Biogeochemical Reconstructions of Life Histories as a Method to Assess Regional Interactions: Stable Oxygen and Radiogenic Strontium Isotopes and Late Intermediate Period Mobility on the Central Peruvian Coast

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Abstract

Biogeochemical reconstructions of life histories of mobility offer a means to obtain nuanced information about regional interactions in the past. We test this method using the Late Intermediate Period Ychsma society on the central Peruvian coast as a case study. Archaeological and ethnohistoric evidence indicates that the Rimac and Lurín Valleys inhabited by the Ychsma served as a key regional hub for the religious and administrative activities of the Inca Empire and the Spanish Viceroyalty. The nature of regional interactions prior to Inca imperial influence, however, remains unclear. Well-known historical narratives describe populations from the adjacent Huarochirí highlands defeating coastal Ychsma populations for agricultural land, but archaeological evidence concerning the timing and extent of coastal-highland interactions is debated. Here, we assess the potential for radiogenic strontium and stable oxygen isotopic reconstruction of mobility over the life course to shed light on the regional interactions of coastal Ychsma groups during the Late Intermediate Period. We present $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ results for 61 regional environmental baseline samples and archaeological human tooth enamel and bone samples from 64 individuals buried at Armatambo and Rinconada Alta, in the Rimac Valley. Results reveal a broad isotopic range for baseline and archaeological samples likely due to diversity in water and bedrock sources. Nevertheless, one individual presents a non-local strontium value indicating mobility to an outside region. We discuss the advantages of a life history approach, the complications of using isotopes to assess mobility in the Central Andes, and suggested directions for future research.

Key words
bone
tooth enamel
soil
water
Central Andes
Rimac Valley

1. Introduction: biogeochemical reconstructions of life histories to assess regional interaction

Biogeochemical analysis has become a widely used technique for investigating paleomobility. Commonly, archaeological human tooth enamel and/or bone elements are analyzed for isotopic or elemental ratios that exhibit geological variation, enabling researchers to identify first-generation immigrants as individuals with tissues that exhibit values distinct from local ranges (e.g., Budd, et al., 2004; Burton, et al., 2003; Buzon, et al., 2011; Knudson and Buikstra, 2007; Knudson, et al., 2012a; Knudson and Price, 2007b; Perry, et al., 2008; Price, et al., 1994; Price, et al., 2000; Webb, et al., 2011). Comparisons of intra-individual biogeochemical values in multiple human tissues that form at different stages over the life course permit the reconstruction of the life history of mobility of individuals (Sealy, et al., 1995). Generally, such biogeochemical life history reconstructions of paleomobility are used to investigate the lived experience of a single individual recovered from a unique burial context (e.g., Frei, et al., 2015; Knudson, et al., 2012b; Müller, et al., 2003). The present study demonstrates how biogeochemical life history reconstructions can also serve as a means to investigate large scale patterns of regional and interregional interactions.

Focusing on the Late Intermediate Period (c. AD 900-1470) Ychsma society on the central Peruvian coast as a case study, this research evaluates the utility of life history reconstructions using radiogenic strontium and stable oxygen isotope analysis as a means to assess the nature of pre-Columbian regional interactions in the area that today forms the capital city of Lima, Peru. The Rimac and Lurín Valleys on the Central Andean coast where Lima is located once served as a prominent regional hub of administrative and religious activities for both the Spanish Viceroyalty and the Inka Empire. Although archaeological evidence indicates that complex societies inhabited the Lima area for well over a millennium prior to Inka arrival, little is yet known about the nature and extent of regional and interregional mobility and interactions in the area preceding Inka imperial influence. The present study demonstrates the advantages of a bigeochemical life history approach to regional interactions, while also highlighting challenges specific to the Central Andean coast.

2. Regional mobility and interactions on the central Peruvian coast

The Spanish Viceroyalty established Lima as its capital city in the Rimac Valley in the coastal desert of the Central Andes in 1535. Early Spanish colonial records indicate that at the time of Spanish arrival, the area comprised by the Rimac and Lurín River Valleys served as a key provincial administrative center for the Inka Empire (Cornejo, 2000; Rostworowski, 2002b). The capital of this Inka Province was Pachacamac, a ceremonial center in the Lurín Valley honoring the coastal deity, also called Pachacamac. The Inkas are said to have sought out this region specifically in search of this world creator deity (Santillan, 1968 [1563]). The Inkas considered the “supreme and invisible Maker and Creator” Pachacamac as complementary to the “most noble part of the visible created universe”, the Sun (Garcilaso de la Vega, 1976 [1609]:67; MacCormack, 1991:344). According to Spanish chroniclers, the Pachacamac ceremonial center was an immensely important pilgrimage site. Father Bernabé Cobo (1990:85) writes, “In magnitude, devotion, authority and richness, the Temple of Pachacama was second only to the magnificent [Cuzco] Temple of the Sun. Since it was a universal sanctuary, people came to the Temple of Pachacama on pilgrimages from all over the Inca empire…” Present-day oral histories continue to describe the Pachacamac deity as the creator of the world, of humans, and of agriculture, and as lord of earthquakes and of the night, and have been recorded among indigenous groups living as far away as jungle villages located on the opposite side of the Andean mountains (Rostworowski, 2002c; Varese, 2006). Such narratives reveal the significance and breadth of influence of this pre-Columbian coastal god.

Debate continues, however, over how far back in time the widespread regional influence of Pachacamac extends. Archaeological evidence shows probable continuous occupation at the site of Pachacamac beginning with the Lima society during the Early Intermediate Period (c. 200 BC-AD 650). Additional constructions were possibly added during the Middle Horizon Period (c. AD 650-1000), and 15 monumental structures were built during the Late Intermediate Period (c. AD 1000-1470) (Eeckhout, 2013; but see Segura and Shimada, 2010). The identification of Wari elements in Pachacamac iconography has led several scholars to suggest pilgrimages to the site began as early as the Middle Horizon (Eeckhout, 2013; Menzel, 1964). Analyses of burial contexts at Pachacamac by Peter Eeckhout (2010), however, so far reveal that funerary rituals practiced during the Middle Horizon and Late Intermediate Periods were local in style.

Ethnohistoric information indicates that, in addition to influencing large-scale, pan-Andean mobility, the Pachacamac site and surrounding region likely also were associated with extensive local regional mobility. The famed *Huarochirí Manuscript*, a collection of narratives compiled by a Spanish priest in the early seventeenth century and written in Quechua, likely by an indigenous scribe, suggests extensive movement and social interactions occurred between the Yunca or Ychsma population from the local coastal area and the Yauyos population from the adjacent Huarochirí highlands (Feltham, 2005; Salomon and Urioste, 1991 [c. 1600]). Specifically, the Huarochirí narratives describe pilgrimages between the coastal shrine of Pacha Camac and the highland shrine of Paria Caca, as well as invasions by highland Yauyos groups into the mid-valley to confiscate Ychsma agricultural lands.

Whether or not such regional interactions pre-date Inka imperial influence, however, remains a source of discussion. Some scholars suggest that highland groups were only able to obtain access to valley lands through Inka control and land redistribution strategies (Cornejo, 1995; Rostworowski, 2002c). Researchers have attempted to establish the location of a boundary between the coastal Ychsma and highland Yauyos groups during the Late Intermediate Period (c. AD 900-1470) using archaeological evidence from the Lurín Valley. The coastal-highland boundary has been variously identified as a specific site in a small ravine (*quebrada*) called Anchucaya (Sánchez, 2000), as a site complex 4 km in area near the modern town of Sisicaya (Cornejo, 1995), and as a mid-valley zone of ~12 km stretching from the site of Río Seco to the site of Avillay in the Sisicaya area (Marcone, 2004; Marcone and Lopez-Hurtado, 2002). These boundary definitions are based largely on differential architectural features that characterize lower, middle, and upper valley sites, although authors disagree over the definitions of such features (e.g., Feltham, 2005; Marcone, 2004; Sánchez, 2000). Other researchers, such as MacNeish and colleagues (1975), have suggested that the border between the Ychsma and Yauyos groups was likely blurred due to continuous raids by each group into one another’s territory. An extensive survey of the Lurín Valley by Feltham (1983) shows that ceramics made from orange littoral clays and those made from brown highland clays gradually gradate in proportion to one another from the coast to the highlands and are intermixed in all parts of all sites in which they co-occur (Feltham, 1983, 1984, 2005).

At middle Lurín Valley sites, evidence of socioeconomic hierarchy evident in domestic architecture may reflect sociopolitical and/or socioeconomic differences between the Ychsma and Yauyos groups. Multi-room adobe structures interpreted as elite residences were constructed near pyramidal platforms with ramps, while simple cane (*quincha*) structures skirted the edges of sites along the *quebrada* slopes (Eeckhout, 1999; Feltham, 2005; Marcone and Lopez-Hurtado, 2002). Feltham (2005:136) argues, however, that neither inter- nor intra-site variation in ceramics, architecture, or settlement is adequate to suggest differences between the Ychsma and Yauyos groups and states that "the archaeological record suggests that both peoples [lived] fairly peaceably together" in the middle valley. No fortified structures, weapons, traumatic skeletal lesions, or other evidence to indicate violent interactions has yet been found in the area (Feltham, 2005; see also Sánchez, 2000). Additional evidence comes from linguistic analyses of names from a census document from Sisicaya, a modern upper mid-valley village associated with the archaeological site of Avillay. Specifically, this document indicates that prior to Inka arrival, highland and coastal groups, who likely spoke distinct languages, shared a name pool and birth-order naming practices, traditions commonly associated with ethnic identification in the region (Salomon and Grosboll, 2011).

