



Geographic insularity and intra-lifetime mobility in Late Intermediate Period (ca. 1000 – 1450 CE) Arequipa, Peru determined from $^{87}\text{Sr}/^{86}\text{Sr}$ isobiographies

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ABSTRACT

Objectives: This study examines mobility adaptations to a time of sociopolitical tumult in the ancient Andes. We examine $^{87}\text{Sr}/^{86}\text{Sr}$ variability in human burials ($n = 21$) dating to the Late Intermediate Period ("LIP," ca. 1100 – 1450 CE) in the Sihuas Valley, Arequipa, Peru. The LIP in the southern and central Peruvian Andes is characterized as a time of drought, inter-community violence, and balkanization. Grave goods reflect ties to the nearby highlands, so we examine whether any Quilcapampa burials were non-locals and characterize their intra-lifetime mobility.

Materials and Methods: We report $^{87}\text{Sr}/^{86}\text{Sr}$ values from tooth enamel samples ($n = 35$) reflecting residential origins during three distinct periods during early-life, and bone ($n = 12$) reflecting origins averaged over the last years of life. We use $^{87}\text{Sr}/^{86}\text{Sr}$ isobiographies to identify individuals who were likely non-local to Quilcapampa at some point in their lifetimes. Because there are no extreme outliers, we define the cumulative local range as mean $\pm 2\sigma$ of archaeological human samples, extended by the range of water $^{87}\text{Sr}/^{86}\text{Sr}$ within 10 km. We determine the proportion of probable non-locals and compare this and intra-lifetime mobility within Quilcapampa subgroups and between neighboring sites.

Results: Two males from the northern sector exhibit non-local $^{87}\text{Sr}/^{86}\text{Sr}$ values, and the northern sector has a higher mean intra-lifetime $^{87}\text{Sr}/^{86}\text{Sr}$ range than the southern sector. Only 4.5% of burials exhibit non-local $^{87}\text{Sr}/^{86}\text{Sr}$ values at some point in their lifetimes—higher than contemporaneous highland sites, but low mid-elevation Arequipa valleys. Quilcapampa, however, shows a higher mean intra-lifetime $^{87}\text{Sr}/^{86}\text{Sr}$ range compared to neighboring mid-valley sites, possibly reflecting adaptive short-term mobility.

Conclusion: Mobility for Quilcapampa individuals was likely constrained to nearby mid-valley communities and highlands, rather than long-distance travel. Immigrants likely leveraged pre-existing intra-regional mobility networks between neighboring valleys with similar geological characteristics.

Tweetable Summary: $^{87}\text{Sr}/^{86}\text{Sr}$ isobiographies show limited intra-lifetime mobility in LIP Sihuas Valley, Peru.

1. Introduction

The Late Intermediate Period (LIP, ca. 1000–1450 CE) is characterized as a time of violent conflict and balkanization after the dissolution of expansive Middle Horizon polities (Wari of the central Peruvian highlands and Tiwanaku of Lake Titicaca). Communities became

aggregated into fewer, larger communities, inter-zonal trade and mobility was reduced, inter-group violence skyrocketed (Arkush, 2022; McCool et al., 2022; Tung, 2021, 2008), and communities became increasingly concerned with defense (Arkush, 2018; Arkush and Tung, 2013; Kohut, 2018). However, much of what is known about LIP lifeways in southern Peru comes from highland (Arkush, 2018; Kohut,

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2018; McCool et al., 2021; Velasco, 2018; Velasco and Tung, 2021; Wernke, 2013) or coastal (Conlee, 2021) communities. We understand little about LIP lifeways and interregional connectedness for *yunga*¹ (intermediate elevation) sites. Prior archaeological research in southern Peru has suggested that harsh LIP drought, cold, and climatic instability drove an influx of highlanders to more temperate lower-elevation valleys (Conlee, 2003; Covey, 2008; Jennings et al., 2021). However, this narrative derives mostly from stylistic analyses of ceramics and architectural types. Beyond limited ancient DNA (Fehren-Schmitz et al., 2014; Nakatsuka et al., 2020), skeletal data corroborating these highland-coastal movements has been lacking.

Here, we investigate $^{87}\text{Sr}/^{86}\text{Sr}$ of human skeletons from LIP tombs at the cemetery of Quilcapampa in the Sihuas Valley, Arequipa, Peru to identify possible first-generation immigrants, examine intra-lifetime mobility, and characterize the proportion of probable non-locals in this LIP burial community relative to sites in the region and beyond. We employ these data to examine how LIP conditions impacted mobility and interzonal movement in *yunga* Arequipa and to highlight how isotopic life history approaches can add nuance to understandings of Central Andean mobility otherwise obscured by single-tissue or enamel-only approaches.

1.1. Intergroup violence, localization, and climate stress in the LIP

The LIP was a period of intense balkanization and violent inter-community conflict, when many communities became aggregated into politically decentralized, defensively-situated hamlets (Bauer and Kellett, 2010; Covey, 2008). LIP settlements show the highest rates of violence-related trauma of any period (Arkush, 2022; Arkush and Tung, 2013; Kurin, 2016; McCool et al., 2022, 2021; Tung, 2021), and settlements were reorganized into fortified hilltop *pukaras* (Arkush, 2018, 2010; Bauer and Kellett, 2010; Kohut, 2018; McCool et al., 2021; Stanish, 2003). This violence (see summary in Arkush, 2022), climate-related stress (Arkush, 2018; Arkush and Ikehara, 2019; McCool et al., 2022; Wilson et al., 2022), and the dissolution of the Wari and Tiwanaku polities seem to have mutually constituted decreased mobility and interregional connections across the Andes. For example, in San Pedro de Atacama, northern Chile, biogeochemical and craniometric data show that the influx of migrants into these oases during the Middle Horizon was curtailed into the LIP and ethnic diversity was greatly decreased (Torres-Rouff and Knudson, 2017). Similarly, $^{87}\text{Sr}/^{86}\text{Sr}$ analyses from central Peruvian coast sites show communities were mostly of locally-born individuals (Marsteller et al., 2017), contradicting ethno-historic records of frequent highland-coastal prior to the Inca era (see summary in Marsteller et al., 2017). A recent meta-analysis (Scaffidi and Knudson, 2020) of $^{87}\text{Sr}/^{86}\text{Sr}$ similarly demonstrates narrow $^{87}\text{Sr}/^{86}\text{Sr}$ ranges and few statistical outliers at the 11 LIP sites examined relative to the preceding Middle Horizon and subsequent Late Horizon.

While evidence for climate-related stress, conflict, and relative insularity is strong at well-studied sites like those around Lake Titicaca (see summary in Covey, 2008), the corpus of LIP research is biased toward highland sites. It remains unknown whether lower-elevation communities were affected by these LIP stressors, and if so, whether they adapted through vertical interzonal mobility. In southern Peru (Fig. 1), the limited data available from LIP contexts is consistent with the narrative of heightened conflict, insularity, and localized sociopolitical power and community identity. A survey of *pukaras* in the highland Colca Valley demonstrates intensified intergroup conflict in the LIP (Kohut, 2016; Wernke, 2013), while bioarchaeological data yields a high cranial trauma rate for adults at Coporaque (Velasco, 2018) and Tuti (Tung, 2021). Colca artifact assemblages suggest some trade with

Lake Titicaca, but LIP material culture (Kohut, 2016; Velasco, 2018; Wernke, 2003) and cranial vault modification styles (Velasco, 2018) show local cultures dominated the Arequipa highland prior to Inca rule. However, Colca highland traditions were distinct from lower elevations, so it is unclear whether LIP social and environmental shifts impacted *yunga* communities similarly.

1.2. Archaeological context and skeletal individuals: The LIP Quilcapampa cemetery

This study tested 26 skeletal from 33 tombs excavated by the Quilcapampa Archaeological Project (Proyecto de Investigación Arqueológico Quilcapampa, 2015–2016). Quilcapampa is a multi-component site, including a Wari-era enclave and LIP tombs (Jennings et al., 2021; Jennings and Reid, 2021) located at 800 masl where the *yunga* spills from desert into *ichu*-grass covered hillsides with the snow-covered Ampato volcano looming in the distance (Fig. 1). Wari-era human skeletons have not been located, but AMS dates from the Quilcapampa monumental core show it was constructed by Wari colonists in the mid-ninth century CE and abandoned a generation later (Jennings, 2024; Jennings and Reid, 2021). The hillsides above the monumental core (approximately 1600 masl) were resettled in the thirteenth and fourteenth centuries, expanding the 2 ha Middle Horizon component to approximately 70 ha (Jennings et al., 2021). LIP areas are unfortified but inaccessible, requiring a 45-minute descent to the Sihuas River for fresh water. Vast stretches of the Sihuas Valley dominate the viewshed from hilltop residences, enabling defensive monitoring and surveillance. LIP Quilcapampa cemetery sectors are situated at the intersection of trails connecting valley floor to desert pampa passing into neighboring *yunga* valleys: Majes to the west and Vitor to the east (Bikoulis et al., 2018; Jennings et al., 2018) (Fig. 1). Sections of the *Qhapac Ñan*, or Inca road system, predate the Inca (Schreiber, 1992), connecting LIP Quilcapampa to the Majes Valley petroglyph site *Toro Muerto*—a ritually and logistically important transit hub for southern Peru (Reid, 2023; Scaffidi, 2018; Woloszyn et al., 2019)—and highland Colca Valley sites like Huanca, Lluta, and Huambo.

