Journal of Archaeological Science 174 (2025) 106142

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: www.elsevier.com/locate/jas

Strontium isotopes and the geographic origins of camelids in the Virú Valley, Peru

Nicole Hultquist[a,c,*], Jean-Francois Millaire[b], Paul Szpak[a]

[a] Department of Anthropology, Trent University, Peterborough, Ontario, K9L 0G2, Canada
[b] Department of Anthropology, The University of Western Ontario, London, Ontario, N6A 5C2, Canada
[c] Department of Anthropology, Boston University, Boston, MA 02215, United States

ARTICLE INFO

Keywords:
Stable isotope analysis
Strontium isotopes
North coast Peru
Early intermediate period
Late middle horizon
Trade
Mobility
Camelids
Andean archaeology

ABSTRACT

This study presents the strontium isotopic composition of camelid tooth enamel from Huaca Santa Clara, Huaca Gallinazo, and Huancaco in the Virú Valley, northern Peru. These sites were occupied during the Early Intermediate Period (EIP, c. 200 BCE-600 CE) with Huaca Santa Clara and Huancaco being associated with ritual sacrifices of camelids during the late Middle Horizon (LMH, 850–950 CE for Huancaco and c. 1150 CE for Huaca Santa Clara). Most camelids had strontium isotopic compositions that fell within the predicted isotopic range for the Virú Valley. Isotopic compositions of the serially sampled teeth suggest most camelids did not move between regions with different strontium isotope baselines during enamel formation. At Huaca Gallinazo, the capital of the Virú Polity during the EIP, all the camelids appeared to be local to the lower Virú Valley. At Huaca Santa Clara, a regional administrative center, butchered individuals associated with the EIP occupation had strontium isotope ratios reflecting primarily local origins, with some evidence of individuals from the highlands. The scarified individuals at Huaca Santa Clara (late Middle Horizon) all had strontium isotope ratios consistent with a local origin in the Viru Valley. At Huancaco, some butchered (EIP) and sacrificed (LMH) camelids were local to the Virú Valley but this site may have included more individuals with higher tooth enamel $^{87}Sr/^{86}Sr$, possibly originating in the middle and upper valley regions relative to the other two sites. These data confirm that camelid husbandry was present on the north coast at least as early as the EIP and this practice was maintained through the late Middle Horizon after the waning of north coast polities such as Virú and Moche.

1. Introduction

1.1. South American camelids

In the Andean region, camelids were fundamental for transportation (beasts of burden) and were used for meat, wool, and fertilizer. They were an integral part of the economic, social, and political developments throughout the region (Bonavia, 2008; Shimada and Shimada, 1985). Previously, camelids were associated exclusively with high altitude habitats. Despite the abundance of their skeletal remains at coastal and low altitude sites, it was suggested that these animals were brought to the coast through trade of livestock or dried meat (Benson, 1972; Murra, 1985). Based on previous studies, camelids found at these sites had considerable isotopic variability in their $\delta^{13}C$ and $\delta^{15}N$ values, suggesting a diverse diet of C_3 and C_4 plants (Szpak et al., 2015, 2016a; Thornton et al., 2011; Dufour et al., 2018). This has been interpreted to be evidence of small groups of animals being raised by families or small social units and being fed agricultural products or byproducts (Szpak et al., 2014). Additionally, textiles made from camelid fiber recovered from the north coast have also been interpreted to be evidence of the presence of local camelid populations using a similar interpretative framework (Szpak et al., 2015, 2018, 2020). Such evidence is, however, equivocal because the diversity in stable carbon and nitrogen isotopic compositions may also be the product of diverse geographic origins for these animals and their products. Strontium isotope compositions of animals primarily reflect the strontium isotope compositions of local bedrock and are therefore a robust indicator of geographic provenance (Bentley, 2006), providing a less ambiguous indicator of geographic origin than stable carbon and nitrogen isotope measurements. In this study, we used strontium isotope analysis of tooth enamel to clarify the geographic origins of camelids at three sites in the Virú Valley.