Additional ethnohistoric data suggest that any attempt to define a border or specific zone of interaction between the Ychsma and Yauyos overlooks the full extent of potential social interactions and possible movement between the two populations. As mentioned previously, the narrative oral histories of the *Huarochirí Manuscript* describe the sites of both Pachacamac on the coast and Pariacaca in the mountains as pilgrimage destinations to which peoples from both regions were said to have trekked (Rostworowski, 2002c; Salomon and Urioste, 1991 [c. 1600]). These narratives also tell of highland Yauyos groups displacing the Ychsma in entire areas of the lower Rimac Valley site of Latim or Ate (currently Rinconada) and the middle Rimac Valley sites of Ñaña and Mama (Cornejo, 2000; Espinoza, 1984). Pedestrian movement between the highlands and the coast has continued in recent history. During seasons of harvest, highland families come down to work and live in the valleys and occasionally intermarry with the local coastal population (Matos Mar, et al., 1964). Family members who have moved permanently to the lower Lurín Valley will occasionally make the one- or two-day hike up to the *lomas* or to highland villages to visit family (S. Marsteller, personal observation, 2010). Permanent highland residents also sometimes take ancient footpaths into the valleys when roads become washed out during the rainy season (F. Salomon, personal communication, 2010).

Numerous other ethnohistoric examples illustrate the malleable nature of Andean kinship suggesting that membership in coastal and highland groups was likely much more fluid than current archaeological interpretations allow. While membership in an *ayllu*, which was "the basic political as well as productive unit of Andean society," was largely kinship-based, it could also more broadly "be simply the acceptance of the responsibilities, ritual as well as productive, inhering in membership" (Isbell, 1997; Spalding, 1984:28-29). In the *Huarochirí Manuscript* narratives, individuals who married into a community gained acceptance via performance of ritual duties (Salomon and Urioste, 1991 [c. 1600]; Spalding, 1984). Children of such marriages chose membership in the group of either parent in order to construct the most advantageous social position possible (Spalding, 1984). Additionally, adoption practices allowed individuals without descendants to pass on their lands and responsibilities and continue their lineage. In one story, a coastal boy who survived highland conquest of his valley was adopted by a Huarochirí leader (*curaca*) and ultimately inherited his adoptive father's position of authority (Spalding, 1984). Even the highland narrators of the Huarochirí Manuscript, the Cheka, describe their ancestors as Yunca, not Yauyos (Salomon, 1991). Although their ancestors came from the Yauyos province to the west, they became Yunca by defeating the previous Yunca inhabitants and incorporating their religious shrines (*huacas*) as their own. The terms "Yauyo" and "potato-eater" (*wak'cha*) are used in the manuscript derogatorily to refer to recent immigrants or poor highlanders (Salomon, 1991:7; Spalding, 1984:53,57).

These various examples indicate that mobility and social interactions on the central Peruvian coast were likely much more complex than the concept of a simple border or zone of interaction between the groups implies. To better understand the regional and interregional mobility in the Lima area prior to Inka imperial influence requires further empirical assessments. The present study seeks to evaluate the utility of life history reconstructions using radiogenic strontium and stable oxygen isotopes in archaeological human remains as a direct measure of past human mobility in the Lima region. To complement previous work centered on the site of Pachacamac and other sites in the Lurín Valley, we focus our analysis on Late Intermediate Period human burials recovered from the lower Rimac Valley.

3. Using isotopes to reconstruct life histories of mobility in the Rimac Valley

3.1 Strontium and oxygen isotopes and paleomobility

Analyses of radiogenic strontium ($^{87}Sr/^{86}Sr$) and stable oxygen ($\delta^{18}O$) isotopes in archaeological human tissues are common techniques used to reconstruct paleomobility (e.g., Budd, et al., 2004; Conlee, et al., 2009; Knudson and Price, 2007a; Knudson, 2009; Knudson, et al., 2012a; Müller, et al., 2003; Perry, et al., 2008; Price, et al., 1994; Turner, et al., 2009; White, et al., 1998; Wright, et al., 2010). Radiogenic strontium and stable oxygen isotope ratios in food and water resources are transferred to bone and tooth enamel during the formation of each skeletal element (Ericson, 1985; Longinelli, 1984; Luz, et al., 1984). In regions where food and water resources are isotopically distinct due to environmental diversity, past mobility can be inferred using archaeological isotope chemistry of the skeleton (Ericson, 1985; Knudson and Price, 2007a; Price, et al., 1994; White, et al., 2004b; White, et al., 1998). Reconstruction of mobility over the life history of an individual is possible via comparison of isotopic values in the local environment with archaeological human tissues that form at different periods over the life course. For instance, permanent incisors and first permanent molars form during the first 4-5 years of childhood, premolars and second permanent molars form during ages 2-9 years, and third permanent molars form during 7-18 years of age (Hillson, 1996:Table 5.1). Bone, by contrast, remodels continuously, such that isotopic values found in bone represent the last years of life (Price, et al., 2002).

Of the four naturally occurring stable isotopes of strontium (^{84}Sr, ^{86}Sr, ^{87}Sr, ^{88}Sr), one is radiogenic (^{87}Sr), decaying to rubidium (^{87}Rb) with a half-life of approximately 50 billion years (Bentley, 2006; Dasch, 1969; Elderfield, 1986; Graustein, 1989). As a result of this decay, soils from older bedrocks generally exhibit higher ratios of $^{87}Sr/^{86}Sr$ than those from younger bedrocks, and this isotopic variation is transferred to the tissues of plants and animal consumers up the food chain (Ericson, 1985; Faure and Powell, 1972; Schroeder, et al., 1972). In biological organisms, elemental strontium substitutes for calcium, such that $^{87}Sr/^{86}Sr$ values in human skeletal elements reflect $^{87}Sr/^{86}Sr$ values in foods rich in calcium consumed during the element's formation or metabolism (Ericson, 1985; Schroeder, et al., 1972). Because erosion and soil transport may combine minerals from different bedrocks with different $^{87}Sr/^{86}Sr$ values, locally available $^{87}Sr/^{86}Sr$ in an ecosystem must be measured through analysis of $^{87}Sr/^{86}Sr$ in partially dissolved soil samples and/or non-migratory small mammals (Knudson, et al., 2014b; Price, et al., 2002). To screen for contamination of archaeological human skeletal elements by solutes from groundwater in the local burial environment, major, minor, and trace elemental concentrations are monitored to verify biogenic ranges of ratios of calcium to phosphorus (Ca/P) and concentrations of uranium (U) and neodymium (Nd) (Hedges, 2002; Kohn, et al., 1999; Price, et al., 1994).

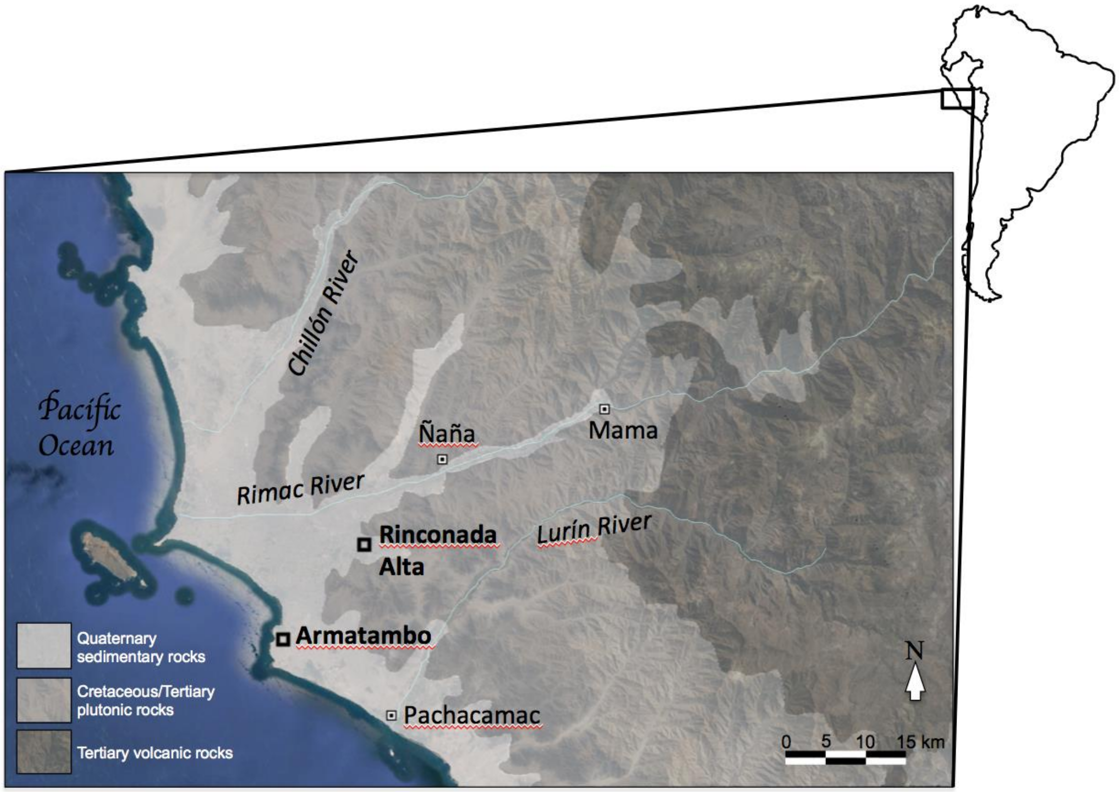
Oxygen exists in nature as three stable isotopes (^{16}O, ^{17}O, ^{18}O). The ratio of stable oxygen isotopes ^{18}O/^{16}O, expressed as δ^{18}O, varies in water sources according to environmental factors such as altitude, precipitation, and temperature (Craig, 1961a, 1961b; Gat, 1996), as well as cultural factors such as specific processes used in boiling and brewing (e.g., Gagnon, 2015). Variation in drinking water δ^{18}O values is incorporated into the carbonate and phosphate of tooth enamel and bone hydroxyapatite at the time of formation of the skeletal element (Longinelli, 1984; Luz, et al., 1984). Correspondingly, archaeological skeletal carbonate or phosphate δ^{18}O is inferred to reflect differences in drinking water sources, allowing for interpretations concerning residential mobility in past populations (e.g., Knudson and Torres-Rouff, 2009; Knudson and Tung, 2007; Turner, et al., 2009; White, et al., 2004b; White, et al., 1998; White, et al., 2004c). In certain regions, multiple diverse environmental zones in close proximity and/or seasonal variation in climate may complicate interpretations of variability in δ^{18}O (Knudson, 2009). Additional complicating factors include variability in groundwater δ^{18}O values and difficulties associated with differentiating ceremonial versus utilitarian wells (e.g., Knudson, et al., 2014a; Quilter, et al., 2012). As a result, archaeological values should be compared to a local stable oxygen isotopic baseline to make inferences regarding differential residence patterns (e.g., Buzon, et al., 2011; Chenery, et al., 2010). In addition, analysis of teeth and bone formed during the early years of life must take into account the enrichment of breast milk δ^{18}O relative to local water sources (Dupras and Tocheri, 2007; Roberts, et al., 1988; White, et al., 2004a; Wright and Schwarcz, 1999).

