NA	-3.76	-2.73	NA
Coyo-3	F1656	CO3-16	45-49	M	URM1	0.707526	NA	NA	NA
Coyo-3	F1657	CO3-16	45-49	M	Rib	NA	-3.61	-2.62	NA
Coyo-3	F1658	CO3-23 (13363)	40-44	F	ULM1	0.707712	NA	NA	NA
Coyo-3	F1659	CO3-23 (13363)	40-44	F	Rib	NA	-4.03	-2.60	NA
Coyo-3	F1661	CO3-32 (13576)	25-29	F	LLM2	0.707653	NA	NA	NA
Coyo-3	F1662	CO3-35 (13608)	30-34	M	ULM1	0.707782	NA	NA	NA
Coyo-3	F1662	CO3-35 (13608)	30-34	M	Rib	NA	-3.98	-2.63	NA
Coyo-3	F1664	CO3-35 (13611)	30-34	F	LM1	0.707641	NA	NA	NA
Coyo-3	F1665	CO3-35 (13611)	30-34	F	Rib	NA	-4.13	-2.53	NA
Coyo-3	F1666	CO3-45	19-20	F	LLM1	0.707667	NA	NA	NA
Coyo-3	F1667	CO3-45	19-20	F	Rib	NA	-4.00	-2.58	NA
Coyo-3	F1668	CO3-46	40-44	M	LRM2	0.706845	NA	NA	NA
Coyo-3	F1669	CO3-46	40-44	M	Rib	NA	-3.73	-2.59	NA
Coyo-3	F1660	CO3-23 (13357)	2	U	Rib	NA	-4.03	-2.55	NA
Coyo Oriental	F1637	CO-3978	40-44	M	ULM2	0.707773	NA	NA	NA
Coyo Oriental	F1638	CO-3981	45-49	M	ULM1	0.707628	NA	NA	NA
Coyo Oriental	F1639	CO-3996	35-39	F	URM2	0.707825	NA	NA	NA
Coyo Oriental	F1641	CO-4049	35-39	M	URM1	0.707023	NA	NA	NA
Coyo Oriental	F1642	CO-4064	35-39	M	ULM2	0.707690	NA	NA	NA
Coyo Oriental	F1643	CO-4090	35-39	M	LRM1	0.708171	NA	NA	NA
Coyo Oriental	F1644	CO-4093	40-44	M	LLM1	0.707713	NA	NA	NA
Coyo Oriental	F1645	CO-4150	40-44	F	URM2	0.707862	NA	NA	NA
Coyo Oriental	F1649	CO-5377	35-39	F	LRP2	0.707879	NA	NA	NA
Coyo Oriental	F1651	CO-5383	40-44	M	LRM1	0.707684	NA	NA	NA
Iwawe	F1199	LVIW-1	44-49	F	URI1	0.708850	NA	NA	NA
Iwawe	F1198	LVIW-1	44-49	F	Rib	NA	-3.06	-2.45	NA
Kirawi	F1195	CK65-1130	20-30	M	LRM1	0.712800	NA	NA	NA
Kirawi	F1194	CK65-1130	20-30	M	Tiba	NA	-3.53	-2.44	NA
Kirawi	F1191	CK65-1027	20-25	F	LRM1	0.707800	NA	NA	NA
Kirawi	F1190	CK65-1027	20-25	F	Radius	NA	-3.45	-2.45	NA
Kirawi	F1193	CK65-1100	12-15	PM	LLM1	0.709462	NA	NA	NA
Kirawi	F1192	CK65-1100	12-15	PM	MT5	NA	-3.78	-2.49	NA
Kirawi	F1197	CK65-1691	35-45	F	LLM1	0.710790	NA	NA	NA
Kirawi	F1196	CK65-1691	35-45	F	Rib	NA	-3.59	-2.67	NA
San Gerónimo	F0726	SG-5785	25-38	F	UM1	0.707338	NA	NA	NA

TABLE 1. (Continued)