* Corresponding author. Department of Anthropology, Boston University, Boston, MA 02215, United States.
E-mail address: nhult@bu.edu (N. Hultquist).

https://doi.org/10.1016/j.jas.2024.106142
Received 1 October 2024; Received in revised form 10 December 2024; Accepted 12 December 2024
Available online 14 December 2024

1.2. Archaeological context

The Virú Valley (Fig. 1) is well-known from Gordon Willey's foundational work on settlement patterns (Willey, 1953). The valley contains many archaeological sites, including Huaca Gallinazo, Huaca Santa Clara, and Huancaco where excavations have been ongoing since the mid-20th century (Willey, 1953; Ericson et al., 1989; Strong and Evans, 1952; Fogel, 1993; Millaire, 2010b; West, 1981). During the Early Intermediate Period (EIP) the valley was occupied by the Virú polity, an archaic state (Millaire, 2010b). During this period, the Virú Valley had its highest population and local elites exercised a monopoly over the valley's resources (Millaire, 2010a; Millaire et al., 2016). In addition to the primary occupations in the EIP, Huancaco and Huaca Santa Clara are associated with ritual sacrifices during the late Middle Horizon (LMH, 600–1000 CE) that postdate the abandonment of many of the EIP occupations, a common phenomenon on the north coast (Millaire, 2015). The practice of sacrificing camelids on the north coast was widespread throughout the LMH. However, the number of camelids used in these sacrifices varied widely. In some cases, these sacrifices consisted of only a few individuals, while in others hundreds of camelids were sacrificed (Goepfert et al., 2020). Moreover, in some cases these sacrificial events involved human children and in others they did not (Millaire, 2015).

Huaca Gallinazo (V-59), located 4 km from the Pacific coast, is part of the Gallinazo Group and has been identified as the capital of the Virú polity (Millaire and Eastaugh, 2011; Bennett, 1950). The Gallinazo Group was once thought of as the centerpiece of a large multivalley state due to the widespread distribution of Gallinazo ceramics contemporaneous to Moche vessels (Fogel, 1993; Millaire et al., 2016). This view is inconsistent with the results of excavations in the region and has been dubbed the 'Gallinazo illusion' by Christopher Donnan (2009) as the ceramics are simple domestic wares without any larger geopolitical significance. The Virú polity is instead associated with a restricted elite ceramic style (Virú Negative), and in light of this interpretation, the cultural and political affiliation of sites throughout the Virú Valley has been critically reanalyzed (Millaire and Eastaugh, 2011; Millaire, 2010b). Although not the center of a multivalley state, Huaca Gallinazo is the largest site to be affiliated with the Virú polity and served as the political center (Millaire and Eastaugh, 2011; Bauer and Covey, 2002).

Occupied during the EIP, Huaca Santa Clara (V-67) is a regional administrative center for the Virú polity (Millaire, 2010b, 2015). From 160 BCE to 780 CE, Huaca Santa Clara played an important role in political structures (Millaire, 2010b). After this occupation, Huaca Santa Clara was the location of a ritual sacrifice in the LMH (c. 1150 CE) that is associated with the sacrifice of over two dozen camelids as well as several young human individuals (Hyland et al., 2021). This ritual event is hypothesized to demonstrate and establish the ruling power of elites during this later time (Millaire, 2015).

Huancaco (V-88 and V-89) was originally thought to be a Moche site occupied during the EIP (Willey, 1953). However, Huancaco is poorly represented in the literature and little has been formally published about this site. Evidence for a group of local elites associated with the Huancaco style of material culture has been observed at the site (Bourget, 2010; Millaire, 2015; Szpak et al., 2016b). Huancaco was abandoned by 680 CE after a short occupation lasting less than 200 years (Bourget, 2010). In addition to this main occupation, postdating the abandonment and during the LMH, at least fourteen llamas were ritually sacrificed (c. 850–950 CE). We present additional AMS radiocarbon dates from the bone and tooth collagen of these camelids to better resolve the