Narrow cist tombs were constructed above the abandoned Wari enclave during the latter half of the LIP across two sectors (Fig. 2) (Jennings et al., 2021). Cist tombs were capped with clay mortar and sealed with local white volcanic tufa (*sillar*). Unlike at the aboveground *chulpa* tombs of LIP highland Arequipa (Velasco, 2014; Wernke, 2003), mummy bundles were desiccated and painted with red pigment outside of cists and then permanently entombed without dirt fill. Based on demographic composition of tomb groupings, clusters of cists likely represent family burial plots (Jennings et al., 2021), but differences between northern (Sector F) and southern (Sector C) sectors hint at social differences between burial groups. For example, Sector F contained painted stone offerings called *placas pintadas*, gourds, maize (*Zea mays*), textile-crafting implements, and ceramics painted in highland LIP styles (Jennings et al., 2021) (Fig. 3, Table 1). Sector C contains fewer grave goods overall, limited to gourds, *cuy* (*Cavia porcellus*), a fetal camelid (*Lama* sp.), textile-crafting implements, coca (*Erythroxylum coca*), maize, and ceramics with local, non-highland designs (Fig. 3, Table 1).

Many crania were poorly preserved, limiting observations relevant to biological sex estimation, social identity (e.g., cranial vault modification), and violence (cranial trauma). Nonetheless, age-at-death and biological sex estimates² demonstrate similar proportions of biological

² Estimation of biological sex from skeletal traits throughout is based on standard bioarchaeological methods, including cranial and pelvic morphology (Buikstra and Ubelaker, 1994). These estimates are based on assumed human sexual dimorphism within a burial population and do not imply a 1:1 relationship with socially constructed gender. None of the individuals described herein were buried with gendered grave goods, and so biological sex estimates inherently provide a limited understanding of social gender.

¹ Peruvian geographer Pulgar Vidal (1946), describes coastal *yunga* as the arid and warm Western slopes of the Andes between the coast and the highlands, approximately 500 – 2300 masl.

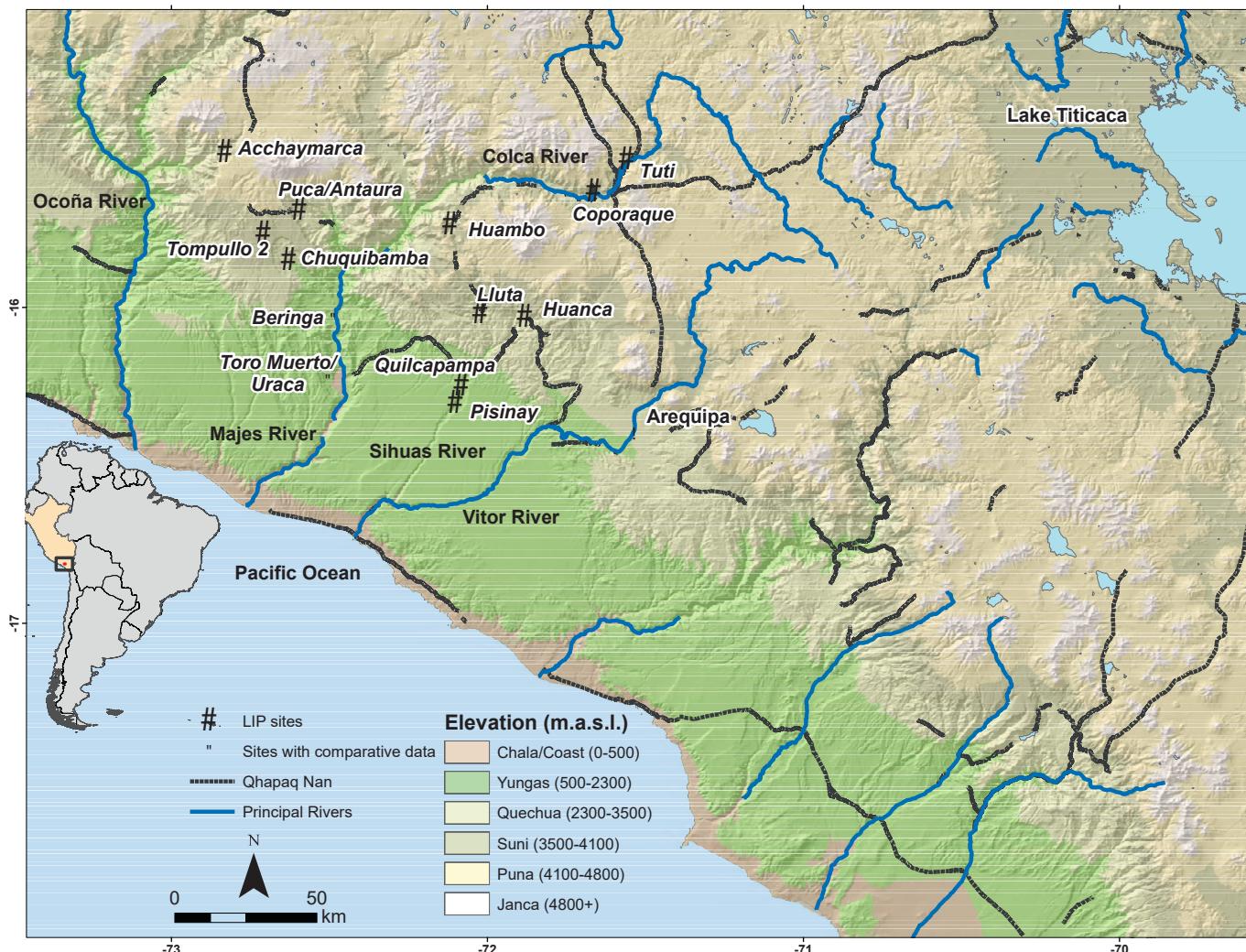


Fig. 1. Overview map of valleys and sites mentioned in this text, overlying digital elevation model coded by elevational zone (WGS 1984 datum, UTM Zone 19S). Lines indicate locations of the *Qhapaq Ñan*, the Inca road network, that may have connected LIP sites in Arequipa to each other and the broader region.

females ($n = 9$), males ($n = 14$), and subadults ($n = 9$) (biological sex could not be estimated for one adult), suggesting burials reflect a once-living community. Three individuals show tabular erect cranial vault modification, a style local to the nearby *yunga* and highlands. One adult male (Tomb 9) exhibited an antemortem depression fracture on the left frontal bone, possibly from interpersonal violence.

1.3. Multi-tissue $^{87}\text{Sr}/^{86}\text{Sr}$ to examine intra-lifetime mobility

Radiogenic strontium isotope analysis ($^{87}\text{Sr}/^{86}\text{Sr}$) is a well-established tool for identifying probable non-local individuals respective to their burial locations (Bentley, 2006; Ericson, 1985; Knudson et al., 2023, 2016; Montgomery, 2010; Price et al., 2002). Briefly, as rubidium (^{87}Rb) in bedrock decays into ^{87}Sr , bedrock $^{87}\text{Sr}/^{86}\text{Sr}$ becomes incorporated into the mix of soils, plants, water, fauna, dust, and sea-spray comprising the human food web, known as bioavailable strontium (Bentley, 2006; Maurer et al., 2012; Montgomery, 2010). Therefore, the $^{87}\text{Sr}/^{86}\text{Sr}$ of dietary catchments varies predictably throughout landscapes (Bataille et al., 2020; Britton et al., 2021; Frei and Frei, 2013; Willmes et al., 2018). In the absence of any diagenetic contamination of skeletal tissues from the burial environment, human tissue $^{87}\text{Sr}/^{86}\text{Sr}$ values differing from local environmental samples (within a margin of error) or beyond the central tendency of human $^{87}\text{Sr}/^{86}\text{Sr}$ at a cemetery (Burton and Hahn, 2016; Price et al., 2014; Scaffidi and Knudson, 2020;

Slovak and Paytan, 2012) suggests an individual lived outside of the area when the sampled tissue was forming. While $^{87}\text{Sr}/^{86}\text{Sr}$ does not provide a “postcode” (Pollard, 2011, p. 634) for residential origins, individuals with outlier $^{87}\text{Sr}/^{86}\text{Sr}$ can be identified as probable non-locals to the burial community.

Furthermore, analyzing $^{87}\text{Sr}/^{86}\text{Sr}$ in multiple tissues from an individual, referred to here as an isobiographical approach (sensu Eerkens and Bartelink, 2023; Scaffidi et al., 2022), allows us to examine whether and to what extent individuals changed residence throughout their life courses. Because teeth mineralize sequentially (Hillson, 2023, 2005), sampling teeth forming in infancy to early childhood (IEC), middle childhood (MC), and teen/adolescent years (T) reflects bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ taken in during enamel formation. First molar enamel begins forming approximately two weeks prior to birth and throughout the infant breastfeeding period until about 3.5 years old (AlQahtani et al., 2014), so it captures child-maternal $^{87}\text{Sr}/^{86}\text{Sr}$. Middle childhood-forming tooth enamel reflects residential origin from approximately 2.3 to 8 years old, and teen-forming tooth enamel reflects residential origin from approximately 8 to 15 years old (Hillson, 2023, 2005). Bone constantly being remodelled until death, so bone sampling reflects $^{87}\text{Sr}/^{86}\text{Sr}$ consumption averaged over the last years of life (Bentley, 2006).