Site (sector)	Lab number	Specimen number	Age	Sex	Dental and skeletal material	Corrected $^{87}\text{Sr}/^{86}\text{Sr}$	Log (Ba/Ca)	Log (Sr/Ca)	$\delta^{18}\text{O}_{\text{sc}}$
San Gerónimo	F0725	SG-5785	25-38	F	Femur	NA	-4.40	-3.23	NA
San Gerónimo	F0730	SG-3796	30-40	M	LM1	0.707038	NA	NA	NA
San Gerónimo	F0732	SG-3796	30-40	M	Femur	NA	-4.38	-3.23	NA
San Gerónimo	F0734	SG-3804	35-45	M	LM1	0.707320	NA	NA	NA
San Gerónimo	F0736	SG-3804	35-45	M	Femur	NA	-4.41	-3.17	NA
San Gerónimo	F0740	SG-1458	35-45	F	UM1	0.707433	NA	NA	NA
San Gerónimo	F0737	SG-1458	35-45	F	Femur	NA	-4.06	-2.85	NA
Solcor-3	F1670	SC3-5	35-39	M	LRM1	0.708206	NA	NA	NA
Solcor-3	F1671	SC3-6 (1078)	25-29	M	LLM1	0.707892	NA	NA	NA
Solcor-3	F1672	SC3-6 (1078)	25-29	M	Rib	NA	-4.08	-3.04	NA
Solcor-3	F1673	SC3-6 (1080)	50-54	F	ULM1	0.707663	NA	NA	NA
Solcor-3	F1674	SC3-6 (1080)	50-54	F	Rib	NA	-4.36	-3.11	NA
Solcor-3	F1675	SC3-8	40-44	F	LRM2	0.707725	NA	NA	NA
Solcor-3	F1676	SC3-8	40-44	F	Rib	NA	-4.08	-2.58	NA
Solcor-3	F1677	SC3-12	20-24	M	LLM1	0.708015	NA	NA	NA
Solcor-3	F1678	SC3-16	20-24	F	LLM1	0.707823	NA	NA	NA
Solcor-3	F1679	SC3-20	30-34	M	LRM1	0.707975	NA	NA	NA
Solcor-3	F1680	SC3-27	40-44	F	LLM1	0.707580	NA	NA	NA
Solcor-3	F1681	SC3-50	40-44	M	URM1	0.712522	NA	NA	NA
Solcor-3	F1683	SC3-50	40-44	M	Rib	NA	-4.01	-2.75	NA
Solcor-3	F1684	SC3-52	30-34	M	LLM1	0.708204	NA	NA	NA
Solcor-3	F1685	SC3-52	30-34	M	Rib	NA	-3.92	-2.64	NA
Solcor-3	F1686	SC3-55	30-34	M	ULM1	0.708118	NA	NA	NA
Solcor-3	F1687	SC3-55	30-34	M	Rib	NA	-3.65	-2.82	NA
Solcor-3	F1688	SC3-67	30-34	M	URM1	0.707699	NA	NA	NA
Solcor-3	F1689	SC3-67	30-34	M	Rib	NA	-3.89	-2.65	NA
Solcor-3	F1690	SC3-69	30-34	M	LRM2	0.708072	NA	NA	NA
Solcor-3	F1691	SC3-69	30-34	M	Rib	NA	-3.91	-2.65	NA
Solcor-3	F1692	SC3-78	40-44	M	LLM1	0.707837	NA	NA	NA
Solcor-3	F1693	SC3-78	40-44	M	Rib	NA	-3.95	-2.60	NA
Solcor-3	F1694	SC3-106	<i>fardo</i>	<i>fardo</i>	LLM1	0.708093	NA	NA	NA
Solcor-3	F1695	SC3-117	25-29	M	LRM1	0.708052	NA	NA	NA
Tilata	F1217	TMV101-392	20-34	F	LRM1	0.708223	NA	NA	NA
Tilata	F1216	TMV101-392	20-34	F	Longbone	0.709684	-3.93	-3.04	NA
Tiwanaku (Akapana East)	F1012	AKE-20727	18-21	F	LRM1	0.710334	NA	NA	NA
Tiwanaku (Akapana East)	F1696	AKE-20727	18-21	F	Femur	NA	-3.28	-2.74	NA
Tiwanaku (Akapana East)	F1013	AKE-8908	18-21	PM	LRM1	0.709674	NA	NA	-16.63
Tiwanaku (Akapana East)	F1697	AKE-8908	18-21	PM	Tibia	NA	-2.72	-2.52	NA
Tiwanaku (Akapana)	F1189	AK-4931	17-30	PF	URI2	0.716256	NA	NA	-16.47
Tiwanaku (Akapana)	F1188	AK-4931	17-30	PF	Rib	0.709595	-2.80	-2.61	NA
Tiwanaku (Akapana)	F1187	AK-12149	50-59	M	LRM1	0.709513	NA	NA	-17.38
Tiwanaku (Akapana)	F1186	AK-12149	50-59	M	Femur	NA	-3.06	-2.71	NA
Tiwanaku (Ch'iji Jawira)	F1014	CJ-35250	30-39	F	URI1	0.709674	NA	NA	-15.85
Tiwanaku (Ch'iji Jawira)	F1699	CJ-35250	30-39	F	Tibia	NA	-3.92	-2.89	NA
Tiwanaku (Mollu Kontu)	F1021	MK-29412	22-24	F	LLM1	0.708320	NA	NA	NA
Tiwanaku (Mollu Kontu)	F1706	MK-29412	22-24	F	Rib	NA	-2.92	-2.70	NA
Tiwanaku (Mollu Kontu)	F1213	MK-39788	40-60	F	LLM1	0.708478	NA	NA	NA
Tiwanaku (Mollu Kontu)	F1212	MK-39788	40-60	F	Longbone	0.708478	NA	NA	NA
Tiwanaku (Mollu Kontu)	F1210	MK-39787	35-45	PM	Rib	NA	-3.17	-2.66	NA
Tiwanaku (Putuni)	F1215	PUT-20995	20-24	F	ULM1	0.709523	NA	NA	-16.95

TABLE 1. (Continued)

Site (sector)	Lab number	Specimen number	Age	Sex	Dental and skeletal material	Corrected ⁸⁷ Sr/ ⁸⁶ Sr	Log (Ba/Ca)	Log (Sr/Ca)	δ ¹⁸ O _{sc}
Tiwanaku (Putumi)	F1022	PUT-24106	20-29	M	LRM1	0.711303	NA	NA	-16.70
Tiwanaku (Putumi)	F1707	PUT-24106	20-29	M	Rib	0.709891	-3.00	-2.76	NA
Tiwanaku (Putumi)	F1023	PUT-25785-1	18-21	F	LLM1	0.711758	NA	NA	NA
Tiwanaku (Putumi)	F1708	PUT-25785-1	18-21	F	Rib	0.709731	-3.26	-2.73	NA
El Yaral	F0677	M8-10166	30-45	F	UM1	0.707202	NA	NA	NA
El Yaral	F0674	M8-10166	30-45	F	Femur	0.707291	-4.44	-3.25	NA
El Yaral	F0665	M8-10187	32-35	F	UM1	0.706886	NA	NA	NA
El Yaral	F0662	M8-10187	32-35	F	Rib	0.706985	-4.24	-2.78	NA
El Yaral	F0669	M8-10212	±50	M	UM1	0.707472	NA	NA	NA
El Yaral	F0666	M8-10212	±50	M	Rib	0.707428	-4.08	-2.87	NA
El Yaral	F0671	M8-10427	32-40	M	UM1	0.717364	NA	NA	NA
El Yaral	F0670	M8-10427	32-40	M	Rib	0.706858	-4.50	-3.06	NA

ically 0.0006–0.0009% standard error, based on 100 dynamic cycles of data collection.

Trace element analysis of archaeological human bone was performed by K.J. Knudson and J.H. Burton, using an Applied Research Labs Model 3520 inductively coupled plasma–atomic emission spectrometer (ICP-AES) in the Laboratory for Archaeological Chemistry at the University of Wisconsin at Madison. Approximately 50 mg of powdered bone ash was dissolved in 1.0 mL ultrapure concentrated HNO₃, heated to 100°C for 1 h, and diluted with 17 mL deionized water. Analyses of Laboratory for Archaeological Chemistry standard reference 9511 yielded the following trace element concentrations in ppm: Ca = 3.12 × 10⁴ ± 1.42 × 10³ (2σ, n = 7), Sr = 142.9 ± 10.0 (2σ, n = 7), Ba = 211.6 ± 7.1 (2σ, n = 7), and P = 5.39 × 10³ ± 2.24 × 10² (2σ, n = 7). Long-term analyses of laboratory standards and international bone standard reference material have determined an accuracy of ±5% and a precision of ±2% (Burton et al., 2003). The Ca/P generated through the ICP-AES identified samples that exhibited diagenetic contamination.

Diagenetic contamination was also monitored through uranium concentrations in a subset of enamel and bone samples; biogenic uranium concentrations should be below the detection limits of inductively coupled plasma–mass spectrometry (ICP-MS). Approximately 4 mg of tooth enamel or bone ash was dissolved in 0.5 mL ultrapure concentrated HNO₃, heated to 100°C for 1 h, and diluted with 19.5 mL deionized water. K.J. Knudson and J.H. Burton obtained the uranium concentrations using a Finnegan Element ICP-MS in the Laboratory for Archaeological Chemistry at the University of Wisconsin at Madison. Total procedural blanks for uranium were below the levels of ICP-MS detection, and strontium carbonate standard NIST 1400 yielded U = 0.024 ± 0.31 ppm (2σ, n = 11). Tooth enamel samples did not exhibit evidence of contamination, although some bone samples did and will be discussed later.