3.2. Environmental diversity on the central Peruvian coast

3.2.1. Bedrock geology

The Lima region and adjacent Huarochirí highlands exhibit variation in bedrock geology that potentially corresponds with variable ratios of ^{87}Sr/^{86}Sr. Specifically, the Rimac and Lurín drainage systems cross three main bedrock types. In the highlands, where both the Rimac and Lurín Rivers originate, Tertiary volcanic rocks form the underlying bedrock (Fig. 1; INGEOMIN, 1975). The middle portions of both rivers cross Cretaceous/Tertiary plutonic rocks, while the lower valleys are comprised of Quaternary sedimentary rocks (Fig. 1; INGEOMIN, 1975).

Fig. 1. Map of the study region. Bedrock geological variation on the central Peruvian coast with archaeological sites mentioned in text indicated. Created using Google Earth © 2016. [*Note: May be printed in color or black and white.*]



3.2.2 Meteoric water sources

In addition to geological variation, the Lima and Huarochirí region exhibits variation in altitude, precipitation, and temperature, which potentially influences δ^{18}O in meteoric water sources. Altitude rises abruptly from sea level to above 4000 m in a span of less than 150 km from the western coastline to present-day towns in the east such as San Lázaro de Escomarca (3730 m), Huarochirí (3140 m), and San Mateo (3170 m). Multiple diverse microclimates exist across this altitude span. First, nearest the Pacific Coast (~0-500 masl) is an extremely arid desert zone known as the *chala* (Pulgar Vidal, 1985). Little precipitation falls in this area due to (1) the rain-shadow effect of the Andean mountain ranges, where moisture from the southern Atlantic air mass is released, and (2) the low oceanic temperatures of the Humboldt Current, which cool Pacific air masses thereby limiting precipitation and creating stable air temperatures (Brush, 1982; Molina and Little, 1981; Rundel, et al., 1991). Water sources in this region include river systems that crosscut the desert enabling irrigation agriculture on alluvial soils, as well as sporadic freshwater springs and marshes produced by underground drainage of Andean precipitation and glacier melt.

Above the desert *chala*, a mid-altitude zone (~500-2300 masl) called the *yungas* receives slightly more precipitation and exhibits a more temperate climate (Brush, 1982; Pulgar Vidal, 1985). Here, the same river systems that reach the *chala* are also used for irrigation agriculture, focused especially on fruit trees, cacti, and succulents (Brush, 1982; Pulgar Vidal, 1985). Further up, ecozones known as the *quechua* (~2300-3500 masl) and *suni* (~3500-4000 masl) experience greater amounts of precipitation and cooler temperatures. The high, narrow aspects of the river valley systems are found in these zones and are used to grow crops such as maize, cereals, and tubers (Pulgar Vidal, 1985; Troll, 1968). The highest altitude zone is the *puna* (~3700-5300 masl), which has an intense rainy season and cold temperatures. High altitude lakes are present, abundant grasslands provide resources for grazing camelids, and tubers and grains may be grown seasonally.

3.3. Rimac Valley sites

The current project investigates whether the geological and environmental variation on the central Peruvian coast enables the use of radiogenic strontium and stable oxygen isotope analysis as tools for reconstructing paleomobility over the life course in this area. In addition to constructing an isotopic baseline, we investigate life history changes in residential mobility during the Late Intermediate Period in the Rimac Valley using archaeological samples recovered from two sites, Rinconada Alta and Armatambo (Fig. 1). Rinconada Alta is located in the district of La Molina in present-day Lima. This site is associated ethnohistorically with the Ate Señorío, also called Latí, Latim, or Late, which controlled lands on the southern bank of the Rimac River. The Ate Canal is known to have served as a principal canal for irrigation of the lower Rimac Valley agricultural fields during the Spanish colonial period (Díaz, 2002; Rostworowski, 2002b). According to ethnohistoric sources, Yauyos groups from the highlands are reported to have replaced the Yunca at Ate and at the middle valley sites of Ñaña and Mama (Fig. 1; Cornejo, 2000; Espinoza, 1984). The timing and extent of such replacements, however, remains unknown.

The second study site, Armatambo, is located less than 1 km from the Pacific Ocean shore and is associated ethnohistorically with a fishing specialist group located within the territory the Surco Señorío, adjacent to the lands of the Ate Señorío (Cornejo, 2000; Rostworowski, 2005). Because of its location at the tip of the Lima Bay, the Armatambo area served as a principal site for indigenous fishing practices during the 18th century (Rostworowski, 2004). Earlier, during the period of Inka imperial influence, Armatambo served as a major administrative center and important stopover location (*tambo* or *tampu*) for travelers on the extensive Inka road system, *Qhapaq Ñan* (Díaz and Vallejo, 2002). The extent to which outsiders came to the site in earlier times during the Late Intermediate Period remains to be evaluated.

4. Materials and Methods

4.1 Sampling strategy

To construct a baseline of local biologically available radiogenic strontium and stable oxygen isotopes for the study region, modern soil, faunal, and water samples from multiple locations within various geological zones and environmental zones within the study region were collected for analysis. For radiogenic strontium ($^{87}Sr/^{86}Sr$) analysis, 24 agricultural soil samples and 15 bone samples from small mammals (*Cavia porcellus*) raised on local crops were collected from various locations in geologically distinct zones within the study area (Fig. 1; Table S1). For stable oxygen isotope ($\delta^{18}O$) analysis, 22 meteoric water samples were collected from throughout the study region at as many types of water sources as possible, focusing on sources that would have been available in pre-Columbian periods including multiple sites along the Rimac and Lurín Rivers, multiple agricultural canals derived from the Lurín River, springs, hand-dug wells, and freshwater marsh ponds (Fig. 1; Table S2). Local ranges for both isotopic systems were defined as the mean for the entire region, plus and minus two standard deviations (Price, et al., 2002). For stable oxygen isotope values, 3.1‰ was added to the regional range to account for inter-laboratory variability in measurements (Pestle, et al., 2014).

Archaeological human bone and tooth enamel samples were collected from 64, or 40%, of the 151 total adult and adolescent individuals recovered from intact burial contexts at Armatambo and Rinconada Alta currently housed in the Museo Nacional de Antropología, Arqueología e Historia del Perú in Pueblo Libre, Lima, Peru, and the associated Annex 1 storage facility in La Victoria, Lima, Peru (Armatambo: *n*=42/104; Rinconada Alta: *n*=22/47; Tables 1, S3). Individuals were chosen via stratified randomization with preference given to individuals with both tooth enamel and bone available for analysis. Overall, the distribution of individuals in each age and sex category, as well as each sector of each site, reflects that of the total sample. Age at death was estimated using information from os coxal joint degeneration, epiphyseal fusion, and cranial suture closure (Baker, et al., 2005; Buikstra and Ubelaker, 1994). Estimations of biological sex were performed through analyses of features of the os coxae and cranium that exhibit sexual dimorphism (Buikstra and Ubelaker, 1994).