There is no consensus on how much $^{87}\text{Sr}/^{86}\text{Sr}$ variability in sequentially forming tissues indicates intra-lifetime movement, as this

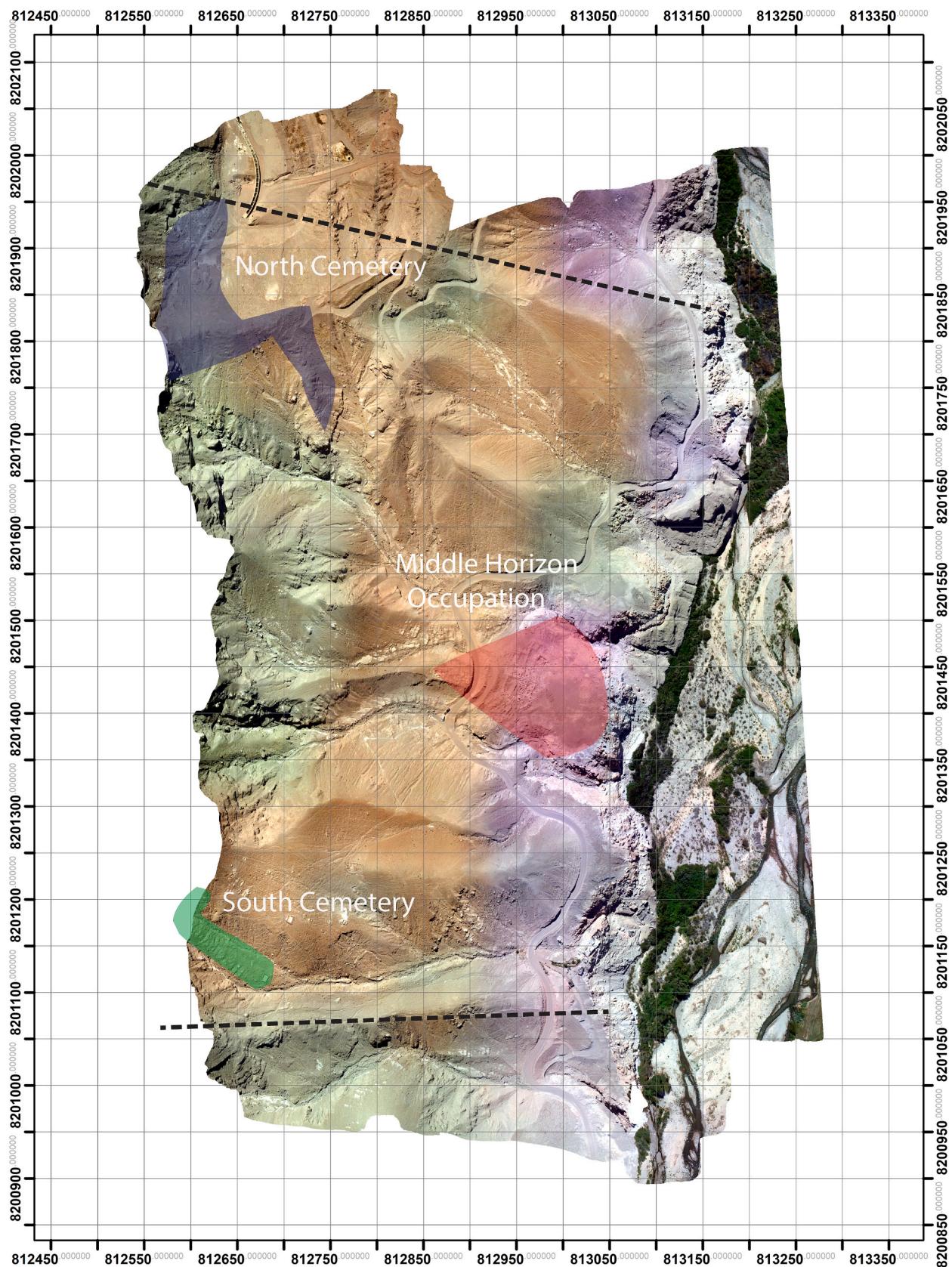


Fig. 2. The LIP northern (Sector F) and southern (Sector C) cemetery sectors at Quilcapampa relative to the Middle Horizon monumental core (UTM Zone 18S, WGS 1984 datum). Dashed lines indicate local roads connecting Quilcapampa to Majes Valley sites. Basemap: ESRI (ArcMap Desktop Version 8.1). Map: Stephen Berquist, Felipe Gonzalez-McQueen, and Beth K. Scaffidi.

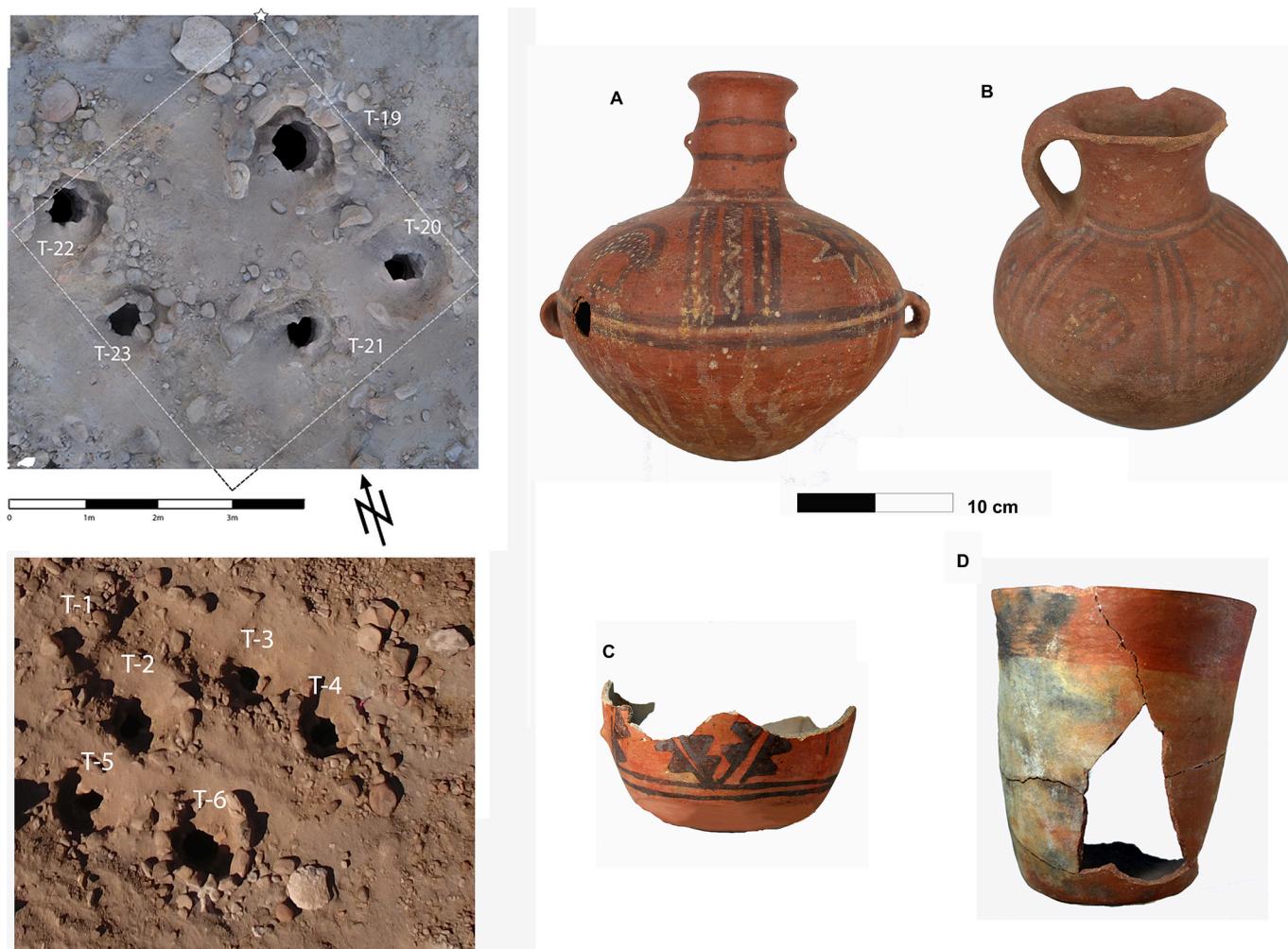


Fig. 3. Typical ceramic vessels for the LIP Quilcapampa cemetery. Top: local, Sihuas-style vessels from the southern sector (C). Bottom: vessels decorated in the highland style from the northern sector (F). Photos: Quilcapampa Archaeological Project.

Table 1

Description of site contexts, AMS dates, and demographic information for sampled individuals. Age category abbreviations are: C = child, T = teen, A = adult, YA = young adult, MA = middle adult.

Cemetery	Unit	Locus	Tomb	Age Category	Age Range	Sex	AMS Date of Tomb [†]	Grave goods
North	14	1311	2	MA	35–50+	M	NA	gourd
North	15	1409	3	C	3–4	?	NA	gourd, sewing needle, maize cob
North	100	9900	4	C	4–6	?	NA	NA
North	100	9904	8	A	30+	F	NA	NA
North	100	9905	9	MA	35–45	M	NA	NA
North	15	1413	11	MA	35–45	F	NA	spindle whorl, sewing needle
North	15	1419	12	YA	25–35	M	NA	bowl, gourd, wood fragment
North	100	9907	13	T	15–17	M?	NA	NA
North	100	9908	14	MA	35–50	M	NA	NA
North	100	9909	15	A	30+	?	NA	NA
North	15	9911	17	T	15–18	?	NA	NA
North	100	9912	18	T-YA	19–23	F	NA	NA
South	30	2906	19	MA	35–45	M	1293–1391 CE	bowl, jar, fetal camelid, gourd
South	30	2922	20	MA	35–50	F	1293–1391 CE	NA
South	30	2932	21	C	9–12	?	1293–1391 CE	NA
South	31	3003	24	T	15–19	?	NA	bowl, jar, guinea pig, wood fragment
South	32	3015	25	T-YA	20–26	M?	1226–1379 CE	bowls, gourd, maize
South	32	3023	26	MA	45+	F	1226–1379 CE	bowl, jar, spindle whorl, sewing needle, coca, maize
South	32	3033	27	YA	30–44	F	1226–1379 CE	bowl, jar
South	32	3042	28	C	2–4	?	1226–1379 CE	spindle, spindle whorl

[†] AMS dates are calibrated 2-sigma range, from Jennings et al. 2021b.