Oxygen isotope analysis on archaeological enamel carbonate (δ¹⁸O_{sc}) was performed by D. Dettman of the Stable Isotope Laboratory in the Department of Geosciences at the University of Arizona. Sample preparation was performed by K.J. Knudson at the Laboratory for Archaeological Chemistry using established methodologies (Koch et al., 1997). Approximately 6 mg of tooth enamel was analyzed for carbon (δ¹³C_{sc}) and oxygen isotope analysis (δ¹⁸O_{sc}), using a Finnigan MAT 252 mass spectrometer, with a Kiel III automated carbonate sampling device. Samples were reacted with 100% orthophosphoric acid at 70°C and normalized using NBS-18 and NBS-19. Replicates of NBS-19 resulted in a reproducibility of ±0.08% (1σ) for δ¹³C and ±0.1‰ for δ¹⁸O. Oxygen isotope ratios (δ¹⁸O_{sc}) are reported relative to the V-PDB carbonate standard and are expressed in per thousand (‰) using the standard formula δ¹⁸O = (((¹⁸O/¹⁶O_{sample})/(¹⁸O/¹⁶O_{standard})) - 1) × 1,000 (Coplen, 1994).

MATERIALS

The sampling strategy of archaeological human remains was designed to reflect the age and sex composition of the cemeteries, which date to a single ceramic phase. At least one tooth enamel sample, preferably a first molar, was collected from each individual; enamel was collected from the buccal or lingual surface, from the cusp to the cement–enamel junction. A rib or femoral fragment was collected when available in order to pro-

TABLE 2. Strontium isotope, trace element concentration, and oxygen isotope data for archaeological and modern fauna samples

Site (sector)	Lab number	Specimen number	Material	Corrected $^{87}\text{Sr}/^{86}\text{Sr}$	Log (Ba/Ca)	Log (Sr/Ca)	$\delta^{18}\text{O}_{\text{sc}}$
Chiribaya Baja	F757	CHB-11804	cuy bone (archeological)	0.707891	NA	NA	NA
Chiribaya Baja	F758	CHB-13176	cuy bone (archeological)	0.706719	NA	NA	NA
Ilo	F1242	I5A	cuy bone (modern)	NA	-4.00	-2.67	NA
Ilo	F1923	I3B	cuy enamel (modern)	NA	-4.05	-2.69	-3.39
Ilo	F1924	I4B	cuy enamel (modern)	NA	-3.97	-2.68	-2.22
Ilo	F1925	I9A	cuy enamel (modern)	NA	-4.51	-2.95	NA
Ilo	F1926	I10A	cuy enamel (modern)	NA	-4.30	-2.85	NA
Ilo	F1927	I11A	cuy enamel (modern)	NA	-3.89	-2.59	NA
Ilo	F1928	I12A	cuy enamel (modern)	NA	-3.91	-2.64	NA
Ilo	F1248	I11A	cuy bone (modern)	0.706709	-3.76	-2.64	-17.25
Ilo	F1238	I3A	cuy bone (modern)	NA	-3.86	-2.64	NA
Ilo	F1236	I1A	cuy bone (modern)	NA	-4.07	-2.70	NA
Ilo	F1239	I3B	cuy bone (modern)	0.706682	-3.86	-2.62	NA
Ilo	F1237	I2A	cuy bone (modern)	NA	-3.88	-2.65	NA
Ilo	F1240	I4A	cuy bone (modern)	NA	-3.82	-2.65	NA
Ilo	F1241	I4B	cuy bone (modern)	NA	-3.81	-2.64	NA
Ilo	F1243	I6A	cuy bone (modern)	NA	-3.84	-2.66	NA
Ilo	F1244	I7A	cuy bone (modern)	NA	-3.89	-2.68	NA
Ilo	F1245	I8A	cuy bone (modern)	NA	-3.89	-2.65	NA
Ilo	F1246	I9A	cuy bone (modern)	NA	-4.37	-2.86	NA
Ilo	F1247	I10A	cuy bone (modern)	NA	-4.20	-2.81	NA
Ilo	F1249	I12A	cuy bone (modern)	NA	-3.81	-2.68	NA
Moquegua	F3070	M3A	cuy enamel (modern)	NA	NA	NA	0.14
Moquegua	F1252	M3A	cuy bone (modern)	NA	NA	NA	NA
Moquegua	F1259	M12A	cuy bone (modern)	NA	-3.61	-2.50	NA
Moquegua	F1257	M10A	cuy bone (modern)	NA	-3.54	-2.50	NA
Moquegua	F1029	M14A	cuy bone (modern)	0.706121	-3.74	-2.35	NA
Moquegua	F1250	M1A	cuy bone (modern)	NA	-3.88	-2.63	NA
Moquegua	F1251	M2A	cuy bone (modern)	NA	-3.81	-2.20	NA
Moquegua	F3069	M2A	cuy enamel (modern)	NA	NA	NA	0.00
Moquegua	F1027	M5A	cuy bone (modern)	0.706184	-3.46	-2.53	NA
Moquegua	F1254	M6A	cuy bone (modern)	NA	-4.03	-2.69	NA
Moquegua	F1931	M6B	cuy bone (modern)	NA	-4.00	-2.68	NA
Moquegua	F1255	M7A	cuy bone (modern)	NA	-3.76	-2.16	NA
Moquegua	F1932	M7B	cuy bone (modern)	NA	-3.74	-2.14	NA
Moquegua	F1256	M8A	cuy bone (modern)	NA	-3.97	-2.64	NA
Moquegua	F1028	M9A	cuy bone (modern)	0.706452	-3.42	-2.45	NA
Moquegua	F1258	M11A	cuy bone (modern)	NA	-3.54	-2.53	NA
Moquegua	F1260	M13A	cuy bone (modern)	NA	-3.57	-2.50	NA
Moquegua	F1933	M6B	cuy enamel (modern)	NA	-4.17	-2.74	NA
Moquegua	F1934	M7B	cuy enamel (modern)	NA	-3.92	-2.15	NA
Moquegua	F1935	M10B	cuy enamel (modern)	NA	-3.68	-2.44	NA
Moquegua	F1936	M11B	cuy enamel (modern)	NA	-3.78	-2.55	NA
Moquegua	F1937	M12B	cuy enamel (modern)	NA	-3.84	-2.52	NA
San Pedro	F1714	SPA1	cuy bone (modern)	NA	-3.86	-2.23	NA
San Pedro (Quitor)	F1635	QT6-18	mouse bone (archaeological)	0.707659	-3.76	-2.49	NA
San Pedro (Quitor)	F1636	QT6-33	dog tibia (archaeological)	0.707762	NA	NA	NA
San Pedro (Quitor)	F1714	SPA1	cuy bone (modern)	0.707511	NA	NA	NA
Titicaca Basin (Chiripa)	F1024	Ch1A	cuy bone (modern)	0.709291	NA	NA	NA
Titicaca Basin (Lukurmata)	F1025	L2A	cuy bone (modern)	0.710561	NA	NA	NA
Tiwanaku	F3073	T3A	cuy enamel (modern)	NA	NA	NA	-5.31
Tiwanaku	F3074	T5A	cuy enamel (modern)	NA	NA	NA	-4.62
Tiwanaku	F1718	T7	cuy bone (modern)	NA	-3.18	-2.41	NA
Tiwanaku	F1912	T5A	cuy bone (modern)	NA	-3.30	-2.51	NA
Tiwanaku	F1026	T1A	cuy bone (modern)	0.709291	-3.72	-2.58	NA
Tiwanaku	F1715	T3A	cuy bone (modern)	NA	-3.43	-2.66	NA
Tiwanaku	F1913	T3B	cuy bone (modern)	NA	-3.48	-2.64	NA
Tiwanaku	F1716	T4A	cuy bone (modern)	NA	-3.48	-2.64	NA
Tiwanaku	F1914	T4B	cuy bone (modern)	NA	-3.48	-2.67	NA
Tiwanaku	F1915	T5B	cuy bone (modern)	NA	-3.34	-2.51	NA
Tiwanaku	F1717	T6A	cuy bone (modern)	NA	-3.31	-2.47	-20.30
Tiwanaku	F1916	T6B	cuy bone (modern)	NA	-3.35	-2.48	NA