Table 1. Distribution of individuals in study sample by age for combined sex categories at Armatambo and Rinconada Alta

	Armatambo (*n* = 42)					**Rinconada Alta (*n* = 22)**				
Age category[a]	**F**[b]	**M**[c]	**A**[d]	**UD**[e]	**% Site Total**	**F**	**M**	**A**	**UD**	**% Site Total**
Adol	1	1	0	0	**2/42 (5%)**	2	0	0	0	**2/22 (9%)**
YA	6	6	0	0	**12/42 (29%)**	2	6	0	0	**8/22 (36%)**
MA	11	8	0	0	**19/42 (45%)**	4	3	0	0	**7/22 (32%)**
OA	7	1	0	0	**8/42 (19%)**	4	0	0	0	**4/22 (18%)**
Adult	0	0	0	1	**1/42 (2%)**	1	0	0	0	**1/22 (5%)**
Total	**25**	**16**	**0**	**1**		**13**	**9**	**0**	**0**	
% Site Total	**25/42 (60%)**	**16/42 (38%)**	**0/42 (0%)**	**1/42 (2%)**	**% Site**	**13/22 (59%)**	**9/22 (41%)**	**0/22 (0%)**	**0/22 (0%)**	

Total

[a] Adult age categories: Adol = Adolescent (15-19 years), YA = Young Adult (20-34 years), MA = Middle Adult (35-49 years), OA = Older Adult (50+ years), Adult = Unknown Adult (20+ years)
[b] 'F' includes individuals estimated as 'Female' and 'Probable Female'.
[c] 'M' includes individuals estimated as 'Male' and 'Probable Male'.
[d] 'A' = Ambiguous
[e] 'UD' = Undetermined

4.2 Sample processing and laboratory analysis

All soil, faunal bone, water, and archaeological human bone and tooth enamel samples were processed for radiogenic strontium and/or stable oxygen isotope analysis in the Arizona State University Archaeological Chemistry Laboratory. Soils for $^{87}Sr/^{86}Sr$ analysis were dried at 120˚C for 48 h, ground with a porcelain mortar and pestle, and ashed at 800˚C for 10 h to eliminate organic matter. Approximately 4.0 g of each soil were partially dissolved in 10 mL of 1 M ammonium acetate (CH_3COONH_4) at room temperature for 24 h. Non-dissolved particulates were filtered and discarded and the resulting extract prepared for analysis as described below.

Sections of faunal and archaeological human bone samples for $^{87}Sr/^{86}Sr$ analysis were mechanically cleaned with a drill equipped with a carbide burr, ashed at 800˚C for 10 h, and ground with an agate mortar and pestle. Approximately 10-15 mg of bone ash powder were dissolved in 0.5 mL of 5 M nitric acid (HNO_3) to be prepared for radiogenic strontium analysis. For archaeological human tooth samples for $^{87}Sr/^{86}Sr$ analysis, external surface enamel was mechanically cleaned with a drill and diamond burr, and 10-15 mg tooth enamel powder were removed from the cleaned section across the extent of the crown height and dissolved in 0.5 mL of 5 M HNO_3. Three molars were excluded from analysis due to an insufficient amount of available clean enamel powder (Table S3). All soil extracts and bone ash and tooth enamel powder solutions were evaporated at 50-100˚C and re-dissolved in 0.25 mL 5 M HNO_3. Each solution was loaded onto EiChrom SrSpec resin (50-100 µL diameter) in fretted glass columns that had been cleaned with distilled and deionized water (18.2MΩ) and equilibrated with 5 M HNO_3. Samples were washed three times with 0.25 mL 5 M nitric acid, and then strontium was separated from the sample matrix via three elutions with 0.5 mL distilled and deionized water (18.2MΩ). A blank and a sample of NIST SRM 1400 bone ash standard were also prepared for $^{87}Sr/^{86}Sr$ analysis using identical procedures alongside each batch of 15-25 samples. All eluted samples were evaporated at 50-100˚C, dissolved in 5 M HNO_3, and diluted to a concentration of 0.32 M HNO_3 for analysis.

Radiogenic strontium isotope ratios ($^{87}Sr/^{86}Sr$) were measured on a Thermo Finnigan Neptune Multi-Collector Inductively-Coupled Plasma Mass Spectrometer (MC-ICP-MS) at Arizona State University. Analyses of strontium carbonate standard SRM-987 for radiogenic strontium isotopes produce mean $^{87}Sr/^{86}Sr=0.71025\pm0.000002$ (n=190, 2σ). Analyses of bone ash standard NIST-1400 produce mean $^{87}Sr/^{86}Sr=0.71312\pm0.00005$ (n=34, 2σ). To assess for diagenesis, approximately 3.0 mg of each powdered bone ash and tooth enamel sample were analyzed for elemental concentrations on a Quadrupole Inductively-Coupled Plasma Mass Spectrometer (Q-ICP-MS) at Arizona State University. Average Ca/P=2.07±0.18 (n=306, 2 σ), with minimum Ca/P=1.91 and maximum Ca/P=2.42, comparable to measurements of Ca/P in modern bone and tooth enamel (e.g., Hancock, et al., 1993; Kohn, et al., 1999; Sillen, 1989). Most measured U and Nd concentrations were below detection or quantification limits. One sample (ACL-4640 RIMAC-ARMA.M213) exhibited a quantifiable U concentration (0.0006 ppb) within normal variation of biogenic human bone (≤0.30 ppm), and quantifiable Nd values are also within levels for biogenic human bone (0.01-0.21 ppm; Hancock, et al., 1993).

Water samples for $\delta^{18}O_{mw[V\text{-}SMOW]}$ analysis were filtered to remove solid particles. Archaeological human bone and tooth enamel samples for $\delta^{18}O_{c[VPDB]}$ analysis were mechanically cleaned with a drill equipped with a carbide or diamond burr. Bone samples were powdered with an agate mortar and pestle, and tooth enamel powder was removed using a drill with a clean diamond burr. The width of each bone section and the entire extent of the tooth crown height were sampled to obtain bulk samples representative of the entire formation period of each. One anterior tooth was excluded from analysis due to an insufficient amount of available clean enamel powder (Table S3). Approximately 15-20 mg of bone or tooth enamel powder were treated with 2% sodium hypochlorite (NaOCl) for 24 h to remove organics, followed by a treatment of 0.1 M acetic acid (CH_3COOH) for 24 h to remove diagenetic carbonate (Koch, et al., 1997). For each treatment, 0.04 mL solution were used per milligram of sample. Following each treatment, samples were rinsed three times with 0.50 mL deionized water, vortexing one minute per rinse. Following the final rinse, samples were dried at 50˚C for 24 h. Analysis of $\delta^{18}O$ was performed on a Delta V Advantage IRMS coupled with a Gas Bench II at Northern Arizona University. Replicates of international and internal standards produce standard deviations ranging from ±0.01-0.16‰ (1σ) for $\delta^{18}O$. Stable oxygen isotope ratios in carbonates ($\delta^{18}O_{c[VPDB]}$) are used in statistical analyses and in comparisons with other carbonate values and are converted to drinking water ($\delta^{18}O_{dw[V\text{-}SMOW]}$) values for comparison to stable oxygen isotope ratios in meteoric water samples ($\delta^{18}O_{mw[V\text{-}SMOW]}$) using the following equations:

(1) $\delta^{18}O_{V\text{-}SMOW} = (1.03091 \times \delta^{18}O_{VPDB}) + 30.91$ (Coplen, et al., 1983)
(2) $\delta^{18}O_{VPDB} = (0.97002 \times \delta^{18}O_{V\text{-}SMOW}) - 29.98$ (Coplen, et al., 1983)
(3) $\delta^{18}O_{c[V\text{-}SMOW]} = (8.5 + \delta^{18}O_{p[V\text{-}SMOW]})/0.98$ or, $\delta^{18}O_{p[V\text{-}SMOW]} = (\delta^{18}O_{c[V\text{-}SMOW]} \times 0.98) - 8.5$ (Iacumin, et al., 1996)
(4) $\delta^{18}O_{dw[V\text{-}SMOW]} = 1.54(\pm0.09) \times \delta^{18}O_{p[V\text{-}SMOW]} - 33.72(\pm1.51)$ (Daux, et al., 2008; Levinson, et al., 1987; Longinelli, 1984; Luz, et al., 1984)

5. Radiogenic strontium and stable oxygen isotope results

5.1 Local isotopic baseline

Radiogenic strontium isotope ($^{87}Sr/^{86}Sr$) values for soil and faunal bone samples are given in Table S1. Across the study region, average soil $^{87}Sr/^{86}Sr$ equals 0.70652±0.00091 (*n*=24, 1σ) and average *Cavia porcellus* bone apatite $^{87}Sr/^{86}Sr$ equals 0.70608±0.00069 (*n*=16, 1σ) (Tables 2-3). One-factor analysis of variance (ANOVA) tests were performed to evaluate potential differences associated with variation in bedrock geology. For soil $^{87}Sr/^{86}Sr$, the variances of the residuals across the three bedrock types are not significantly different (Levene's test: $W_{2,21}$=0.21, P=0.98), and the residuals are normally distributed (Shapiro-Wilk test: W=0.96, P=0.36), indicating the assumptions for the ANOVA test are met (Zar, 2010). The ANOVA results indicate means are not the same for all bedrock types ($F_{2,21}$=5.24, P=0.01). Specifically, significant differences are observed between soils collected from areas with Quaternary sedimentary rocks and those from areas with Tertiary volcanic rocks (Tukey-Kramer test: mean difference, $^{87}Sr/^{86}Sr$=0.00130, P=0.01), although neither of these bedrock types is significantly different from soils collected from areas with Cretaceous/Tertiary plutonic rocks (Fig. 2). In contrast, a one-factor ANOVA test on faunal bone apatite $^{87}Sr/^{86}Sr$ reveals no significant difference among faunal samples collected from areas with different bedrock geology (ANOVA: $F_{2,13}$=0.68, P=0.52; Levene's test: $W_{2,13}$=1.43, P=0.27; Shapiro-Wilk test: W=0.89, P=0.0549). Because neither soil nor faunal bone apatite $^{87}Sr/^{86}Sr$ values from different geological areas are significantly different across the study region, we follow Price et al. (2002) in defining a local biologically-available $^{87}Sr/^{86}Sr$ range for the entire study region as the average of the small mammal $^{87}Sr/^{86}Sr$ values, plus and minus two standard deviations, or $^{87}Sr/^{86}Sr$=0.70470-0.70746.