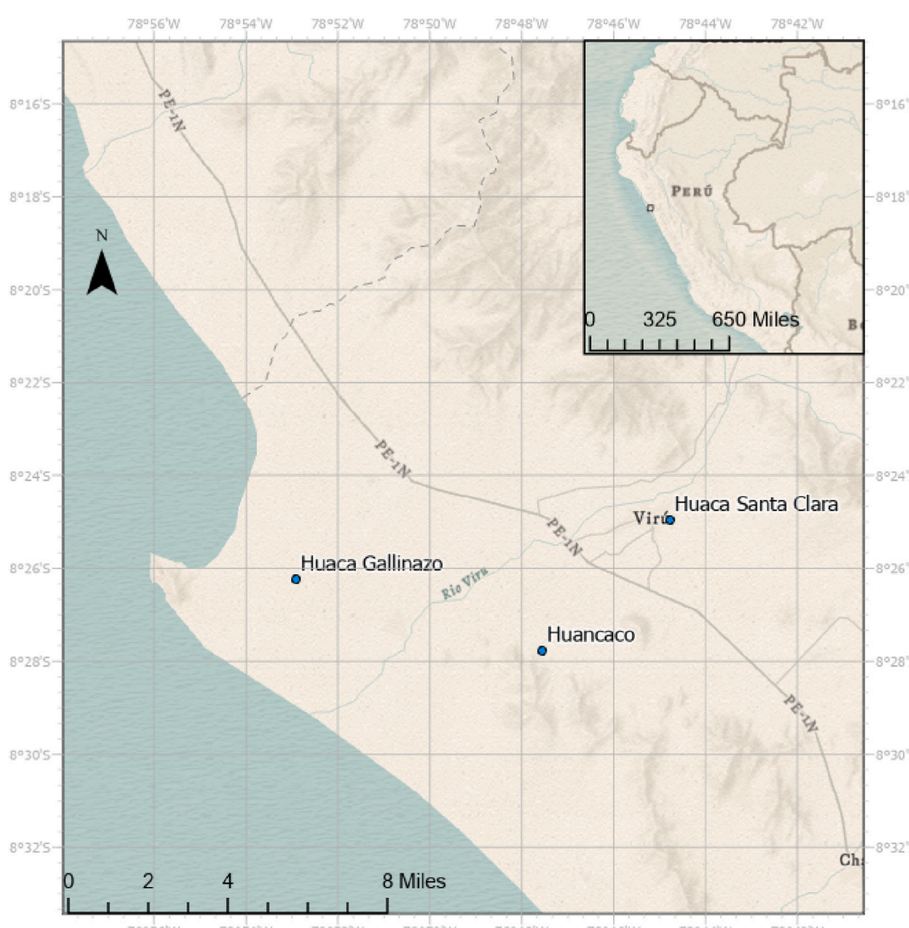

Fig. 1. Map of the lower Virú Valley showing the three sites from which samples were selected.

chronology of the site.

Previous stable isotope analysis has examined the diets of the camelids at all three sites (Szpak et al., 2014, 2016b), as well as the diet and mobility of humans at Huaca Santa Clara and Huaca Gallinazo (Hyland et al., 2021). Humans had a diet based primarily on C_4 plants and had diverse geographic origins that included the highlands (Hyland et al., 2021). The camelids had a diet that consisted of, on average, ~50% C_4 plants although sacrificed camelids at Huancaco revealed a diet based on slightly more C_3 plants (Szpak et al., 2014, 2016b).

1.3. Environmental context

Peru features eight distinct ecological zones identified by their elevations, climate, vegetation, and land use (Pulgar Vidal, 1996). These consist of the *chala, yunga, quechua, suni/jalca, puna, janca, rupa-rupa*, and the *omagua*. All eight zones were accessible to ancient societies and trade routes expanded through zones to reach other societies (Malpass, 2016; Murra, 1980). Different methods of resource extraction from these various zones have been hypothesized, the two most well-known being "verticality" (Murra, 1972) and "horizontality" (Rostworowski de Diez Canseco, 1970). Verticality suggests that populations living in the altiplano dealt with the limitations of their local environment by establishing colonies in other ecological zones, thereby diversifying their resource base, increasing resource diversity, reducing overall risk, and increasing resilience of both coastal and highland regions. Rostworowski de Diez Canseco (1970) proposed an alternative model in which coastal populations emphasized locally-produced resources and expanded their influence north-south to other coastal regions rather than relying on exchange with highland groups. This is based on the idea that different coastal sites and areas would have occupational specialties that would contribute to the local economy and create larger political structures that could expand throughout the coastal regions across valleys. Camelids have primarily been associated with high altitude habitats and were not typically considered an important part of economic activities associated with low elevation sites.