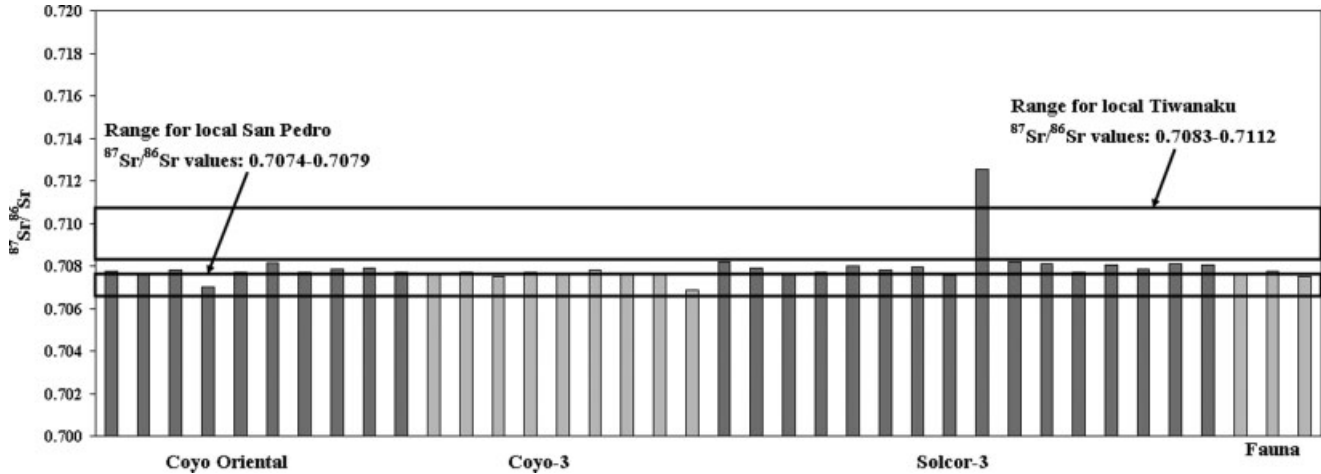


Fig. 3. Strontium isotope ratios from human tooth enamel from the cemeteries of Coyo Oriental, Coyo-3, and Solcor-3, as well as modern fauna bone from San Pedro de Atacama, Chile.

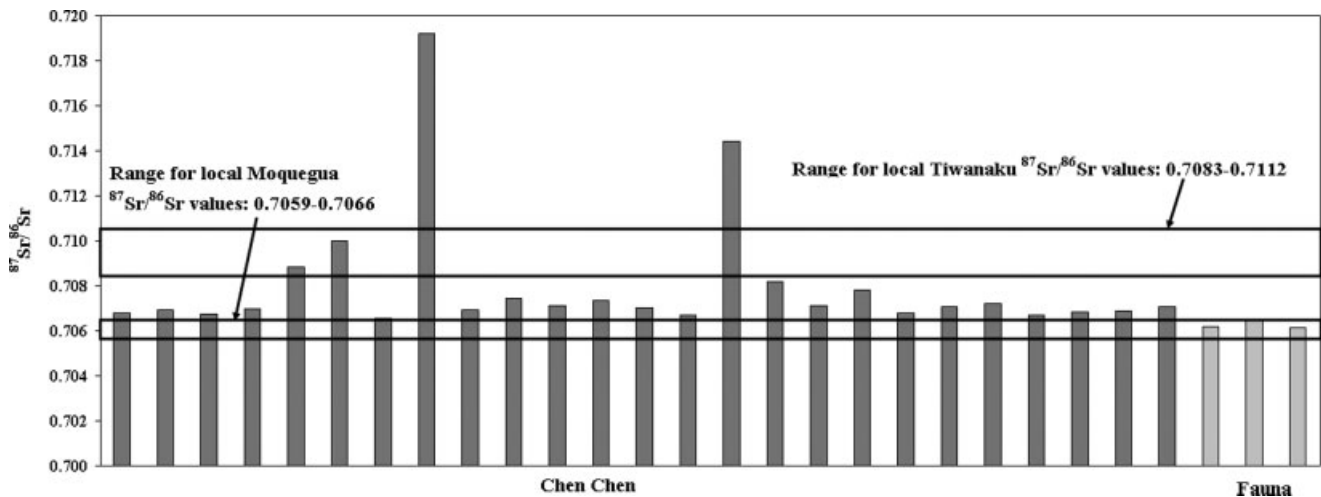


Fig. 4. Strontium isotope ratios from human tooth enamel from the cemetery of Chen Chen, as well as modern *cuy* bone from Moquegua, Peru.

vide information about the place of residence before death. The samples are listed in Table 1 and detailed contextual information is given in previous publications (Lozada Cerna and Buikstra, 2002; Blom et al., 2003; Knudson, 2004; Knudson et al., 2004). In addition, K.J. Knudson collected modern and archaeological small mammal samples from the study regions (Table 2). Modern guinea pigs were purchased from their owners, who provided the necessary life history information on these animals and their diets. Archaeological faunal samples were collected when modern guinea pigs were unavailable.