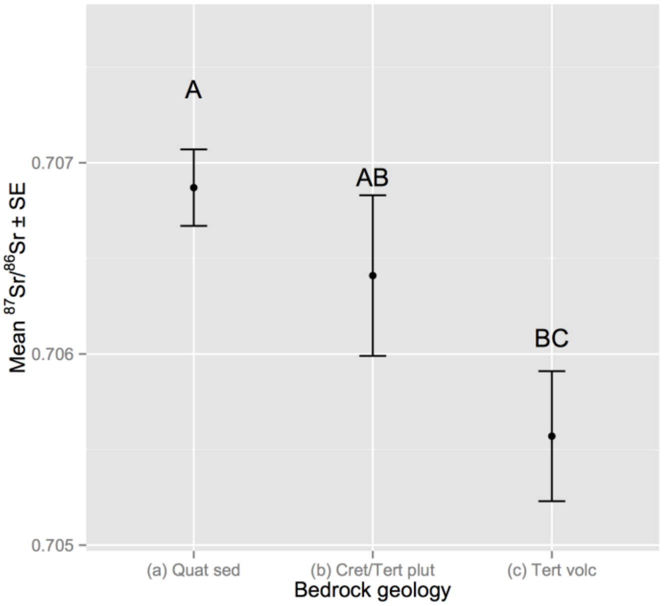
Table 2. Radiogenic strontium isotope ($^{87}Sr/^{86}Sr$) values for agricultural soils in the study region

Bedrock type	***n***	**Average $^{87}Sr/^{86}Sr$**	**1σ**	**Minimum $^{87}Sr/^{86}Sr$**	**Maximum $^{87}Sr/^{86}Sr$**
Tertiary volcanic rocks	5	0.70557	0.00075	0.70479	0.70676
Cretaceous/Tertiary plutonic rocks	8	0.70641	0.00084	0.70519	0.70707
Quaternary sedimentary rocks	15	0.70687	0.00078	0.70542	0.70805
Entire region	**24**	**0.70652**	**0.00091**	**0.70479**	**0.70805**

Table 3. Radiogenic strontium isotope ($^{87}Sr/^{86}Sr$) values for bone apatite from Cavia porcellus *reportedly raised on crops local to the study region*

Bedrock type	***n***	**Average $^{87}Sr/^{86}Sr$**	**1σ**	**Minimum $^{87}Sr/^{86}Sr$**	**Maximum $^{87}Sr/^{86}Sr$**
Tertiary volcanic rocks	10	0.70593	0.00082	0.70481	0.70667
Cretaceous/Tertiary plutonic rocks	4	0.70640	0.00033	0.70592	0.70662
Quaternary sedimentary rocks	2	0.70619	0.00030	0.70597	0.70640
Entire region	**16**	**0.70608**	**0.00069**	**0.70481**	**0.70667**

Fig. 2. Mean differences in $^{87}Sr/^{86}Sr$ among soils in areas with different bedrock. Results of Tukey-Kramer tests among soils from areas with Quaternary sedimentary (Quat sed), Cretaceous/Tertiary plutonic (Cret/Tert plut), and Tertiary volcanic (Tert volc) rocks.



Tables 4 and S2 show stable oxygen isotope ($\delta^{18}O_{mw[V\text{-}SMOW]}$) results for water samples. Average water $\delta^{18}O_{mw[V\text{-}SMOW]}$ for the total region equals -12.4±1.0‰ (*n*=22, 1σ). A one-factor ANOVA test indicates no significant difference among sample means when grouped by ecozone (ANOVA: $F_{4,17}$=0.68, P=0.61; Levene's test: $W_{4,17}$=0.27, P=0.89; Shapiro-Wilk test: W=0.92, P=0.10). For this reason, we define a local $\delta^{18}O_{mw}$ range for the entire study region as the mean $\delta^{18}O_{mw}$ for the entire region, plus and minus two standard deviations or $\delta^{18}O_{mw}$= -14.4‰ to -10.4‰. Taking into account the 3.1‰ MMD (Pestle, et al., 2014), the regional range for $\delta^{18}O_{mw[V\text{-}SMOW]}$ =-17.5‰ to -7.3‰.

Table 4. Stable oxygen isotope ($\delta^{18}O_{mw}$) results for water sources in the study region by ecozone

Ecozone	***n***	**Average $\delta^{18}O_{mw\ (V\text{-}SMOW)}$ ‰**	**1σ**	**Minimum $\delta^{18}O_{mw(V\text{-}SMOW)}$ ‰**	**Maximum $\delta^{18}O_{mw(V\text{-}SMOW)}$ ‰**
Chala	11	-12.1	1.0	-14.4	-10.6
Yungas	5	-12.8	0.9	-14.3	-12.0
Quechua	3	-13.0	1.4	-14.6	-12.0
Suni	2	-12.4	0.9	-13.0	-11.7
Puna	1	-12.0	NA	NA	NA
Entire region	**22**	**-12.4**	**1.0**	**-14.6**	**-10.6**