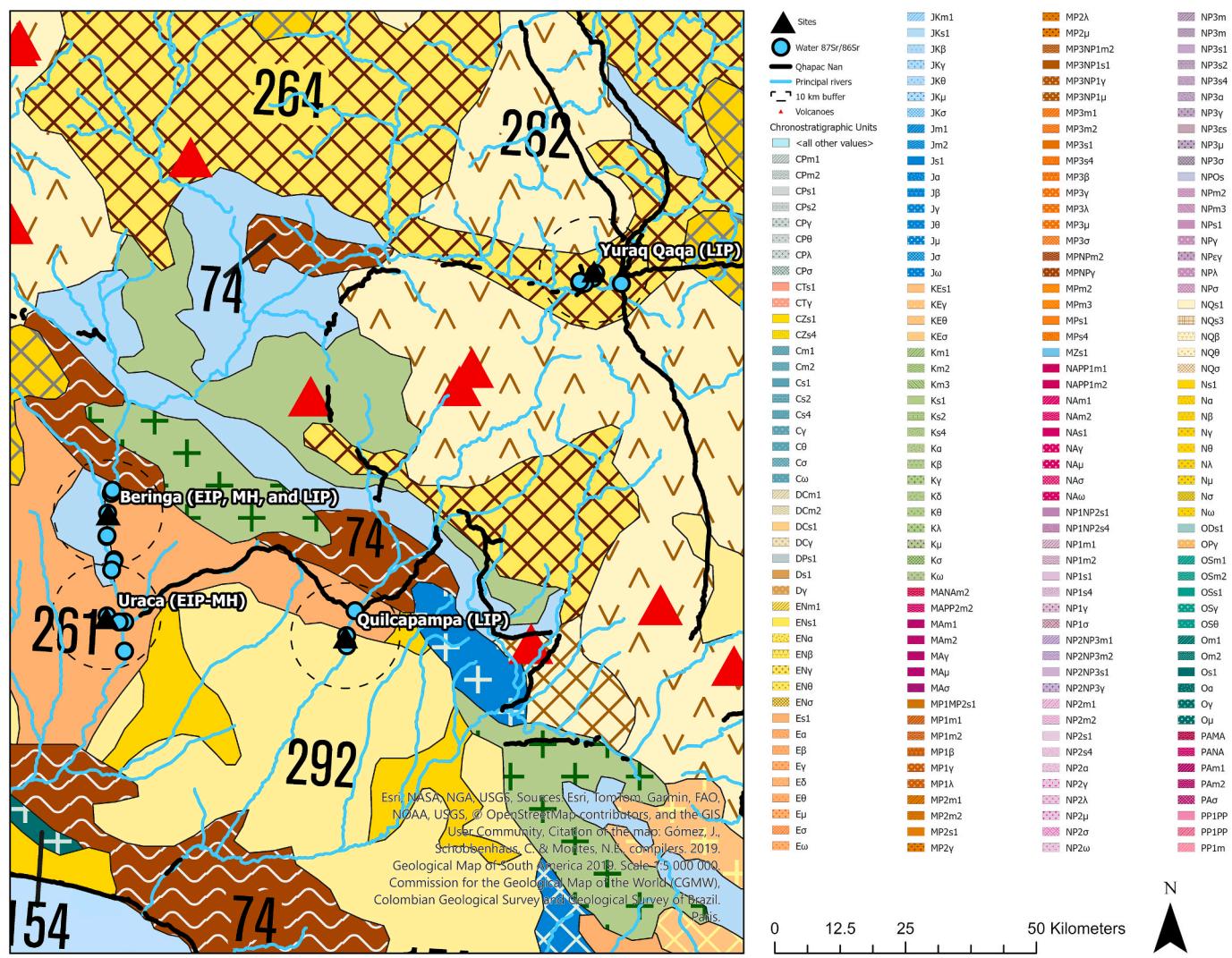
likely varies between populations depending on underlying geological heterogeneity. Because the first permanent molar enamel begins forming *in utero*, a change in $^{87}\text{Sr}/^{86}\text{Sr}$ from the first to second molar would not necessarily indicate intra-lifetime movement (Burton & Hahn, 2016) but might instead reflect a different place of maternal residence before and after birth or weaning. Nonetheless, since infants do not move themselves, and since there is negligible within-body or maternal-fetal $^{87}\text{Sr}/^{86}\text{Sr}$ fractionation (Bentley, 2006; Knudson et al., 2010), intra- or inter-tissue differences of >0.001 likely reflect residential change within the lifetime (Evans et al., 2012; Knipper et al., 2018; Knudson et al., 2016; Kootker et al., 2024; Slater et al., 2014). Others counter that when local environmental $^{87}\text{Sr}/^{86}\text{Sr}$ is well-sampled and intra-individual offsets are small for most individuals from a burial location, differences in the fourth or fifth decimal place can be meaningful and suggest intra-lifetime movement (Hrnčíř and Laffoon, 2019; Knipper et al., 2018). Examining movements within life is just as important as identifying first-generation migrants buried at a site, since patterns in the age when movement occurred could reflect motivations for mobility.

1.4. Baseline and comparative $^{87}\text{Sr}/^{86}\text{Sr}$ in Arequipa

Bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ is primarily determined by lithology and age of bedrock underlying food sources (Bentley, 2006; Knudson et al., 2014). According to recent chronostratigraphic unit models (Alcárce and Gutiérrez et al., 2023; Gómez Tapias et al., 2019), Quilcapampa lies at

the border of a ridge of sedimentary siliciclastic rock from the Paleogene (Fig. 4) and Quaternary Periods; the former continues westward underneath Uraca and Toro Muerto and the latter comprises the expansive desert pampa of the Sihuas and Vitor valleys. Neighboring sites La Real and Beringa are on an older Jurassic outcrop of the same rock type. Following paths to the north passes through roughly east–west strips of metamorphic rock from the Proterozoic Eon, Plutonic granitic rock from the Cretaceous Period, and sedimentary siliciclastic rock from the Paleogene (Cabanaconde) and volcanic sedimentary rock from the same period lying underneath Coporaque, Tuti, and most Colca Valley sites. Younger volcanic soil food webs of the Western Cordillera tend to show lower $^{87}\text{Sr}/^{86}\text{Sr}$ ($\sim 0.705\text{--}0.709$) relative to older granitic soils of the Eastern Cordillera (>0.709) (summary in Knudson et al., 2014). We expect highland sites on volcanic soils to show slightly higher $^{87}\text{Sr}/^{86}\text{Sr}$ than Quilcapampa's younger sedimentary soils due to this broad trend.

To clarify the local bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ range, it has become standard practice to test site baseline materials (e.g., water, soils, plants, small home range fauna). However, despite years of robust baseline sampling and isoscape modeling in the Andes (Barberena et al., 2017, 2019, 2021; Bataille et al., 2020; Knudson et al., 2014; Scaffidi et al., 2020; Scaffidi and Knudson, 2020; Serna et al., 2020), a standardized means of accomplishing this in the geologically-complex and volcanic Andes has not yet been achieved. Local diet and landscape practices



further complicate defining ‘local’ by site-specific geological substrates. For example, landscape $^{87}\text{Sr}/^{86}\text{Sr}$ will not register $^{87}\text{Sr}/^{86}\text{Sr}$ of high calcium/strontium imported foods like marine foods, seabird guano fertilizers, or salt, which may have played significant roles in diets. Furthermore, since Andean people likely consumed food at a variety of sites, best approaches would consider $^{87}\text{Sr}/^{86}\text{Sr}$ of multiple quasi-local isotopic catchments rather than the burial site alone (Velasco et al., 2024). For these reasons, assessments of local and non-locals based on $^{87}\text{Sr}/^{86}\text{Sr}$ ideally should account for archaeological human, faunal, and baseline $^{87}\text{Sr}/^{86}\text{Sr}$ (Bentley, 2006; Slovac & Paytan, 2011).

Velasco et al. (2024) report the only contemporaneous LIP archaeological $^{87}\text{Sr}/^{86}\text{Sr}$ for 36 highland Colca Valley samples, confirming local origins and limited intra-lifetime movement, but highlighting discrepancies between human and environmentally-defined definitions of local in that region. Small home-range archaeological fauna and modern plants were unavailable for testing, so baseline samples for Quilcapampa are unfortunately limited to three previously published seasonal stream samples (Scaffidi et al., 2020) plotted in Fig. 4. Cumulatively, these datasets enable us to test whether mobility was a response to LIP changes for *yunga* Quilcapampa burials and explore whether they moved vertically between altitudinal zones—perhaps impacted by LIP stresses, vertical mobility traditions, or unique local circumstances.

2. Materials and methods

2.1. Sampling and $^{87}\text{Sr}/^{86}\text{Sr}$ analysis of tooth enamel and bone

We sampled 20 of 26 individuals excavated for isotopic analysis: 12 individuals from Sector F and eight from Sector C (biological profiles and grave goods are presented in Table 1). Seven individuals were AMS-dated to the 11th and 12th centuries (Jennings et al., 2021). We extracted and exported whole teeth and bone fragments for isotopic analysis. Whenever possible, we selected enamel formed in each developmental phase—infancy-early childhood (IEC), middle childhood (MC), and teen (T)—and bone (phalanges, ribs, vertebra, and vomer) which averages strontium intake over late life (LL) (Table 2).

We prepared samples for analysis in the Archaeological Chemistry Laboratory (ACL), Center for Bioarchaeological Research (CBR), Arizona State University (ASU), according to established methods (Knudson et al., 2016; Marsteller et al., 2017). We cleaned samples with Millipore water ($18.2\text{ M}\Omega$), ablated surfaces with a multispeed rotary tool, and collected 3–6 mg of bulk enamel powder or crushed bone. To minimize diagenetic contamination, we ablated $>2\text{ mm}$ of bone surface (Rasmussen et al., 2020). We then chemically cleaned samples through sonication with alternating rinses of Millipore water and soaks of 0.8 M acetic acid (CH_3COOH), dried rinsed powder at 50°C , and ashed bone at 800°C for 10 h.