STRONTIUM ISOTOPE RESULTS

The strontium isotope values found in geologic analyses of exposed bedrock and groundwater closely match the strontium isotope ratios in modern fauna from the regions included in this study. Since strontium isotope ratios in bedrock, soil, and water within a given region can vary widely, the biologically available strontium isotope ratios were determined using modern fauna (Price

et al., 2002). Analysis of modern and archaeological faunal bones as well as samples from one archaeological mouse and one archaeological dog from the southern Lake Titicaca Basin, the Moquegua Valley, the Ilo Valley, and the San Pedro de Atacama oasis support the strontium isotope ratios reported in the geologic literature (Knudson, 2004; Knudson et al., 2004). By taking the mean of the *cuy*, or guinea pig, bone strontium isotope data plus and minus two standard deviations (Price et al., 2002), the local ranges of the strontium isotope signatures for the regions included in this study are as follows: $^{87}\text{Sr}/^{86}\text{Sr} = 0.7083\text{--}0.7112$ for the southeastern Lake Titicaca Basin, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7074\text{--}0.7079$ for the San Pedro de Atacama region, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7059\text{--}0.7066$ for the Moquegua Valley, and $^{87}\text{Sr}/^{86}\text{Sr} = 0.7058\text{--}0.7082$ for the Ilo Valley. The strontium isotope signatures for the southeastern Lake Titicaca Basin, the San Pedro de Atacama region, and the Moquegua Valley are distinct and nonoverlapping, and are similar to the published geologic values. However, not surprisingly, the strontium isotope signatures of the Moquegua and Ilo Valleys cannot be distinguished.

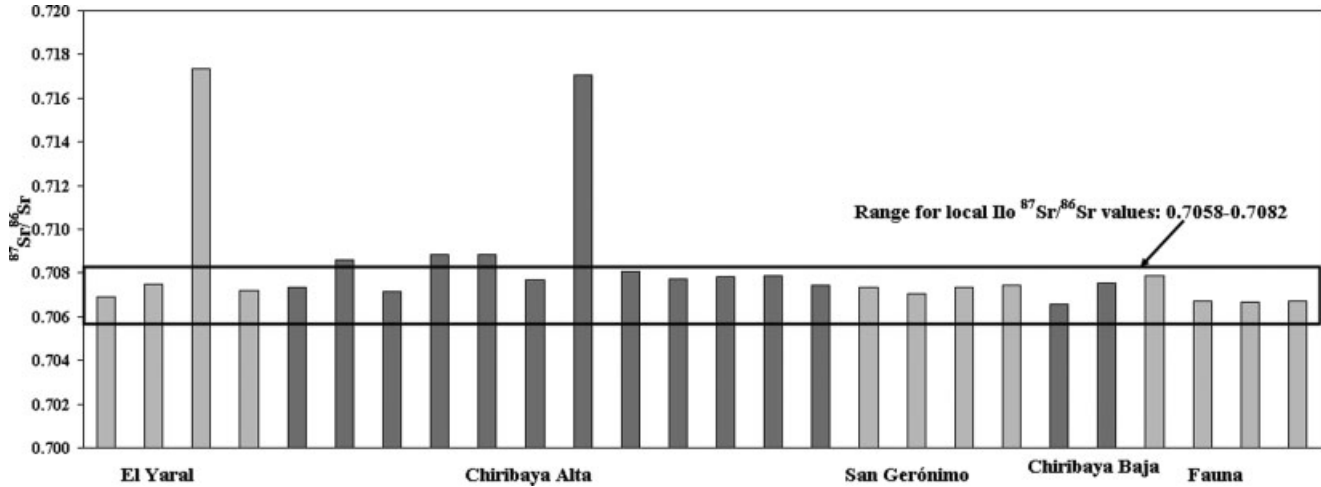


Fig. 5. Strontium isotope ratios from human tooth enamel from the cemeteries of El Yaral, Chiribaya Alta, San Gerónimo and Chiribaya Baja, as well as archaeological *cuy* bone from the site of Chiribaya Baja and modern *cuy* bone from Ilo, Peru.

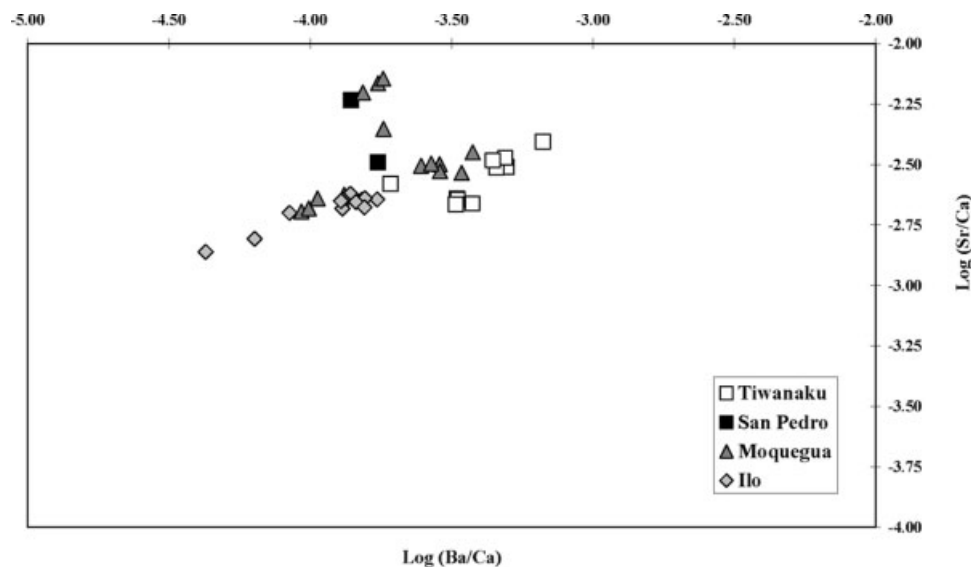


Fig. 6. $\text{Log}(\text{Ba}/\text{Ca})$ versus $\text{log}(\text{Sr}/\text{Ca})$ for archaeological and modern *cuy* and mice bone samples from the south central Andes.

Strontium isotope analysis of individuals buried in Tiwanaku- and Chiribaya-affiliated sites shows that residential mobility was variable. As shown in Figure 3, strontium isotope analysis of archaeological human tooth enamel from the cemeteries of Coyo Oriental, Coyo-3, and Solcor-3 shows that none of the individuals analyzed have strontium isotope ratios that match those in the southeastern Lake Titicaca Basin (Fig. 3, Table 1) (Knudson, 2004).