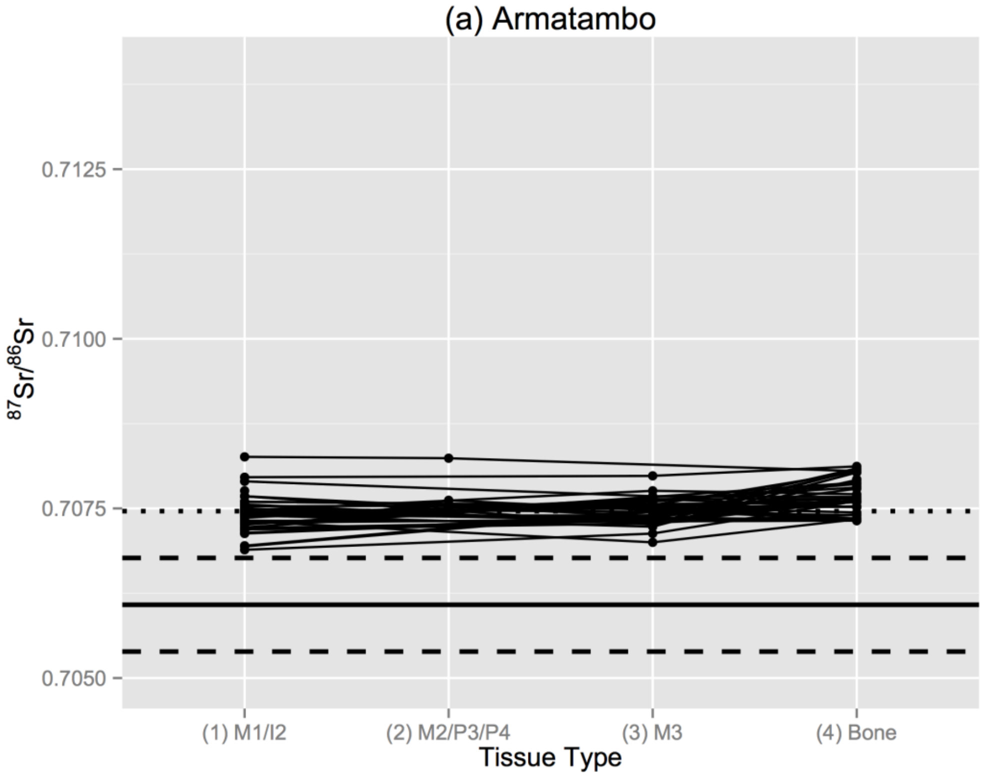
5.2 Armatambo and Rinconada Alta

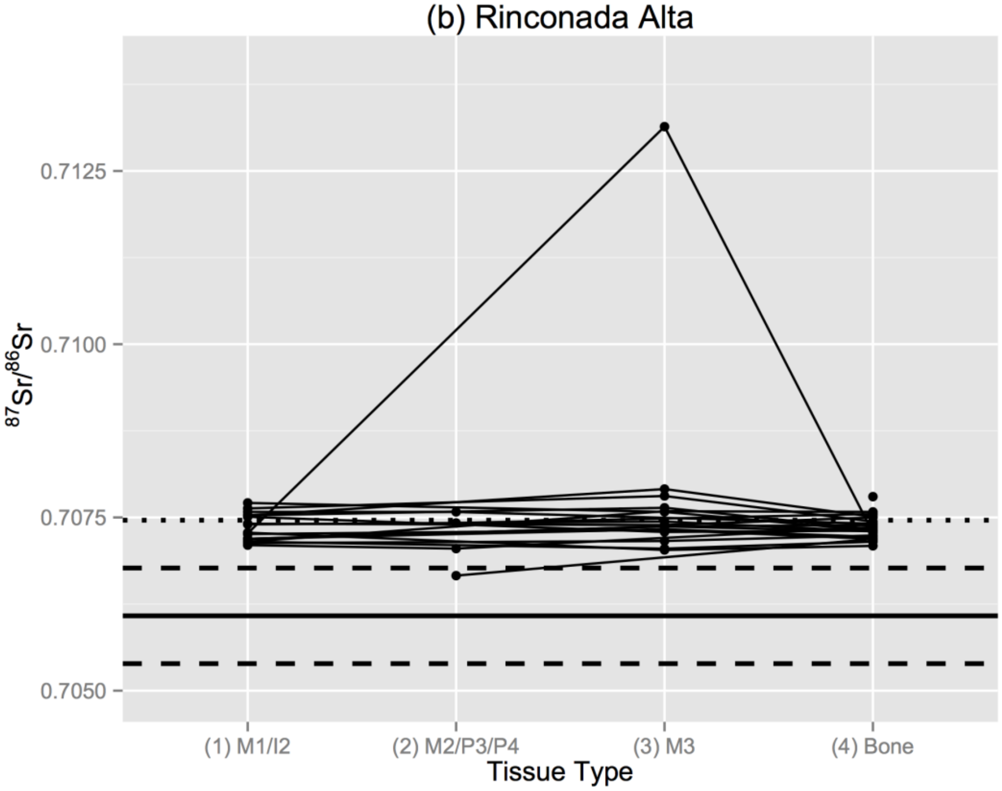
Radiogenic strontium isotope ($^{87}Sr/^{86}Sr$) values in archaeological human bone apatite and tooth enamel from Armatambo and Rinconada Alta are presented in Fig. 3 and Table S3. Overall, $^{87}Sr/^{86}Sr$ values are homogenous across the entire sample. Average

$^{87}Sr/^{86}Sr$=0.70750±0.00050 (*n*=176, 1σ), with minimum $^{87}Sr/^{86}Sr$ =0.70666 and maximum $^{87}Sr/^{86}Sr$ =0.71314. For bone apatite, average $^{87}Sr/^{86}Sr$=0.70756±0.00027 (*n*=64, 1σ), and ranges from $^{87}Sr/^{86}Sr$=0.70709 to $^{87}Sr/^{86}Sr$=0.70812 (Fig. 3). Although increased relative to the biologically available $^{87}Sr/^{86}Sr$ calculated from *Cavia porcellus* bone apatite values, the general homogeneity of these values suggests they represent local $^{87}Sr/^{86}Sr$. Analysis of $\delta^{15}N$ in bone collagen reveals consumption of marine foods at both sites (Marsteller, et al., 2017), which likely accounts for the observed increase in $^{87}Sr/^{86}Sr$ towards the ocean signature of $^{87}Sr/^{86}Sr$=0.70920 (Elderfield, 1986; Veizer, 1989).

Average tooth enamel $^{87}Sr/^{86}Sr$=0.70747±0.00060 (*n*=112, 1σ), with minimum $^{87}Sr/^{86}Sr$=0.70666 and maximum $^{87}Sr/^{86}Sr$=0.71314. One distinct outlier, a third permanent molar sample from one adult female from Rinconada Alta (RINC-G9698.II-0567-ENT116), presents a $^{87}Sr/^{86}Sr$ value equal to 0.71314 (Fig. 3). Tests for diagenesis show that trace elemental concentrations and the calcium to phosphorous ratio for this sample are well within normal biogenic ranges (U below detection limits; Nd=0.10 ppm; Ca/P=2.01), indicating the result is not caused by contamination from the burial environment. Instead, this individual likely consumed resources from a different region during the formation of this tooth between age 7-18 years (Hillson, 1996). Strontium ($^{87}Sr/^{86}Sr$) values for this same individual's first molar tooth enamel and bone samples, which reflect her early childhood and last years of adult life, respectively, fall within the local biologically available $^{87}Sr/^{86}Sr$ range (Fig. 3; Table S3).

Fig. 3. Archaeological human bone $^{87}Sr/^{86}Sr$ values for all skeletal samples from (a) Armatambo and (b) Rinconada Alta. Samples from the same individual connected with a line. Mean $^{87}Sr/^{86}Sr$ for local faunal bone apatite (solid line) and one (dashed lines) and two (dotted lines) standard deviations are indicated.

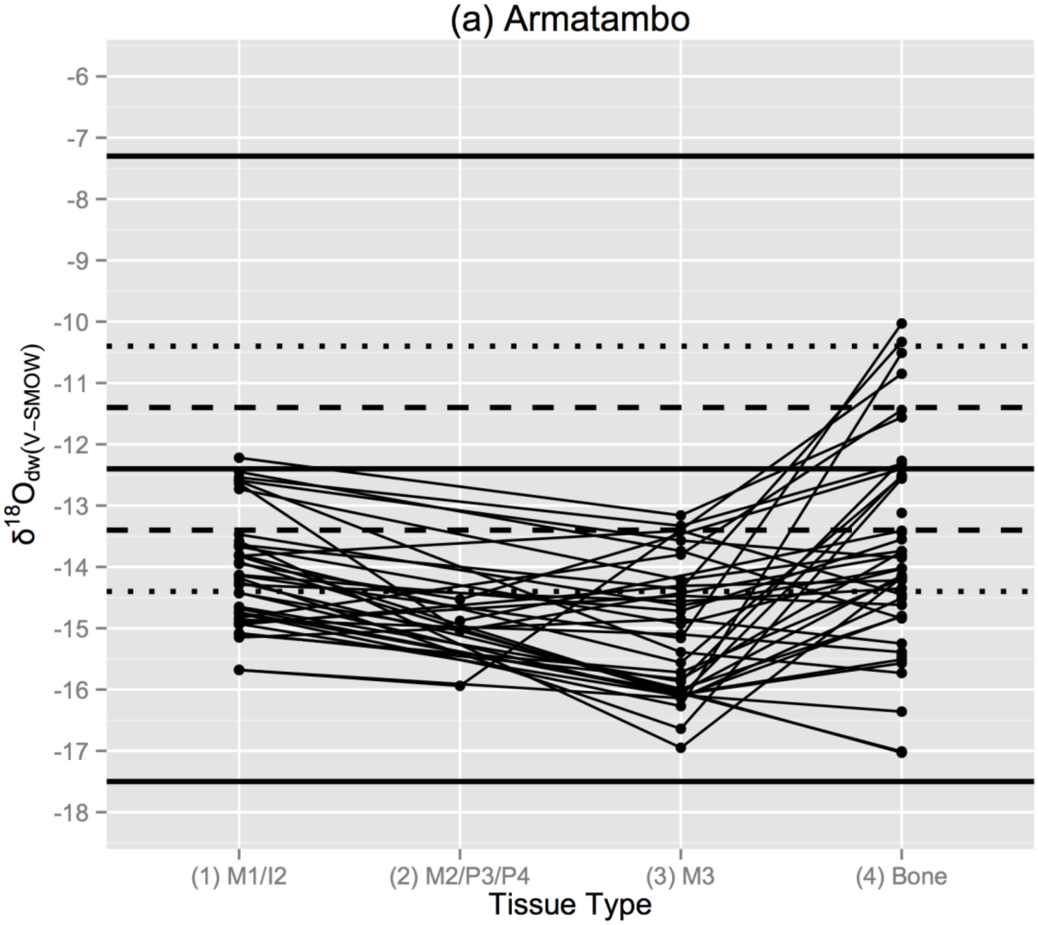

(a) Armatambo
$^{87}Sr/^{86}Sr$
0.7125
0.7100
0.7075
0.7050
(1) M1/I2
(2) M2/P3/P4
(3) M3
(4) Bone
Tissue Type