1.4. Isotopic context

Strontium has four naturally-occurring isotopes (^{84}Sr, ^{86}Sr, ^{87}Sr, ^{88}Sr), with ^{87}Sr being radiogenic. Strontium in bedrock is most likely found in the isomorphic substitution of calcium (Ca^{2+}), as the result of the β^- decay of ^{87}Rb (Faure and Powell, 2012; Pankhurst, 1982; MacGregor and Wiedenbeck, 1952). Strontium isotopes exhibit very little fractionation in nature, due to the small relative mass difference among the isotopes (Bentley, 2006; Fogel and Cifuentes, 1993). Passing from the bedrock to the biosphere, the differences in strontium isotope ratios among living organisms come from the mixing of the end-members rather than from discrimination against any isotope of strontium due to chemical or biological processes (Bentley, 2006). Substituting for calcium, the strontium from the local bedrock becomes incorporated into plants and animals, making the ratio of strontium isotopes in an organism reflective of the strontium isotope ratios in the local bedrock (Bentley, 2006; Faure and Powell, 2012).

Strontium occurs as part of bioapatite in calcified biological tissues (Price et al., 2002). While an organism is living, strontium becomes incorporated into the mineral portion of bones and teeth, however, after the organism dies, diagenetic strontium can also substitute for calcium in skeletal remains, changing the ratio of ^{87}Sr/^{86}Sr to reflect that of the local soil (Price et al., 2002; Horn and Müller-Sohnius, 1999; Bentley, 2006). Strontium contamination from the surrounding environment has been demonstrated to be a particular problem for bones, but not for tooth enamel (Hoppe et al., 2003; Nelson et al., 1986). Tooth enamel primarily consists of tightly packed apatite crystals that have a relatively small surface area compared to bone apatite crystals, creating fewer opportunities for contamination in tooth enamel (Driessens and Verbeeck, 1990; Hoppe et al., 2003; Trickett et al., 2003).

In order to infer geographic origin or residential mobility through the ratio of ^{87}Sr/^{86}Sr, rather than simply identifying non-locals in a population, a strontium isoscape for the region must be developed. In South America, the subduction of the Nazca Plate underneath the South American Plate encourages the growth of the Andes, creating elevational differences in the region. The Nazca plate pushes older rocks, with higher ^{87}Sr/^{86}Sr ratios, to the surface of the Andes mountains (Klerkx et al., 1977; Salda et al., 1992). Scaffidi and Knudson (2020) used archaeological biota to construct a strontium isoscape of the central Andean region (Fig. 2). The bioavailable strontium isotope ratios for the Virú Valley region in Scaffidi and Knudson' (2020) isoscape are in general agreement with the strontium isotope ratios of the geologically available strontium in the Virú Valley determined by Hewitt (2013). While a more detailed regional isoscape of the north coast generated from archaeological small fauna would be beneficial, the area around and encompassing the Virú Valley is well represented in the Scaffidi and Knudson (2020) isoscape.

2. Methods

The samples analyzed in this study consisted of the tooth enamel of 62 camelid teeth that produced a total of 162 incremental or bulk samples. They were serially sampled at approximately 1 cm intervals along the lingual or buccal surface of the tooth. Camelid samples associated with the EIP occupations and later ritual contexts are summarized in Table 1.