In contrast, strontium isotope analysis shows that some individuals buried in the Tiwanaku-affiliated site of Chen Chen may have lived in the southeastern Lake Titicaca Basin during the first years of life (Fig. 4, Table 1) (Knudson, 2004; Knudson et al., 2004). Two individuals have strontium isotope ratios that are within the Lake Titicaca Basin signature, even though they were buried at Chen Chen (Knudson, 2004; Knudson et al., 2004). As shown in Table 1, bone strontium isotope values show that the individuals with nonlocal enamel strontium iso-

tope signatures all have bone strontium isotope ratios that approach the local signature at Chen Chen, implying that these individuals lived at or near Chen Chen long enough to incorporate local strontium isotope ratios into the bones. The bone samples analyzed from Chen Chen had uranium concentrations below the detection limits of the ICP-MS, with the exception of M1-3660-1, which had a low uranium concentration of 0.196 ppm (Knudson, 2004). This is no doubt due in part to the exceptional preservation at Chen Chen.

As shown in Figure 5, individuals whose tooth enamel strontium isotope signatures are nonlocal to the region were buried at El Yaral and Chiribaya Alta (Fig. 5, Table 1). Strontium isotope ratios were also most variable at the site of Chiribaya Alta, where mortuary assemblages, cranial modification styles, and paleodiet were also highly variable (Lozada Cerna and Buikstra, 2002; Tomczak, 2003; Buikstra et al., 2005). Smaller coastal Chiribaya sites, such as San Gerónimo and Chiri-

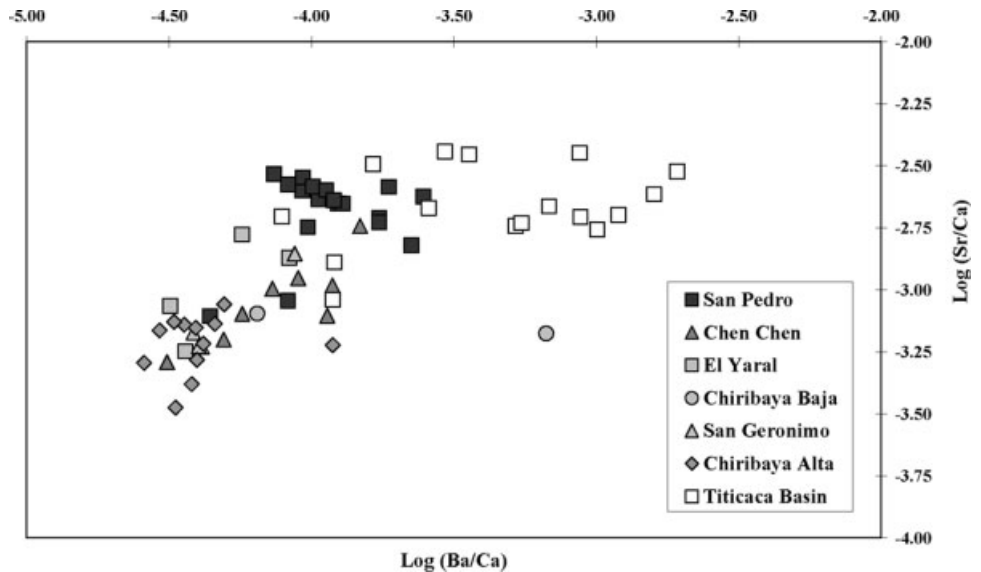


Fig. 7. Log (Ba/Ca) versus log (Sr/Ca) for archaeological human bone from the south central Andes.

baya Baja, show less variability in enamel strontium isotope ratios. However, the local range as determined by modern and archaeological fauna from Ilo and Chiribaya Baja is quite large, and in fact encompasses the local Moquegua range. Therefore, strontium isotope analysis alone cannot distinguish movement between the Moquegua and Ilo Valleys, and other chemical techniques to identify migration must be used.

TRACE ELEMENT CONCENTRATION RESULTS

In an attempt to obtain a higher resolution on movement between different geologic zones in the south central Andes, trace element concentration analysis using ICP-AES was performed on archaeological human bone samples from the San Pedro de Atacama sites of Coyo-3 and Solcor-3, the Moquegua Valley sites of Chen Chen and El Yaral, the Ilo Valley sites of Chiribaya Alta, Chiribaya Baja, and San Gerónimo, and the Lake Titicaca Basin sites of Tiwanaku, Kirawi, Iwawe, and Tilata. First, trace element analysis using ICP-AES was performed on modern and archaeological guinea pig, or *cuy*, bone samples and one mouse bone from the south central Andes. The faunal bone data in Figure 6 show that modern *cuy* from the southeastern Lake Titicaca Basin clusters as do the San Pedro de Atacama faunal samples, while the samples from the Moquegua Valley overlap with the samples from the Ilo Valley (Fig. 6, Table 2). Enamel samples taken from a subset of the same animals show the same trends, though the enamel is depleted in barium and, to a lesser extent, strontium because of biopurification during enamel formation in utero and during infancy (Table 2).

The archaeological human bone samples follow the same general geographic trends as the modern and archaeological fauna data, although the Sr/Ca and Ba/Ca ratios for the faunal samples reflect their trophic position as herbivores (Fig. 7, Table 1). The trace element concentrations in archaeological human bone samples show that some regions cluster together while others clearly overlap. The San Pedro de Atacama data set is homogenous, which was also seen in the strontium isotope data. However, there are some bone samples from

San Pedro de Atacama that do not cluster with the other San Pedro samples. Although the first molar enamel values implied that this woman (SC-6(1080), $^{87}\text{Sr}/^{86}\text{Sr} = 0.707663$) spent the first 3–4 years of her life in the San Pedro de Atacama region (Hillson, 1996), the bone values (SC-6(1080), Ba/Ca = -4.36 , Sr/Ca = -3.11) imply that this woman spent the last years of her life in another geologic zone or in eating imported foods. There is no evidence of large amounts of imported foods in San Pedro de Atacama, and so it is likely that the trace element data have identified movement during adulthood in this woman and in the other San Pedro de Atacama outliers. In addition, as in the Chen Chen bone samples, the majority of the San Pedro de Atacama bone samples presented here did not exhibit any signs of diagenetic contamination based on the Ca/P ratios present. The one exception was a rib sample from SC-8; in this sample Ca/P = 2.30, which is higher than the biogenic ratio of Ca/P = 2.1 (Sillen, 1989; Price et al., 1994).

In the Lake Titicaca Basin, the variability in the Sr/Ca and Ba/Ca ratios is similar to variability in enamel strontium isotope ratios from the same individuals (Knudson, 2004; Knudson et al., 2004). However, the bone data from the southeastern Lake Titicaca Basin exhibits more evidence of diagenesis than the other regions included in this study, largely because of the sites' hydrology and poor preservation of the bone (Knudson, 2004).