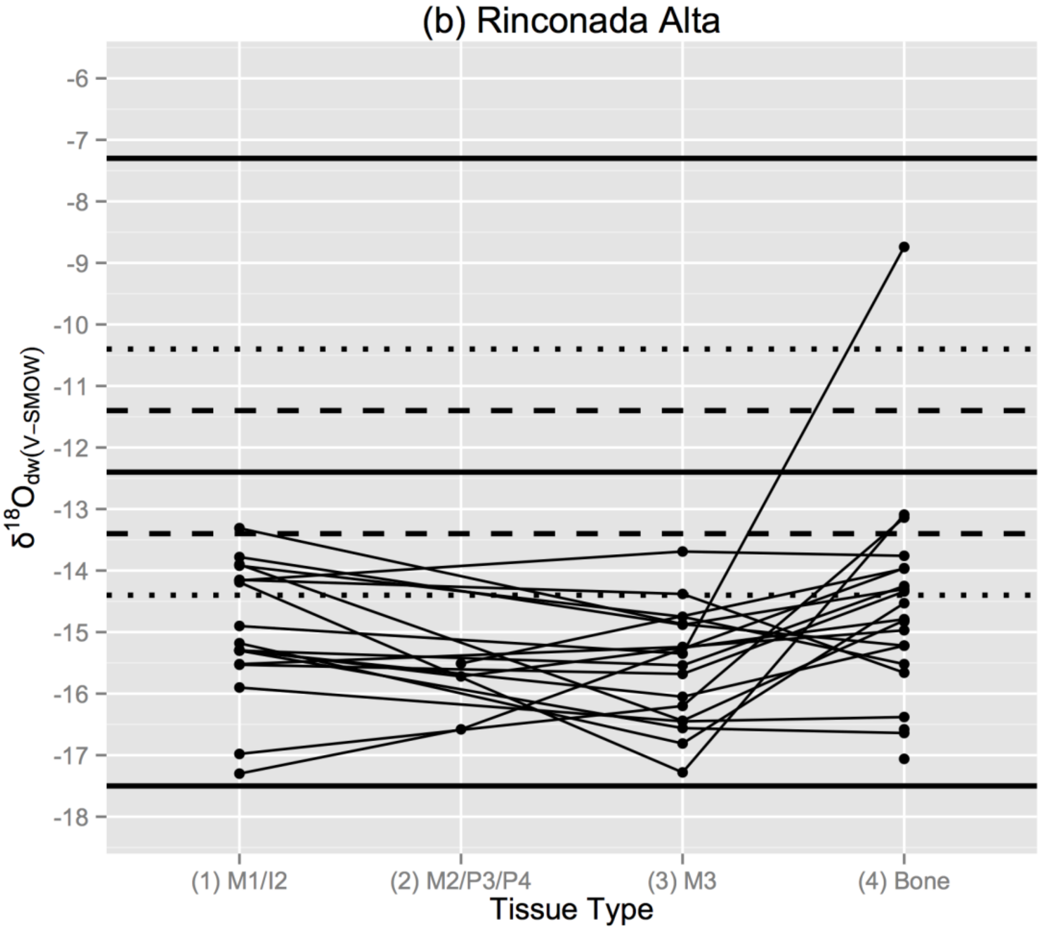


Stable oxygen isotopes in carbonates ($\delta^{18}O_{c[VPDB]}$) in archaeological human bone and tooth enamel are presented in Fig. 4 and Table S3. Because of the error introduced in converting carbonate stable oxygen isotope values ($\delta^{18}O_{c[VPDB]}$) to drinking water stable oxygen isotope values ($\delta^{18}O_{dw[V\text{-}SMOW]}$) (Daux, et al., 2008), converted values are used only in direct comparisons to baseline water stable oxygen isotope values ($\delta^{18}O_{mw[V\text{-}SMOW]}$). Average bone $\delta^{18}O_{c[VPDB]}$= -8.9±1.1‰ (n=64, 1σ) and range from $\delta^{18}O_{c[VPDB]}$=-10.9‰ to $\delta^{18}O_{c[VPDB]}$=-5.5‰. Converted to $\delta^{18}O_{dw[V\text{-}SMOW]}$, values range from $\delta^{18}O_{dw[V\text{-}SMOW]}$=-15.2‰ to $\delta^{18}O_{dw[V\text{-}SMOW]}$=-8.3‰ with mean bone $\delta^{18}O_{dw[V\text{-}SMOW]}$=-12.7±1.4‰ ($n$=64, 1σ).

For tooth enamel samples, $\delta^{18}O_{c(VPDB)}$ values range from -11.6‰ to -7.7‰ with average tooth enamel $\delta^{18}O_{c(VPDB)}$ equal to -9.5±0.7‰ (n=114, 1σ). Converted to $\delta^{18}O_{dw(V\text{-}SMOW)}$, values range from -16.1‰ to -11.2‰ with average tooth enamel $\delta^{18}O_{dw(V\text{-}SMOW)}$ equal to -13.4±1.0‰ (n=114, 1σ). Similar to the bone samples, these tooth enamel $\delta^{18}O_{dw(V\text{-}SMOW)}$ values fall within the locally defined $\delta^{18}O_{mw(V\text{-}SMOW)}$ range (Fig. 4).

Fig. 4. $\delta^{18}O_{dw(V\text{-}SMOW)}$ values for all skeletal samples from (a) Armatambo and (b) Rinconada Alta. Samples from the same individual connected with a line. Mean $\delta^{18}O_{mw(V\text{-}SMOW)}$ for local waters (center solid line) and one (dashed lines) and two (dotted lines) standard deviations are indicated. Outer solid lines mark the 3.1‰ MMD.





6. Discussion and conclusions

6.1 Implications for reconstructions of paleomobility within central Peruvian coast

The above results have important implications not only for current inferences about of the interregional interactions of the Ychsma society prior to the arrival of the Inka Empire in the Lima region, but also for future isotopic reconstructions of paleomobility on the central Peruvian coast more broadly. Specifically, despite clear differences in the geological and environmental zones of the study region, we observed a wide range of radiogenic strontium and stable oxygen isotopic values among soil, faunal, and water samples from the region that do not correspond to geological or environmental differences in sample locations. The range of isotopic baseline ^{87}Sr/^{86}Sr values observed are comparable to values for agricultural soils and *Cavia porcellus* bone apatite from the region reported by other researchers. We observed average soil ^{87}Sr/^{86}Sr=0.70652±0.00091 (n=24, 1σ), with the total range of ^{87}Sr/^{86}Sr=0.70479-0.70805. Soils from modern agricultural fields near Lima, Peru, analyzed by Knudson and colleagues (2014b) present average ^{87}Sr/^{86}Sr=0.70722±0.00036 (n=12, 1σ) with the total range of ^{87}Sr/^{86}Sr=0.70654-

0.70772. Soils from archaeological burials at the site of Ancón in the nearby Chillón Valley exhibit average $^{87}Sr/^{86}Sr=0.70774\pm0.00018$ (n=2, 1σ), with a total $^{87}Sr/^{86}Sr$ range of 0.70761 to 0.70786 (Slovak, et al., 2009). For faunal samples, we found average *Cavia porcellus* bone apatite $^{87}Sr/^{86}Sr=0.70608\pm0.00069$ (n=16, 1σ), with a total range of $^{87}Sr/^{86}Sr$ from 0.70481 to 0.70667. Modern rodent bone samples from the lower Lurín Valley (Pachacamac, Peru) analyzed by Knudson and colleagues (2014b) exhibit average $^{87}Sr/^{86}Sr$ equal to 0.70684±0.00016 (n=9, 1σ), while modern and archaeological *Cavia porcellus* bone samples from Ancón shows average $^{87}Sr/^{86}Sr$ equal to 0.70654±0.00012 (n=5, 1σ) (Slovak, et al., 2009).

All of these results clearly fall within the range of $^{87}Sr/^{86}Sr$ values obtained in the current study. The greater overall range of $^{87}Sr/^{86}Sr$ values observed here is likely a reflection of the wider range of locations sampled. While we found significant differences in $^{87}Sr/^{86}Sr$ values between soils from highland regions with Tertiary volcanic rocks and soils from low altitude areas with Quaternary sedimentary rocks, these differences were not observed among the small mammal bone samples analyzed from the same regions, indicating overlap in the ranges of biologically available $^{87}Sr/^{86}Sr$ in these areas. We suggest that the observed broad and overlapping ranges of local strontium isotopic values for the different geological areas on the central Peruvian coast is likely due to mixing of different bedrock types in local soils through processes of weathering and river, stream, and groundwater transport (Bentley, 2006). The archaeological human $^{87}Sr/^{86}Sr$ values measured at Armatambo and Rinconada Alta also span this broad range of local values. Together, these results indicate that, despite underlying geological variation on the central Peruvian coast, radiogenic strontium isotopes cannot be used to identify local regional mobility within this region. As detailed below, we propose that additional isotopic systems and elemental ratios be explored for the purposes of this task. We also note that radiogenic strontium isotope analysis does remain useful, however, for discerning the presence of mobility to outside regions as described in the following section.

Similar to the radiogenic strontium isotopic baseline presented here, stable oxygen isotope analysis also reveals a broad range of local water $\delta^{18}O_{mw[V\text{-}SMOW]}$ values for the central Peruvian coast. Overall, $\delta^{18}O_{mw[V\text{-}SMOW]}$ ranges from -14.6‰ to -10.6‰ with average $\delta^{18}O_{mw[V\text{-}SMOW]}=-12.4\pm1.0$‰ ($n$=22, 1σ). We are unaware of other $\delta^{18}O_{mw[V\text{-}SMOW]}$ data collected from water samples in this region. Buzon and colleagues (2011) analyzed modern water samples from the desert *chala* and mid-altitude *yungas* regions of the Nazca River drainage system on the southern Peruvian coast and found average $\delta^{18}O_{mw[V\text{-}SMOW]}=-11.9\pm0.46$‰ ($n$=8, 1σ), with the total range of $\delta^{18}O_{mw[V\text{-}SMOW]}$ equal to -11.1‰ to -12.6‰ (Buzon, et al., 2011). While these results from Nazca would suggest that the *chala* and *yungas* regions exhibit little variability, the broader range of $\delta^{18}O_{mw[V\text{-}SMOW]}$ observed in the current study indicates that increased sampling may detect increased variability across these two ecozones at Nazca and other regions in the Central Andes. In addition, we found that $\delta^{18}O_{mw[V\text{-}SMOW]}$ values in water sources from the lowland *chala* and *yungas* on the central Peruvian coast overlap substantially with those from water sources in adjacent higher altitude ecozones. Given this finding, we urge caution when using stable oxygen isotopes to infer paleomobility on the central Peruvian coast and the Central Andean coast more broadly. Such a wide range of $\delta^{18}O_{mw[V\text{-}SMOW]}$ is likely attributable to the availability of multiple water sources across the broad assortment of environmentally diverse areas associated with both expansive watersheds and the rapid altitudinal ascent inland from the Pacific Ocean shore (see Knudson, 2009). In particular, these features of the central Peruvian coast prevent the use of stable oxygen isotopes to assess local regional mobility within this area in the past.