At the ASU Metals, Environmental, and Terrestrial Analytical Laboratory (METAL), we dissolved 3 mg of sample into 0.5 mL of trace-metal grade concentrated nitric acid (HNO_3) and Millipore water to create stock solutions, and analyzed diluted aliquots for elemental concentrations on the Thermo-Finnigan Q-ICP-MS. We then collected biogenic strontium with the automated PrepFAST system for blanks, internal standards, and NIST-1400, and compared pre- and post-separation aliquots to assess instrumental accuracy and precision (Romaniello et al., 2015). Finally, we evaporated and redissolved strontium cuts for $^{87}\text{Sr}/^{86}\text{Sr}$ analysis on the Neptune MC-ICP-MS alongside the strontium carbonate standard (SRM-987, $^{87}\text{Sr}/^{86}\text{Sr} = 0.710089 \pm 0.00009$, $n = 12$). We report $^{87}\text{Sr}/^{86}\text{Sr}$ to five decimal places, since higher precision is anthropologically insignificant (Bentley, 2006; Knudson et al., 2016) and report replicate averages for quality control and instrumental precision (Table 1).

2.2. Diagenesis determinations in archaeological bone

We evaluated elemental concentration data for diagenetic

contamination of tooth enamel according to established maximum threshold concentrations (MTC) (Kamenov et al., 2018). Samples with multiple elements beyond the MTC are considered strongly contaminated. While porous bone is more susceptible to diagenesis, Grimstead et al. (2018, p. 697) argue bone is likely to be uncontaminated below maximum threshold values (MTV) for V (2.41 ppm) and U (0.017 ppm). Acceptable Ca/P is defined based on the range in living bone (mean = 2.17 ± 0.31 , 1σ , $n = 78$) (Zaichick and Tzaphlidou, 2002). That said, bone and enamel diagenesis measures are dependent on local geologies and diets, so comparative archaeological materials should inform acceptable thresholds (Hedges, 2002; Maurer et al., 2012; Rasmussen et al., 2020; Simpson et al., 2021).

2.3. Local $^{87}\text{Sr}/^{86}\text{Sr}$ determination and statistical analysis

To date, the most comprehensive $^{87}\text{Sr}/^{86}\text{Sr}$ models for the Central Andes come from a meta-analysis of published archaeological $^{87}\text{Sr}/^{86}\text{Sr}$ data (Scaffidi & Knudson, 2020) and surface water $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape (Scaffidi et al., 2020). The water $^{87}\text{Sr}/^{86}\text{Sr}$ model performs reasonably well at predicting human skeletal $^{87}\text{Sr}/^{86}\text{Sr}$ for non-highland sites; however, water tends to show lower $^{87}\text{Sr}/^{86}\text{Sr}$ values than plants and skeletal materials from the same site (Scaffidi et al., 2020). We combined both measures to preserve this variability, defining the *local cumulative range* as the archaeological site mean $\pm 2\sigma$, extended by minimum and maximum water $^{87}\text{Sr}/^{86}\text{Sr}$ of any published samples within 10 km of site centroids (water sample $n = 25$, Table 4, Fig. 4).

We assessed normality (Shapiro-Wilk) before comparing $^{87}\text{Sr}/^{86}\text{Sr}$ between subgroups using the independent two-sample *t*-test for normally distributed data and Mann-Whitney U for non-normally distributed data. We compared proportions of non-local to local samples between Quilcapampa and neighboring sites as well as estimated biological sex, site, sector, and tissue (i.e., bone vs. enamel) subgroups with Chi-squared tests of association (males/probable males and females/probable females were collapsed for statistical analysis). We calculated individual intra-lifetime $^{87}\text{Sr}/^{86}\text{Sr}$ range as the difference of maximum and minimum $^{87}\text{Sr}/^{86}\text{Sr}$ of all sampled tissues.

3. Results

3.1. Assessment of diagenetic alteration

Elemental concentrations show mean Ca/P = 2.21 ± 0.09 (2σ , $n = 47$), with all but one sample within the accepted human Ca/P range (Zaichick and Tzaphlidou, 2002) (Table 2, Table S1). Mean U/Ca = $2.973 \times 10^{-8} \pm 2.973 \times 10^{-7}$ (1σ , $n = 78$) is similar to published uncontaminated enamel and bone from similar geologies (Knudson et al., 2012, p. 315; Scaffidi et al., 2022). According to the diagenesis metrics cited herein, six samples could potentially show diagenetic contamination leading to a false “local” designation: three enamel samples from Tomb 17 (ACL-10541, ACL-11365) and Tomb 27 (ACL-10548) each show three elemental concentrations higher than Kamenov et al.’s (2018) MTC’s; bone samples from Tomb 25 (ACL-11343) and Tomb 8 (ACL-11344) failed Grimstead et al.’s MTV threshold for Vanadium; and bone from Tomb 13 (ACL-11340) showed Ca/P that was only 0.1 higher than Zaichick and Tzaphlidou’s (2002) threshold (Table 2, Table S1). However, the sets of high MTC elements were not uniform for the three flagged enamel samples. $^{87}\text{Sr}/^{86}\text{Sr}$ for these enamel samples was nearly identical to unflagged enamel and bone, consistent with the local range from the same respective individuals. Furthermore, enamel and bone samples were exceptionally well-preserved with no to minimal soil contact *in situ*—as described above, the only soils in the tomb shafts were located at the base of the interment and did not envelop the sides and top of the burials. These factors combined make it more likely that the very limited deviance from the cited diagenesis metrics are related to biogenic rather than diagenetic chemical signals. We also emphasize that the diagenesis metrics relied on here are based on samples from

Table 2

$^{87}\text{Sr}/^{86}\text{Sr}$ across multiple tissues of 20 individuals from LIP Quilcapampa. Probable non-local samples are bolded and the mean $\pm 2\sigma$ of interlaboratory replicates is reported where relevant. Bdl indicates concentrations below the detection limit, and *indicates possibly contaminated samples according to enamel MTC (Kamenov et al., 2018) or bone MTV (Grimstead et al., 2018). Developmental periods reflected by isotopic signatures are abbreviated as follows: IEC = infancy/ early childhood, MC = middle childhood, T = teen years, and LL = late life.

Tomb	Cemetery	ACL#	Export#	Age	Age Range	Sex	Element	Period	$^{87}\text{Sr}/^{86}\text{Sr}$	Ca/P	U/Ca	Site Mean $\pm 2\sigma$	Cumulative Local Range (water)
2	North	10,532	501	MA	35–50+	M	ULM3	T	0.70793	2.13	4.17154E-09	local	local
2	North	10,533	502	MA	35–50+	M	LLM1	IEC	0.70795	2.13	3.04363E-09	local	local
2	North	11,363	503	MA	35–50+	M	LLM2	MC	0.70795	2.18	1.96266E-09	local	local
3	North	11,337	516	C	3–4	U	Vertebra	LL	0.70774 ± 0.00001 (n = 2)^t	2.22	1.56462E-08	non-local	local
4	North	10,539	455	C	4–6	U	ULM1	IEC	0.70798	2.13	9.0507E-09	local	local
8	North	11344*	475	A	30+	F	Proximal hand phalanx	LL	0.70793	2.27	5.30852E-07	local	local
9	North	10,534	519	MA	35–45	M	URM3	T	0.70800	2.15	7.29438E-09	local	local
9	North	11,352	518	MA	35–45	M	LLP1	MC	0.70800	2.17	3.05342E-09	local	local
9	North	11,354	517	MA	35–45	M	LLI2	IEC	0.70813	2.17	4.75114E-09	non-local	non-local
11	North	10,535	505	MA	35–45	F	URM3	T	0.70791	2.14	3.82786E-09	local	local
11	North	10,536	506	MA	35–45	F	ULM1	IEC	0.70801	2.20	7.68558E-10	local	local
11	North	11,359	507	MA	35–45	F	ULM2	MC	0.70793	2.19	9.22142E-10	local	local
12	North	10,537	466	YA	25–35	M	URM1	IEC	0.70798	2.19	bdl	local	local
12	North	10,538	468	YA	25–35	M	ULM3	T	0.70792 ± 0.00002 (n = 3)^t	2.18	bdl	local	local
12	North	11,347	469	YA	25–35	M	Vomer	LL	0.70810	2.14	6.43477E-09	local	local
12	North	11,362	467	YA	25–35	M	URM2	MC	0.70800	2.17	2.74077E-09	local	local
13	North	10,540	521	T	15–17	M?	LLM3	T	0.70822	2.15	1.25198E-09	non-local	non-local
13	North	11340*	522	T	15–17	M?	Rib	LL	0.70791	2.49	7.73908E-08	local	local
14	North	11,341	504	MA	35–50	M	Rib	LL	0.70802	2.43	4.34971E-08	local	local
15	North	11,346	534	A	30+	U	Rib	LL	0.70795	2.35	1.1056E-08	local	local
17	North	10541*	509	T	15–18	U	LRM1	IEC	0.70807	2.19	8.96735E-09	local	local
17	North	10,542	511	T	15–18	U	LRM3	T	0.70810	2.13	5.80676E-09	local	local
17	North	11,342	512	T	15–18	U	Proximal hand phalanx	LL	0.70786	2.28	2.7372E-08	local	local
17	North	11365*	510	T	15–18	U	LRM2	MC	0.70805	2.20	1.63913E-08	local	local
18	North	11,339	527	T-YA	19–23	F	Rib	LL	0.70792 ± 0.00003 (n = 2)^t	2.38	4.12972E-08	local	local
19	South	10,543	486	MA	35–45	M	LRM3	T	0.70799	2.10	1.53518E-11	local	local
19	South	11,348	487	MA	35–45	M	Proximal hand phalanx	LL	0.70797	2.29	1.74578E-08	local	local
19	South	11,351	485	MA	35–45	M	11,048	MC	0.70793	2.15	2.98477E-09	local	local
20	South	10,544	478	MA	35–50	F	LLM3	T	0.70795	2.13	9.00207E-11	local	local
20	South	11,353	477	MA	35–50	F	LLM2	MC	0.70794	2.16	2.48135E-09	local	local
20	South	11,355	476	MA	35–50	F	LRI2	IEC	0.70789	2.16	1.29566E-08	local	local
21	South	11,357	480	C	9–12	U	LRI2	IEC	0.70794	2.18	2.66925E-09	local	local
21	South	11,358	481	C	9–12	U	LLP1	MC	0.70794	2.19	1.08403E-08	local	local