Finally, the trace element data does not clearly distinguish between the Moquegua and Ilo Valleys, where Chen Chen and the Chiribaya-affiliated sites are located. Given the overlap in the *cuy* trace element concentration data between the two regions, it is impossible to determine whether the overlap in the human trace element concentration data results from movement between the Moquegua and Ilo Valleys or whether these are local populations living in areas with variable trace element concentrations. Therefore, another means of identifying movement between the Moquegua Valley and the Ilo Valley must be utilized in order to test the hypotheses regarding Chiribaya origins and relationships with Tiwanaku-affiliated populations in the Moquegua Valley.

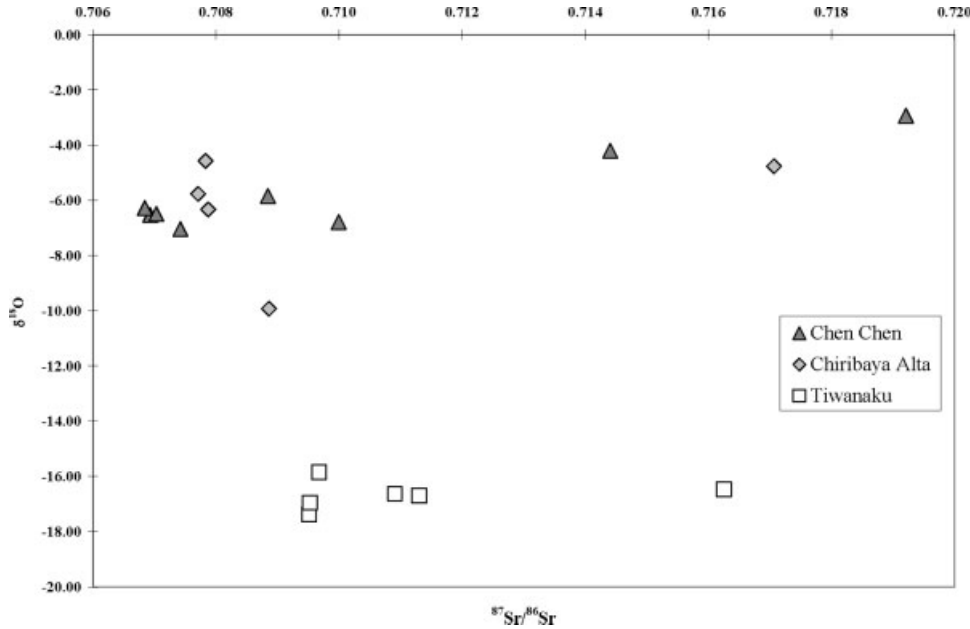


Fig. 8. Strontium isotope ratios versus oxygen isotope ratios for archaeological human tooth enamel from the south central Andean sites of Chen Chen, Chiribaya Alta, and Tiwanaku.

OXYGEN ISOTOPE RESULTS

As shown in Figure 8, the oxygen isotope data showed clear differences between individuals buried at Tiwanaku and the sites of Chen Chen and Chiribaya Alta (Fig. 8, Table 1). Individuals buried at Tiwanaku have much lower oxygen isotope values ($\delta^{18}\text{O}_{\text{sc}}$) than do the lower-altitude sites of Chen Chen and Chiribaya Alta. One outlier was a human sacrifice on the Akapana pyramid (AK-4931, $\delta^{18}\text{O}_{\text{sc}} = -16.47$) (Knudson et al., 2004).

However, the two individuals who were buried at Chen Chen and exhibited Lake Titicaca Basin strontium isotope signatures do not exhibit Lake Titicaca Basin oxygen isotope signatures in their tooth enamel (M1-3840, $^{87}\text{Sr}/^{86}\text{Sr} = 0.708843$, $\delta^{18}\text{O}_{\text{sc}} = -5.84$, and M1-S/NB092, $^{87}\text{Sr}/^{86}\text{Sr} = 0.709995$, $\delta^{18}\text{O}_{\text{sc}} = -6.78$). In addition, a third nonlocal individual at Chen Chen (M1-2947, $^{87}\text{Sr}/^{86}\text{Sr} = 0.719211$, $\delta^{18}\text{O}_{\text{sc}} = -2.93$), based on strontium isotope ratios, has a very high $\delta^{18}\text{O}_{\text{sc}}$ that is most similar to published $\delta^{18}\text{O}_{\text{sc}}$ values from coastal Ilo Valley sites (Tomczak, 2001). The material culture at Chen Chen does not point to coastal contacts, and instead points to affiliations with the Lake Titicaca Basin. Similar strontium and oxygen isotope values are seen in an individual buried at Chiribaya Alta (CHA-1475, $^{87}\text{Sr}/^{86}\text{Sr} = 0.717065$, $\delta^{18}\text{O}_{\text{sc}} = -4.77$). Although high strontium isotope ratios are found in the northern Lake Titicaca Basin (Grove et al., 2003), the oxygen isotope evidence shows that this individual was not in fact from the northern Lake Titicaca Basin. However, the variability in the Chiribaya Alta oxygen isotope ratios makes it difficult to distinguish the local oxygen isotope signatures at Chen Chen and Chiribaya Alta.

RESIDENTIAL MOBILITY AT TIWANAKU- AND CHIRIBAYA-AFFILIATED SITES

At the northern Chilean oasis of San Pedro de Atacama, interpretations of the nature of Tiwanaku influence have varied. For example, based on biodistance analysis of cranial nonmetric traits and the presence of Tiwanaku-style artifacts in the cemeteries of Coyo Ori-

ental, Coyo-3, and Solcor-3, some scholars have argued that a population of immigrants from the Lake Titicaca Basin was present in the oasis of San Pedro de Atacama (Oakland Rodman, 1992; Varela and Cocilovo, 2000). However, based on mortuary ceramics, cranial modification styles, and the presence of locally produced mortuary artifacts, other researchers have argued that there was not a population of Tiwanaku immigrants at the oasis (Stovel, 2002; Torres-Rouff, 2002).

Strontium isotope analysis of individuals buried in the Tiwanaku-affiliated cemeteries of Coyo Oriental, Coyo-3, and Solcor-3 shows that none of the individuals analyzed have strontium isotope ratios that match those in the southeastern Lake Titicaca Basin. These data do not support the hypothesis that San Pedro was a Tiwanaku colony populated by immigrants from the Lake Titicaca Basin. Trace element data from San Pedro de Atacama bone samples also show homogeneity in Sr/Ca and Ba/Ca, and support the hypothesis that the San Pedro de Atacama cemetery populations were composed of locals and not immigrants from the Lake Titicaca Basin. While there are individuals with enamel strontium isotope ratios that are outside of the local San Pedro de Atacama signature, these individuals do not match the southeastern Lake Titicaca Basin signature and instead are likely individuals who had contacts with, and presumably moved from, other regions in contact with the San Pedro de Atacama oasis, such as northwestern Argentina.