6.2 Evidence for pre-Inka interregional interactions at Armatambo and Rinconada Alta

Although the broad range of radiogenic strontium and stable oxygen isotope values precludes the use of these isotopic systems to evaluate local paleomobility on the central Peruvian coast, the data presented above do indicate that radiogenic strontium isotopes are useful for identifying interregional movement. Specifically, radiogenic strontium isotopes reveal evidence of movement by one individual to an outside region. Specifically, one adult female buried at Rinconada Alta (RINC-G9698.II-0567-ENT116) exhibits a $^{87}Sr/^{86}Sr$ value (0.71314) in her third permanent molar, which lies far outside the local biologically available range ($^{87}Sr/^{86}Sr$=0.70470-0.70746). Local $^{87}Sr/^{86}Sr$ values in this female's first permanent molar ($^{87}Sr/^{86}Sr$=0.70727) and bone ($^{87}Sr/^{86}Sr$=0.70728) samples indicate this individual may have spent her childhood in the study region, travelling outside of the area between ages 7-18, during the time of formation of her third permanent molar (Hillson, 1996).

Potential locations for her travel are revealed through comparison with previously published Andean soil $^{87}Sr/^{86}Sr$ data. Specifically, the $^{87}Sr/^{86}Sr$ values from Rinconada Alta female 0567-ENT116 fall within or near the ranges of values recorded for only two of the 17 regions included in Knudson and colleagues' (2014b) survey of soils from the south-central Andes. These two regions were the only two highland regions investigated: Cuzco (0.70771-0.71894) and Puno (0.70696-0.71191). Rinconada Alta female 0567-ENT116 may have traveled to a similar highland location during her late childhood and adolescence. This Rinconada Alta female's bone $^{87}Sr/^{86}Sr$ value (0.70728) and first permanent molar $^{87}Sr/^{86}Sr$ value (0.70727) also fall within or near the wide $^{87}Sr/^{86}Sr$ ranges observed for these highland regions, which could suggest she moved multiple times during the period of her residence outside the Lima/Huarochirí region. Thus, although Rinconada Alta 0567-ENT116's first permanent molar and bone $^{87}Sr/^{86}Sr$ values fall within the local Rimac and Lurín Valley and Huarochirí range, they may instead correspond to a non-local region with similar biologically available $^{87}Sr/^{86}Sr$ values. Indeed, it is important to caution that other local $^{87}Sr/^{86}Sr$ values observed among additional individuals from Armatambo and Rinconada Alta could instead be non-local values which cannot be identified as such using radiogenic strontium isotopes due to the similarity of $^{87}Sr/^{86}Sr$ values from the central coast region to $^{87}Sr/^{86}Sr$ values in various other regions of the Andes (see Knudson, et al., 2014b).

Additional isotopic analyses of dietary practices at Rinconada Alta reveal that isotopic evidence of diet may not always be able to discern non-local individuals or foreign travel. Specifically, stable carbon and nitrogen isotopic data indicate that Rinconada Alta 0567-ENT116 consumed a diet focused on C_4 and/or low-trophic level marine protein resources and an increased proportion of C_4 versus C_3 non-protein (carbohydrates and lipids) resources (Marsteller, et al., 2017). This dietary pattern falls within normal trends among individuals at the site suggesting that 0567-ENT116's foreign associations may not have impacted her diet (Marsteller, et al., 2017). Alternatively, she may have consumed different types of resources with similar isotopic signatures. For example, the high altitude C_4 pseudocereal, *Amaranthus caudatus* (kiwicha) may exhibit $\delta^{15}N$ signatures similar to those of low trophic level marine protein resources (e.g., Turner, et al., 2010).

In contrast, preliminary evaluation of mortuary contextual data at Rinconada Alta suggests that 0567-ENT116 may have received a somewhat unusual burial treatment. In particular, 0567-ENT116 was buried in a flexed position on her right side, a position observed in only one other mortuary context at Rinconada Alta and only among seven burials at Armatambo (*n*=7/88, 8%) (Marsteller, 2015). Burial on the right side may thus have corresponded to a form of foreign affiliation assigned by mourners at the time of death, though further studies are needed to verify this possibility.

Overall, these results imply that at least some individuals in the Lima region traveled long distances across the larger Andes during the Late Intermediate Period, prior to Inka imperial influence. Contrary to social organizational models that assume highlanders were unable to access lower valley regions prior to Inka control (e.g., Cornejo, 1995; Rostworowski, 2002a), our finding of an individual with non-local ties instead supports hypotheses that the Lima region was of pan-Andean interest prior to the Late Horizon Period and the social transformations inferred to have been imposed by the Inka Empire. More studies will be necessary to further evaluate the extent and nature of interregional and local regional mobility to and from the Lima region during the Late Intermediate Period.

6.3 Advantages of a biogeochemical life history approach to paleomobility

The results of this study reveal the major advantages of a life history approach to paleomobility using biogeochemical analyses. First and foremost, examining multiple skeletal elements from each individual analyzed allows for the identification of mobility that occurred during specific periods over the life course which would be obscured by analyses focused only one element. The case of Rinconada Alta 0567-ENT116 described above illustrates this particularly well. Had analysis focused only on tooth enamel from an early forming tooth, such as the first molar, as has generally become standard practice, the movement of this individual to a distant region during her late childhood and adolescent years would have been overlooked.

Second, a life history approach to paleomobility allows for an assessment of differences in inter-individual variability of isotope values from skeletal elements with different formation times. In a study of radiogenic strontium isotopes in archaeological bone and human tooth enamel from first molars, second molars, and third molars, from individuals in Siberia, Haverkort et al. (2008) found an overall convergence of values, similar to that observed in the present study. In terms of variability of values, Haverkort et al. (2008) found first molar values to exhibit the highest variability and bone sample values the lowest. They interpret their results to reflect the averaging effects of bone remodeling and/or the increased susceptibility of bone to diagenetic contamination from the burial environment. The present study similarly shows early forming first molars and incisors to exhibit the highest variability among radiogenic strontium isotope values at Armatambo and bone values the lowest variability at this site (Fig. 3a). At Rinconada Alta, however, excluding outlier 0567-ENT116, third molar values exhibit greater variability in radiogenic strontium isotope ratios than either first molar or bone sample values (Fig. 3b). Patterns among stable oxygen isotope values, in contrast, show greatest variability among bone sample values at both sites. Thus, the averaging effect of bone remodeling and increased potential for diagenesis are insufficient to explain differences in variability among tissue types. The large variability in potential water sources in the Rimac and Lurín Valley region may explain the larger variability observed among bone stable oxygen isotope values. While this pattern may reflect increased variation in local water sources used during adulthood, these results suggest that caution should be made in relying on variability in bone stable oxygen isotope values alone to infer differences in residence.

6.4 Suggestions for future research

Briefly, we end with a few suggestions for future studies of biogeochemical life history approaches to paleomobility in general and on the central Peruvian coast more specifically. First, we recommend that new projects consider additional isotopic systems and/or elemental ratios such as stable lead isotope ratios or ratios of elemental barium or strontium to calcium, which may be less impacted by geological mixing processes or environmental diversity. For example, stable lead isotopes ($^{20n}\text{Pb}/^{204}\text{Pb}$), which co-vary with geological bedrock variation similar to radiogenic strontium isotopes, can be analyzed in conjunction with radiogenic strontium and stable oxygen isotope values to refine inferences about the potential origins of immigrants and travelers in the past (e.g., Turner, et al., 2009). Because stable lead isotope variation is transferred to human tissues through inhalation of soil and dust particles rather than through the diet (Kamenov, 2008), this process may also involve less mixing of different bedrock types than likely occurs within agricultural soils. Additionally, unlike radiogenic strontium isotopes, stable lead isotopes are unaffected by the consumption of marine foods. Alternatively, ratios of elemental barium or strontium to calcium (Ba/Ca, Sr/Ca) may also be used in conjunction with radiogenic strontium and stable lead and oxygen isotopes to infer past mobility in regions with geological and/or environmental variation (Burton, et al., 2003).

Second, combining archaeological biogeochemical reconstructions of life histories of mobility with isotopic evidence of individual changes in diet over the life course through analysis of stable carbon, nitrogen, and/or sulfur isotopes in archaeological human tissues that form at different times could be used to provide information on the impacts of mobility on dietary practices. For example, at Rinconada Alta and Armatambo, analyses of hair keratin-bone collagen pairs reveal some individuals' diets changed substantially prior to death (Marsteller, et al., 2016), which may be associated with changes in residence undetected by the radiogenic strontium and stable oxygen isotope results presented here.

Finally, analyzing patterns of biological distance in tandem with biogeochemical reconstructions of mobility and diet could offer additional details concerning the nature of social interactions associated with mobility practices. Biological distance analysis can be used to address a variety of questions regarding kin relations, such whether cemetery layout was structured according to kinship, the nature of postmarital residence patterns, and the degree of changes in population structures over time (Stojanowski and Schillaci, 2006). Combining such biological distance information with isotopic evidence of immigration and mobility could enhance understanding of who and why particular individuals and groups in the past changed their location of residence over the course of their lives.

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