Preparation of the teeth included cleaning the teeth to remove any dirt or contaminants that could change the strontium isotope ratio following the protocol outlined by Miller et al. (2018). Serial sampling was done on each tooth for which the crown and root could be distinguished. Fragmented teeth were sampled in bulk. An NSK dental drill with a diamond-tipped burr was used to separate the enamel from the dentin. Once the enamel was separated from the dentin, strontium was extracted by column chemistry using Eichrom strontium resin (50–100 μm) (Horwitz et al., 1991). Isolated Sr was collected in ultraclean Teflon vials and diluted with 2% HNO_3 to produce a 50 parts per billion (ppb) solution of strontium (Horwitz et al., 1991). Each sample was then analyzed on a Nu Plasma II Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS) at the Trent University Water Quality Center. Blanks were used to quantify contamination of the resin and the columns; blanks were measured at their original concentration (see Supplementary Material).

Strontium isotope ratios were determined using a Nu Plasma II MC-ICP-MS in the Trent University Water Quality Center. Each reported value consists of 50 individual measurements taken by the MC-ICP-MS to assess analytical precision. The strontium standard NIST-987 (^{87}Sr/^{86}Sr = 0.710236) was used to calibrate the instrument and assess analytical accuracy and precision. The total analytical precision on repeated measurements of NIST-987 was $\pm 1.37 \times 10^{-6}$ at 1σ.

Collagen was extracted from 8 phalanges and 2 M from camelids from Huancaco (5 samples from the EIP occupation and 5 from the later sacrificial event). The exterior surface of the samples was cleaned using a dental drill equipped with a diamond-tipped cutting wheel, then a chunk of bone weighing 150–250 mg was removed using this same cutting wheel. The samples were demineralized in 0.5 M HCl at room temperature under constant motion (on an orbital shaker) until fully demineralized after approximately 48 h. The samples were rinsed to neutrality with Type I water and refluxed in 0.01 M HCl at 75 °C for 36 h. The resulting solution was then filtered using Centriprep ultrafilters with a 30 kDa molecular weight cut-off and the high molecular weight fraction was freeze-dried. The samples were processed alongside a radiocarbon blank (Hollis Mine Mammoth; Martinez De La Torre et al., 2019) and a muskox bone from Banks Island that has been dated 15 times with a date of 3470 ^{14}C years BP. The samples were ^{14}C dated at the W. M. Keck Carbon Cycle Accelerator Mass Spectrometer (KCCAMS) Facility at the University of California at Irvine. The radiocarbon dates are reported