In the Lake Titicaca Basin, the variability in the Sr/Ca and Ba/Ca ratios in the bone samples from the Lake Titicaca Basin sites is similar to variability in enamel strontium isotope ratios from the same individuals (Knudson, 2004; Knudson et al., 2004). This may support our hypothesis that a number of individuals buried as dedicatory offerings and human sacrifices at Tiwanaku and smaller Titicaca Basin sites do not represent a local population (Knudson et al., 2004). More specifically, the strontium isotope data from Tiwanaku had already identified one individual, a human sacrifice on the Akapana pyramid, as a nonlocal (AK-4931, $^{87}\text{Sr}/^{86}\text{Sr} = 0.716256$) (Knudson et al., 2004). The trace element data on a rib fragment from this individual (AK-4931, Ba/Ca = -2.80,

Sr/Ca = -2.61) and the enamel oxygen isotope data (AK-4931, $\delta^{18}\text{O}_{\text{sc}} = -16.47$) support our earlier hypothesis that this individual was not from Tiwanaku but was likely from another part of the Lake Titicaca Basin (Knudson, 2004; Knudson et al., 2004). Here, the combination of strontium and oxygen isotope analysis provides more detailed information on this individual's geographic origin than either technique alone.

The Tiwanaku-affiliated site of Chen Chen in southern Peru has been hypothesized to be a Tiwanaku colony or a diaspora community (Goldstein, 1992, 2005; Kolata, 1993). Researchers have used mortuary and residential artifact analyses, biodistance analyses of cranial nonmetric traits, and aDNA data from archaeological human tooth enamel to argue that a population of Tiwanaku immigrants inhabited Chen Chen (Blom et al., 1998; Goldstein, 2005; Lewis, 2005). However, it is possible that Tiwanaku material culture was adopted by local populations or that decreased biological distance between Tiwanaku and Chen Chen is the result of individuals moving from Chen Chen to Tiwanaku. The Chen Chen strontium isotope data, in conjunction with evidence for residential architecture, artifact, and biodistance studies using cranial nonmetric traits, support the hypothesis that Chen Chen was a Tiwanaku colony (Goldstein, 1992; Blom et al., 1998; Knudson et al., 2004). The individuals buried at Chen Chen predominately ate locally grown food, as determined by carbon and nitrogen isotope analysis and paleobotanical remains at the associated residential sites, and so it is unlikely that the variability in the strontium isotope ratios is the result of non-local food consumption (Tomczak, 2001).

However, the two individuals who were buried at Chen Chen and exhibited Lake Titicaca Basin strontium isotope signatures do not exhibit Lake Titicaca Basin oxygen isotope signatures in their tooth enamel (M1-3840, $^{87}\text{Sr}/^{86}\text{Sr} = 0.708843$, $\delta^{18}\text{O}_{\text{sc}} = -5.84$, and M1-S/NB092, $^{87}\text{Sr}/^{86}\text{Sr} = 0.709995$, $\delta^{18}\text{O}_{\text{sc}} = -6.78$). In addition, a third nonlocal individual at Chen Chen (M1-2947, $^{87}\text{Sr}/^{86}\text{Sr} = 0.719211$, $\delta^{18}\text{O}_{\text{sc}} = -2.93$), based on strontium isotope ratios, has a very high $\delta^{18}\text{O}_{\text{sc}}$ that is most similar to published $\delta^{18}\text{O}_{\text{sc}}$ values from coastal Ilo Valley sites (Tomczak, 2001). The material culture at Chen Chen does not point to coastal contacts, and instead points to affiliations with the Lake Titicaca Basin. In these cases, the oxygen isotope data point to a different origin than the strontium isotope, material culture, biodistance, and aDNA data (Blom et al., 1998; Goldstein, 2005; Lewis, 2005). One way to test the validity of the oxygen isotope data is to determine the local baseline $\delta^{18}\text{O}_{\text{sc}}$ values in the south central Andes from an independent source of data. This will enable us to better understand the discrepancy between the strontium and oxygen isotope signatures in individuals buried at Chen Chen. Future work with modern and archaeological fauna from a variety of regions can help determine these baseline $\delta^{18}\text{O}_{\text{sc}}$ values. In addition, a better understanding of the effects of and interplay between altitude, precipitation patterns, temperature, and distance from the ocean will strengthen the use of oxygen isotope analysis to determine archaeological residential mobility.

Finally, of the Chiribaya-affiliated sites, the site of Chiribaya Alta showed a variety of enamel strontium isotope ratios. This may result from increased access to resources from a variety of ecological zones, or it may support the hypothesis that Chiribaya Alta was a burial ground for elites from a variety of sites. However, nei-

ther strontium isotope ratios nor trace element concentrations could distinguish the coastal region, where most Chiribaya-affiliated sites are located, from the mid-valley zones, where both Tiwanaku-affiliated and Chiribaya-affiliated sites are located. Oxygen isotope data were similarly variable. For example, one individual has high strontium and oxygen isotope ratios (CHA-1475, $^{87}\text{Sr}/^{86}\text{Sr} = 0.717065$, $\delta^{18}\text{O}_{\text{sc}} = -4.77$). Although high strontium isotope ratios are found in the northern Lake Titicaca Basin (Grove et al., 2003), the oxygen isotope evidence shows that this individual was not in fact from the northern Lake Titicaca Basin. However, the variability in the Chiribaya Alta oxygen isotope ratios makes it difficult to distinguish the local oxygen isotope signatures at Chen Chen and Chiribaya Alta. Once again, future work on $\delta^{18}\text{O}_{\text{sc}}$ baseline values will help resolve these questions.

CONCLUSION

We investigated the nature of Tiwanaku influence in the south central Andes through strontium isotope, trace element concentration, and oxygen isotope analyses. Although Tiwanaku-style mortuary artifacts are present at San Pedro de Atacama, we identified no first-generation Tiwanaku immigrants at three cemeteries in the oasis. Strontium isotope analysis identified nonlocals at Chen Chen with strontium isotope signatures that matched those in the southeastern Lake Titicaca Basin, although oxygen isotope data did not support the hypothesis that these individuals were first-generation Tiwanaku immigrants. Future work will better establish the oxygen isotope baselines for these regions to resolve this issue. Trace element analysis was valuable in identifying diagenetically contaminated samples and certain geologic regions in the south central Andes. None of these techniques have adequately distinguished between the Moquegua and Ilo Valleys, and so have not definitively identified Chiribaya origins.

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