(continued on next page)

Table 2 (continued)

Tomb	Cemetery	ACL#	Export#	Age	Age Range	Sex	Element	Period	$^{87}\text{Sr}/^{86}\text{Sr}$	Ca/P	U/Ca	Site Mean $\pm 2\sigma$	Cumulative Local Range (water)
24	South	10,545	531	T	15–19	U	URM3	T	0.70787	2.16	1.6791E-08	local	local
24	South	11,345	533	T	15–19	U	Proximal foot phalanx	LL	0.70787	2.48	6.408E-08	local	local
24	South	11,350	529	T	15–19	U	URI1	IEC	0.70791	2.18	5.42987E-08	local	local
24	South	11,361	530	T	15–19	U	URM2	MC	0.70789	2.19	1.57553E-08	local	local
25	South	10,546	457	T-YA	20–26	M?	URM1	IEC	0.70788	2.13	4.83292E-09	local	local
25	South	10,547	459	T-YA	20–26	M?	LRM3	T	0.70799	2.21	4.12873E-10	local	local
25	South	11343*	461	T-YA	20–26	M?	Proximal foot phalanx	LL	0.70782	2.36	2.27419E-07	local	local
25	South	11,356	458	T-YA	20–26	M?	LRM2	MC	0.70791	2.17	1.06816E-09	local	local
26	South	11,360	536	MA	45+	F	URC	MC	0.70798	2.18	3.08385E-09	local	local
27	South	10548*	462	YA	30–44	F	URM1	IEC	0.70795	2.23	1.33715E-08	local	local
27	South	10,549	465	YA	30–44	F	LRM3	T	0.70796	2.23	2.37881E-09	local	local
27	South	11,364	463	YA	30–44	F	URM2	MC	0.70794	2.20	1.18243E-08	local	local
28	South	10,550	499	C	2–4	U	LRM1	IEC	0.70796	2.17	bdl	local	local
28	South	11,338	494	C	2–4	U	Rib	LL	0.70779 ± 0.00001 (n = 2) [†]	2.22	1.58483E-08	local	local

[†] Indicates interlaboratory replicates were analyzed and the mean $\pm 2\sigma$ is reported here along with the number of replicates.

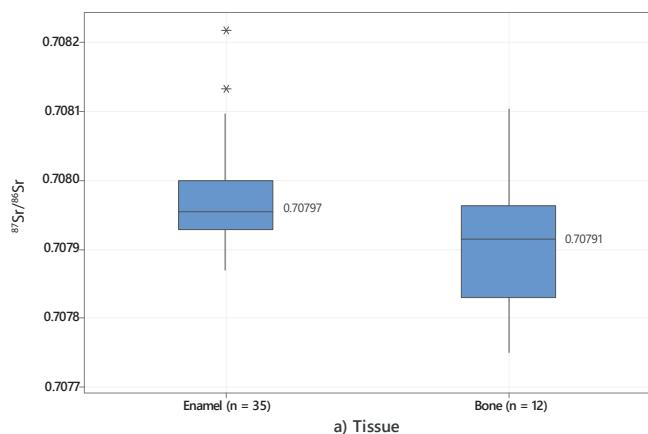
completely different geologies than this study's coastal to mid-valley Peruvian bedrock systems and that even among these studies there are no hard limits on the number of elemental concentrations over the threshold that would qualify a sample as diagenetically contaminated. Finally, we emphasize that there have not yet been intra-laboratory validation studies that justify the application of the MTC, MTV, and Ca/P metrics used here to assess enamel and bone samples across all geologies. Therefore, while we report elemental concentrations and apply these metrics in an abundance of caution, we do not find uniform or high enough deviance from diagenesis metrics to exclude any $^{87}\text{Sr}/^{86}\text{Sr}$ reported herein from statistical analysis.

3.2. Low proportion of non-local $^{87}\text{Sr}/^{86}\text{Sr}$

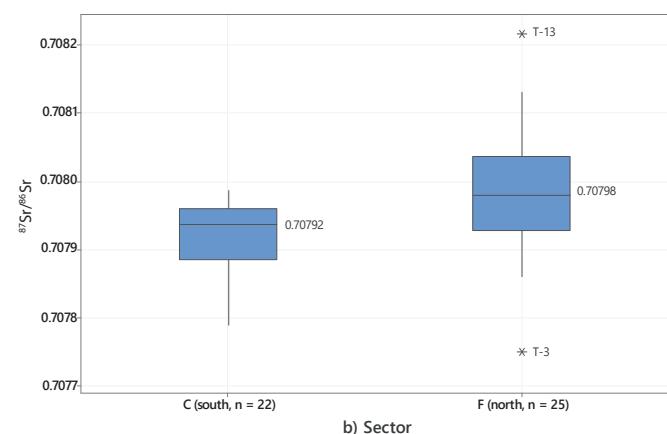
$^{87}\text{Sr}/^{86}\text{Sr}$ ($n = 47$) (Table 2) ranges from 0.70774 to 0.70822 (mean = 0.70795, $1\sigma = 0.00008$, normally distributed, $W = 0.958$, $p = 0.860$). Males (mean = 0.70798, $n = 20$) and females (mean = 0.70794, $n = 12$)

are similar ($t(25) = -1.700$, $p = 0.101$). Enamel samples (mean = 0.70797, $n = 35$) are nearly significantly higher $^{87}\text{Sr}/^{86}\text{Sr}$ than bone (mean = 0.70791, $n = 12$), $t(15) = -2.050$, $p = 0.058$ (Fig. 5a). Sector F samples are significantly higher $^{87}\text{Sr}/^{86}\text{Sr}$ (mean = 0.70798, $n = 25$), than Sector C (mean = 0.70792, $n = 22$), $t(45) = 2.674$, $p = 0.010$ (Fig. 5b).

Tissues from three Sector F individuals fall outside the site mean $\pm 2\sigma$ ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70778–0.70810$), cumulative local range ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70759–0.70812$), and inter-quartile range (Table 2, Fig. 6). Tomb 3 (a child) bone is higher than the site mean $\pm 2\sigma$ but within the local cumulative range, so they were probably local at death around 3 to 4 years old. Only Tomb 9 (adult male with cranial trauma), and Tomb 13 (teen-young adult male), or 10.0 % (2/20) were non-local at some point in their lifetimes. Only Tomb 9 shows non-local $^{87}\text{Sr}/^{86}\text{Sr}$ in infancy-early childhood consistent with first-generation immigration.



a) Tissue



b) Sector

Fig. 5. $^{87}\text{Sr}/^{86}\text{Sr}$ by tissue development phase for the 20 sampled individuals (IEC = infancy to early childhood, MC = middle childhood, T = teen, and LL = late life). Reference lines indicate the cumulative local $^{87}\text{Sr}/^{86}\text{Sr}$ range.

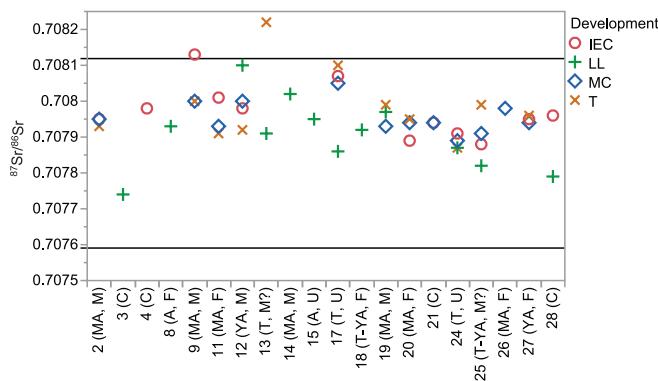


Fig. 6.

Table 3

Absolute intra-lifetime ranges for individuals ($n = 13$) with $^{87}\text{Sr}/^{86}\text{Sr}$ from tissues that formed in two or more phases: Infancy-early childhood (IEC), middle childhood (MC), teen (T), and late-life (LL). Bolded data indicates values beyond the cumulative local range defined in Table 4.