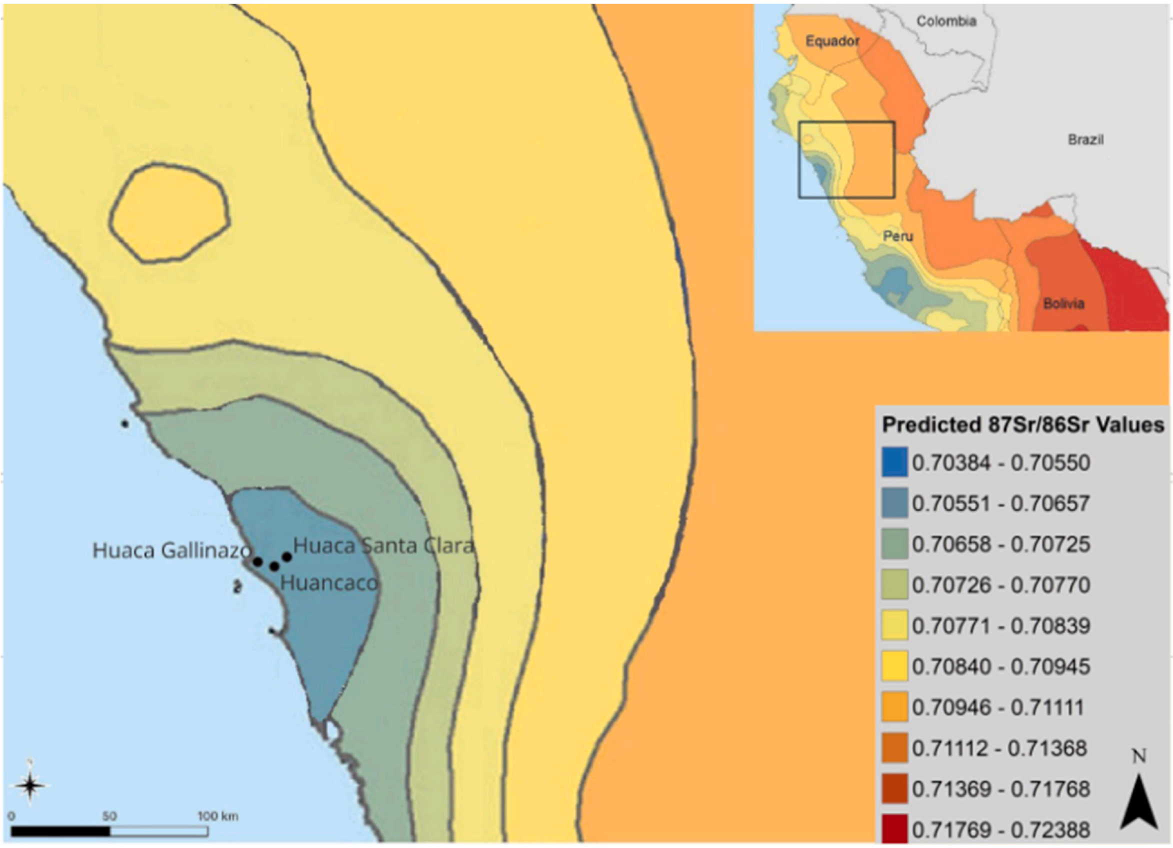

Fig. 2. Predicted Strontium isotope ratios in and near the Virú Valley; adapted from Scaffidi and Knudson (2020).

Table 1
Summary of the number of camelid teeth sampled in this study by site and time period.

Period	Site	Number of Individuals	Number of Sampled Teeth	Total Number of Segments
Early Intermediate	Huaca Gallinazo	8	8	35
	Huaca Santa Clara	10	10	28
	Huancaco	7	7	26
	All Sites	25	25	89
Late Middle Horizon	Huaca Santa Clara	13	13	24
	Huancaco	10	24	49
	All Sites	23	37	73
All Periods	All Sites	48	62	162

following the conventions of Stuiver and Reimer (1993).

3. Results

3.1. Radiocarbon dates

Ten radiocarbon dates helped clarify the chronology at Huancaco. Both the EIP and LMH dates are consistent with one another, suggesting an EIP occupation dating to 420-570 AD and placing the sacrifices somewhere between 890 and 990 AD (Table 2). These dates are in line with previous interpretations about timing of the EIP occupation and LMH sacrifice at Huancaco (Fig. 3).

3.2. Strontium isotope results

For Huaca Gallinazo, eight camelid teeth from eight individuals (35 total samples) produced $^{87}Sr/^{86}Sr$ values that ranged from 0.70498 to 0.70664. For the 23 camelid teeth from 23 individuals from Huaca Santa Clara (52 samples), the $^{87}Sr/^{86}Sr$ values ranged from 0.70502 to 0.70865. For the 31 camelid teeth from 17 individuals from Huancaco (75 samples), the $^{87}Sr/^{86}Sr$ values ranged from 0.70494 to 0.70776. The Sr isotopic compositions of the camelid tooth enamel are summarized in Table 3, Figs. 4–6. Sr isotopic compositions and elemental concentrations for each sample and the variation for each tooth is in the supplementary material (Table S1). The Sr isotopic compositions for each individual camelid are presented in the supplementary material (Figs. S1–S48).

4. Discussion

Strontium isotope ratios from Huaca Gallinazo, Huaca Santa Clara, and Huancaco demonstrate that many camelids deposited at these sites during both the EIP and LMH were raised in low-altitude or coastal environments. The use of these camelid enamel strontium isotope ratios in conjunction with the isoscape presented by Scaffidi and Knudson (2020), allows us to interpret these isotope ratios and better understand the use of camelids in these Andean societies. For this study, the local strontium isotope signature is defined as between 0.7055 and 0.70657 while the highland strontium isotope signature is defined as above 0.70770 (Fig. 2). Because of the east-west variation in Sr isotope ratios

Table 2
Radiocarbon dates for camelids from Huancaco. Radiocarbon dates have been calibrated to SHCal20 (Hogg et al., 2020), using Calib 8.2 (Stuiver and Reimer, 1993).