Tomb	Age	Age Range	Sex	$^{87}\text{Sr}/^{86}\text{Sr}_{\text{IEC}}$	$^{87}\text{Sr}/^{86}\text{Sr}_{\text{MC}}$	$^{87}\text{Sr}/^{86}\text{Sr}_{\text{T}}$	$^{87}\text{Sr}/^{86}\text{Sr}_{\text{LL}}$	Intra-lifetime $^{87}\text{Sr}/^{86}\text{Sr}$ Range
2	MA	35–50+	M	0.70795	0.70795	0.70793	NA	0.00002
9	MA	35–45	M	0.70813	0.70800	0.70800	NA	0.00013
11	MA	35–45	F	0.70801	0.70793	0.70791	NA	0.00010
12	YA	25–35	M	0.70798	0.70800	0.70792	0.70810	0.00018
13	T	15–17	M?	NA	NA	0.70822	0.70791	0.00031
17	T	15–18	?	0.70807	0.70805	0.70810	0.70786	0.00024
18	T-YA	19–23	F	0.70793	0.70799	0.70797	NA	0.00006
19	MA	35–45	M	0.70789	0.70794	0.70795	NA	0.00006
20	MA	35–50	F	0.70794	0.70794	NA	NA	0.00000
21	C	9–12	?	0.70791	0.70789	0.70787	0.70787	0.00004
24	T	15–19	?	0.70788	0.70791	0.70799	0.70782	0.00017
26	MA	45+	F	0.70795	0.70794	0.70796	NA	0.00002
28	C	2–4	?	0.70796	NA	NA	0.70779	0.00017

3.3. Limited intra-lifetime mobility

Individual intra-lifetime $^{87}\text{Sr}/^{86}\text{Sr}$ differences (Table 3) range from 0.0000 to 0.00031 ($n = 13$ individuals, mean = 0.00012, normally distributed, $W = 0.899$, $p = 0.130$). Quilcapampa males show greater intra-lifetime ranges (mean = 0.00014, $n = 6$) than females (mean = 0.00006, $n = 3$), but not significantly so ($t(6) = -1.80$, $p = 0.122$). Intra-lifetime $^{87}\text{Sr}/^{86}\text{Sr}$ ranges are significantly higher for Sector F (mean = 0.00016, $n = 6$) than Sector C (mean = 0.00005, $n = 7$), $t(7) = 2.37$, $p = 0.049$.

$^{87}\text{Sr}/^{86}\text{Sr}$ from multiple tissue development phases per individual (Fig. 6), shows possible movement for the Tomb 9 middle adult male with cranial trauma, who has a non-local IEC tooth but local MC and Teen teeth (bone was unavailable). The Tomb 13 teen-young adult male shows local bone, but a non-local third molar. This could demonstrate mobility in years before death, but the local-looking bone could also be due to diagenetic contamination since this bone failed the V threshold and given it should show similar $^{87}\text{Sr}/^{86}\text{Sr}$ to the teen-forming enamel (IEC and MC teeth were unavailable).

4. Discussion

4.1. Comparisons to neighboring and contemporaneous sites

To contextualize the proportion of non-locals at Quilcapampa, we compare results to nearby *yunga* sites Beringa (Knudson & Tung, 2011) and Uraca³ (Scaffidi et al., 2022) in the Majes Valley, 50 km across the

pampa from Quilcapampa dating to the Early Intermediate Period (“EIP,” ca. 200 BCE – 600 CE) and Middle Horizon (600 – 1000 CE) (Scaffidi, 2018; Scaffidi & Tung, 2020; Tung, 2007, 2012; Tung & Knudson, 2018), and to the LIP highland Colca Valley of Yuraq Qaqa (Velasco, 2014), 60–80 km north (Fig. 1, Fig. 4, Table 4). Human $^{87}\text{Sr}/^{86}\text{Sr}$ ranges for Quilcapampa, Uraca, and Beringa overlap, while Colca⁴ only overlaps for two individuals using the cumulative (water-extended) range (Table 4). Despite overlapping ranges, $^{87}\text{Sr}/^{86}\text{Sr}$ medians are distinct between Quilcapampa vs. Beringa (Mann-Whitney U, $U = 13.0$, $z = 8.517$, $p < 0.001$), Uraca (Mann-Whitney U, $U = 50.0$, $z = -7.127$, $p < 0.001$), and Quilcapampa vs. Yuraq Qaqa (Mann-Whitney U, $U = 3.0$, $z = 7.7414$, $p < 0.001$).

Based on cumulative local ranges assigned here, proportions of probable non-locals at Quilcapampa (4.5 %) are like Beringa (4.0 %), lower than Uraca (25.0 %), and higher than contemporaneous Yuraq Qaqa (0.0 %). Intra-lifetime ranges are non-normally distributed, $W(27)$

= 0.450, $p < 0.001$, and significantly broader at Quilcapampa than Uraca (Table 4), $U = 8.0$, $z = 2.931$, $p = 0.004$, but like Beringa, $U = 44.5$, $z = -0.396$, $p = 0.968$. Nonetheless, all four Arequipa sites show narrow intra-lifetime ranges and only one individual—a female from Beringa—has an intra-lifetime range > 0.001 suggestive of long-distance immigration.

4.2. Relative insularity of LIP Quilcapampa

LIP Quilcapampa $^{87}\text{Sr}/^{86}\text{Sr}$ shows a low proportion of possible non-locals, likely from nearby *yunga* communities in the Sihuas or neighboring valleys. Only one IEC tooth is likely non-local (Tomb 9 male with cranial trauma), and only one other person (Tomb 13 teen male) might have traveled beyond immediate Quilcapampa in their late life. These two males with non-local $^{87}\text{Sr}/^{86}\text{Sr}$ likely hailed from or visited nearby communities in neighboring *yunga* valleys as they are consistent with archaeological human $^{87}\text{Sr}/^{86}\text{Sr}$ from Majes Valley sites, located one-two days’ walk away. The absolute range does not overlap with highland Colca sites and only for one individual overlaps with the cumulative (water extended) range. However, there are water samples with $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.70810 to 0.70900 from the *yunga* Vitor Valley to the east, the highland Chuquibamba Valley just west of the Majes Valley, and some parts of the highland Colca Valley, which displays highly heterogeneous water $^{87}\text{Sr}/^{86}\text{Sr}$ (Scaffidi et al., 2020) and bedrock geology (Alcázar-Gutiérrez et al., 2023; Gómez Tapias et al., 2019; Schenk et al., 1999). While it seems most likely that the non-local LIP Quilcapampa burials leveraged desert pampa trails to visit Majes sites with

³ Uraca data in this comparison excludes adult male trophy heads who were probable non-locals (Scaffidi et al., 2022).

⁴ Uraca data in this comparison excludes adult male trophy heads who were probable non-locals (Scaffidi et al., 2022).

Table 4
Comparisons of the proportions of probable non-locals at Quilcapampa and neighboring *yunga* Arequipa sites based on the cumulative local ranges of archaeological human $^{87}\text{Sr}/^{86}\text{Sr}$ and local surface water $^{87}\text{Sr}/^{86}\text{Sr}$ (from Scaffidi and Knudson, 2020). The number of non-locals calculated here includes individuals with non-local $^{87}\text{Sr}/^{86}\text{Sr}$ at any phase of their life, so it produces a greater proportion of probable non-locals than a calculation of first-generation immigrants from IEC teeth alone.

Site	Abs Range Human $^{87}\text{Sr}/^{86}\text{Sr}$ (n)	Mean $^{87}\text{Sr}/^{86}\text{Sr}$	Median $^{87}\text{Sr}/^{86}\text{Sr}$	2 σ $^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$ (n)	Mean Human $^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$ (n)	Median Intra-lifetime range (n)	Range Water $^{87}\text{Sr}/^{86}\text{Sr}$ (n)	Cumulative $^{87}\text{Sr}/^{86}\text{Sr}$ Range	# Non-locals	% Non-locals	Reference
Beringa	0.70802–0.70960 (n = 52)	0.70842	0.70838	0.0005	0.70788–0.70896 (n = 7)	0.00005 (n = 7)	0.70781–0.70893 (n = 7)	0.70787–0.70896	2	3.9	Knudson and Tung, 2011
Colca	0.70680–0.70780 (n = 36)	0.70737	0.70739	0.0006	0.70677–0.70800 (n = 27)	0.00005 (n = 27)	0.70600–0.70834 (n = 10)	0.70600–0.70834	0	0.0	Velasco et al., 2024
Quilcapampa	0.70774–0.70822 (n = 47)	0.70795	0.70795	0.0002	0.70778–0.70810 (n = 13)	0.00010 (n = 13)	0.70759–0.70771 (n = 3)	0.70759–0.70812	2	4.5	This article
Uraca*	0.70719–0.70862 (n = 33)	0.70828	0.70828	0.0004	0.70786–0.70870 (n = 8)	0.00002 (n = 8)	0.70778–0.70871 (n = 5)	0.70719–0.70871	8	24.0	Scaffidi et al., 2022

* This sample only includes individuals not transformed into trophy heads, given the likelihood they are not local.

similar geology rather than Yuraq Qaka in the Colca, we cannot rule out the possibility that they originated in other nearby highland communities (e.g., Huambo, Huanca, and Lluta, Fig. 1) where skeletal and environmental data have not yet been excavated or analyzed. We also cannot rule out the possibility that any or all the tested individuals routinely sampled multiple geological locations around Quilcapampa given the site is situated at the intersection of two distinct bedrock geologies (Fig. 4).

Quilcapampa's low mobility is consistent with the LIP in much of the Andes—all but two of 24 LIP sites aggregated in recent compilations (Pezo-Lanfranco et al., 2024; Scaffidi and Knudson, 2020) (Table S2) show site-wide SD < 0.001, and all but two have proportions of non-locals under 10.0 % (Andrushko et al., 2009; Aufderheide and Santor, 1999; Barberena et al., 2017; Bethard et al., 2008; Conlee et al., 2009; Gil et al., 2014; Hewitt, 2013; Knudson et al., 2016, 2015; Knudson and Price, 2007; Knudson and Tung, 2011; Lofaro et al., 2019; Marsteller et al., 2017; Velasco et al., 2024; Washburn et al., 2022). In contrast, 12/20 Middle Horizon sites compiled in Scaffidi and Knudson (2020) show proportions of non-locals over 10.0 %. The comparative data from *yunga* Arequipa and the broader Andes highlights that mobility at Quilcapampa was low for this vertically intermediate zone but typical for the period.

Given only 2/47 samples or 2/20 individuals were probable non-locals at some period in their lifetimes, LIP Quilcapampa people seem to have been relatively insular. It is worth noting that $^{87}\text{Sr}/^{86}\text{Sr}$ data can only detect movement within individual lifetimes and thus can only speak to mobility within the generation(s) buried in a cemetery. It is possible that the LIP individuals we excavated, dating to the 11th and 12th centuries CE, lived their lives at and around the site, but they were the children of the first or second generation of highland immigrants from preceding centuries (Jennings et al., 2021). Quilcapampa's LIP inhabitants may have maintained familial ties and exchange networks with highlanders or people from their ancestral communities even if those people ultimately returned home and are therefore not reflected in the burial sample excavated. Nonetheless, $^{87}\text{Sr}/^{86}\text{Sr}$ values from Quilcapampa shows incredibly constrained mobility during the 11th and 12th centuries CE. This, together with the inaccessibility of the LIP domestic sector, suggests that the community may have been impacted by LIP violence like communities in highland Arequipa (Kohut, 2016) and the broader region (Arkush, 2008, 2018; Arkush & Ikebara, 2019; Arkush & Tung, 2013; Arkush, 2011; Tung, 2021).

Finally, given that only adult males without grave goods (one who suffered cranial trauma) from the northern sector display non-local $^{87}\text{Sr}/^{86}\text{Sr}$ values at some point in their lifetimes, some aspect of social or geographic identity may have structured mobility and burial location. That said, this study only has incomplete evidence for social construction and practiced gender norms—e.g., we do not know that individuals estimated as biological males performed masculine identities impacting their mobility histories. Nonetheless, isobiographical data show similar residential trajectories for these two individuals who share biological sex and age characteristics. Intra-lifetime mobility for these individuals may have occurred in response to social and climate stresses of the LIP or may have been structured by other local circumstances.

4.3. Comparing breadth of intra-lifetime mobility

In *yunga* Arequipa, isobiographical $^{87}\text{Sr}/^{86}\text{Sr}$ proves useful in addition to calculations of probable first-generation immigrants as another measure of geographic mobility—even when the two lines of data produce different results. For example, while we find that LIP Quilcapampa burials have a low proportion of first-generation immigrants relative, at least, to Uraca, a neighboring community dating to the preceding era (Table 4), Quilcapampa shows the broadest intra-lifetime $^{87}\text{Sr}/^{86}\text{Sr}$ range of the three Arequipa *yunga* sites. So, while LIP Quilcapampa did not experience much immigration (at least not as evinced by the sample excavated), inhabitants moved around the vicinity more within their

lifetimes than neighbors. Furthermore, since IEC teeth reflect some portion of maternal diet and residence, the calculation of isobiographical ranges necessarily includes the movement of the mother and sampled individual, which can be thought of as reflecting an early-life familial residential catchment.

More variable $^{87}\text{Sr}/^{86}\text{Sr}$ Quilcapampa could reflect actual movement during tissue development phases between neighbouring zones, or perhaps seasonal mobility to procure resources from different zones during wet and dry seasons. Perhaps this variability reflects consumption of a high proportion of foods imported from neighbouring regions compared to mostly local diets at Uraca and Beringa in the Majes Valley. Interestingly, there were no river prawns in the LIP tombs unlike at Majes valley tombs. The Sihuas River can dry to a trickle even in wet months. Perhaps LIP Quilcapampa inhabitants had to source proteins from neighbouring communities when the river was unreliable and traveled to do so. Short-distance travel to trade for or procure resources from other valleys or consuming a high proportion of non-local foods could certainly increase the variety of $^{87}\text{Sr}/^{86}\text{Sr}$ catchments individuals consumed or imbibed from. We note, however, that because only six individuals had bone available for testing, the actual range of intra-lifetime mobility represented by this small sample may be underestimated or overestimated.

These intra-lifetime mobility comparisons must be approached with caution, however, given that the absolute range of $^{87}\text{Sr}/^{86}\text{Sr}$ variation within the site is only 0.00048, lower than the threshold of 0.001 often used as a minimum threshold for intra-lifetime mobility (Knipper et al., 2014; Knudson et al., 2016; Kootker et al., 2016; Slater et al., 2014). Notwithstanding the fact that Quilcapampa isobiographical $^{87}\text{Sr}/^{86}\text{Sr}$ ranges are broad relative to the region, if we apply the 0.001 threshold, none of the sampled individuals would have moved in their lifetimes. More recent studies (Hrnčíř & Laffoon, 2019; Knipper et al., 2018) argue that intra-life differences as small as 0.0006 can reflect mobility between tissue development phases and recommend meaningful differences be calibrated to regional and site-specific levels. Doing so, six Quilcapampa individuals have ranges greater than the mean (0.00011). We tentatively suggest the threshold for intra-lifetime mobility in this case could be lower than 0.001, although additional testing of sequentially forming tissues and baselines throughout the region is needed.

Ultimately, this seemingly high intra-lifetime mobility at Quilcapampa relative to the region could reflect local adaptations to LIP resource scarcity or to social factors encouraging close-range mobility around the site. Ethnographic and ethnohistoric data show that Andean people are incredibly adept at interregional mobility (Allen, 2002; Harris and Larson, 1995; Hirsch, 2018; Platt, 2009; Skar, 1994; Skarbø and VanderMolen, 2016). This includes long-term migration and other movements that do not necessarily result in permanent relocation—voluntary and otherwise—examining isobiographical $^{87}\text{Sr}/^{86}\text{Sr}$ provides a useful additional measure of mobility that may shed light on the embodied practice of intra-lifetime movement that is otherwise obscured by focusing on first-generation migrants alone.

5. Conclusions

In sum, this study found a low proportion of possible non-locals at LIP Quilcapampa, consistent with the narrative of relative insularity between LIP communities in the face of internecine violence and resource stress during this time of extended drought, cold, and significant social restructuring. Importantly, the isobiographical $^{87}\text{Sr}/^{86}\text{Sr}$ data add important nuance to our understanding of LIP ‘insularity’—whatever the social and environmental conditions that structured limited immigration at Quilcapampa, they seem not to have prohibited all extra-community movements. Indeed, establishing more localized spheres of movement may have been an effective strategy for *yunga* communities to persist in challenging times. Examining isobiographical $^{87}\text{Sr}/^{86}\text{Sr}$ —especially when interrogated comparatively in regions where mobility routes, cultural sequences, and isotopic catchments are

understood—provides a useful additional measure of mobility that may shed light on intra-lifetime movement otherwise obscured by focusing on first-generation migrants alone.

In addition to our emphasis of $^{87}\text{Sr}/^{86}\text{Sr}$ isobiographies as an additional metric of mobility, this study is significant in applying a different approach to defining local $^{87}\text{Sr}/^{86}\text{Sr}$ ranges. By extending the archaeological human mean $^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$ by the upper and lower ranges of water $^{87}\text{Sr}/^{86}\text{Sr}$ from the APU Project (Scaffidi et al., 2020), we aimed to preserve the primacy of human $^{87}\text{Sr}/^{86}\text{Sr}$ as perhaps the best measure of multi-source $^{87}\text{Sr}/^{86}\text{Sr}$ mixing, while accounting for the environmental baseline that provides theoretical limits of landscape $^{87}\text{Sr}/^{86}\text{Sr}$. That said, Scaffidi et al. (2020) point out that using water $^{87}\text{Sr}/^{86}\text{Sr}$ to predict human archaeological $^{87}\text{Sr}/^{86}\text{Sr}$ is limited in the geologically heterogeneous highlands, and testing bioavailable strontium in other parts of the food web would improve local $^{87}\text{Sr}/^{86}\text{Sr}$ designations. Importantly, because we do not yet have $^{87}\text{Sr}/^{86}\text{Sr}$ data from the nearby highlands, we cannot exclude the possibility that LIP Quilcapampa inhabitants hailed from geologically-similar nearby highlands that are proposed as the ancestral home of Quilcapampa’s burials (Jennings et al., 2021). Furthermore, plant $^{87}\text{Sr}/^{86}\text{Sr}$ better reflects the $^{87}\text{Sr}/^{86}\text{Sr}$ mixed into human dietary sources, so additional baseline sampling is essential for understanding the complex geology and soil matrices in these heavily farmed *yunga* valleys. Since predecessor roads to the *Qhapaq Ñan* likely connected Quilcapampa to highland sites, sampling along these routes together with archaeological site survey would be a productive path for further clarifying landscape dynamics.

Finally, integrating additional human and environmental reference samples from the subregion and the Andes, contextualized by ongoing archaeological research into interregional connections and mobility routes, will continue to clarify how immigration and intra-lifetime mobility changed through time and across space. As we demonstrate, even with its limitations, radiogenic isotope analysis continues to be an excellent proxy for identifying people who moved in their lifetimes, reconstructing where they likely traveled, and understanding the push and pull factors that motivated different scales and spheres of movements.

Author contributions

JJ directed excavation and funded analysis.

BKS excavated and analysed skeletons, collected and analysed samples, and funded analysis.

TAT analysed skeletons, collected, and exported samples.

GG provided laboratory support and oversaw elemental concentration and $^{87}\text{Sr}/^{86}\text{Sr}$ analysis.

KK provided laboratory logistics, funding, and supervision of isotopic preparation and analysis.

BKS, JJ, TAT, GG, and KK wrote and revised the manuscript.

CRediT authorship contribution statement

Beth K. Scaffidi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Justin Jennings:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tiffany A. Tung:** Writing – review & editing, Resources, Project administration, Formal analysis, Data curation. **Gwyneth Gordon:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation. **Kelly J. Knudson:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2025.105355>.

Data availability

I have shared all data in the text and supplementary attachments.

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