UCIAMS Lab ID	Sample ID	Context	Element	^{14}C Age (^{14}C years BP)	Calibrated Date (2 Sigma Range) (CE)
275953	1215	EIP	Molar	1615 ± 20	420-541, 556-569
275954	12134	EIP	Phalanx	1620 ± 20	419–539
275955	12136	EIP	Phalanx	1585 ± 20	436-462, 464-581
275956	12140	EIP	Phalanx	1610 ± 20	422-543, 564-571
275957	14909	EIP	Molar	1615 ± 20	420-541, 556-569
275958	12102 (Llama 4)	LMH	Phalanx	1135 ± 20	895-936, 956–993, 1005-1017
275959	12109 (Llama 6)	LMH	Phalanx	1155 ± 20	897-944, 949-991
275960	12111 (Llama 5)	LMH	Phalanx	1175 ± 20	888-975, 977-988
275961	12116 (Llama 9)	LMH	Phalanx	1175 ± 20	888-975, 977-988
275962	12117 (Llama 10)	LMH	Phalanx	1165 ± 15	893-944, 949-988

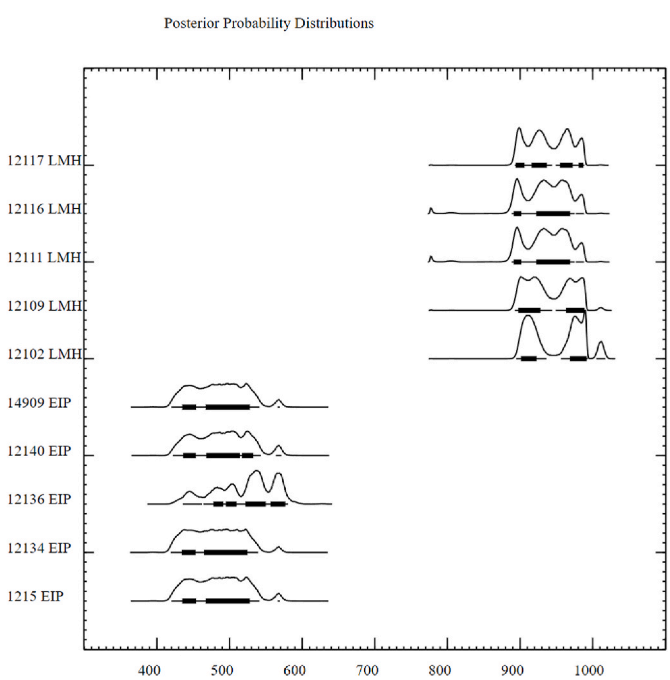

Fig. 3. Probability distributions of the ten radiocarbon dates from Huancaco (2 Sigma Range). Radiocarbon dates have been calibrated to SHCal20 (Hogg et al., 2020), using Calib 8.2 (Stuiver and Reimer, 1993).

presented in Scaffidi and Knudson's (2020) isoscape, ratios between 0.70657 and 0.70770 likely represent intermediate altitudes. As the small enamel subsamples of strontium represent relatively brief periods in the lives of these camelids, it is unlikely that a mixture of signatures between low coastal and high highland strontium isotope ratios would produce intermediate values. While many camelids from these three sites have strontium isotope ratios consistent with local origins, others demonstrate strontium isotope ratios that are more consistent with the geology from several regions including the upper valley (*yungas*), intermontane valleys at higher altitudes, and the highlands (*puna*). The

Table 3
^{87}Sr/^{86}Sr values for camelids.

Sample ID	Site	Occupation	N Increments	^{87}Sr/^{86}Sr (Mean ±1σ)	^{87}Sr/^{86}Sr (Range)
14997	Huaca Gallinazo	EIP	4	0.70629 ± 0.00003	0.70624-0.70664
14998	Huaca Gallinazo	EIP	5	0.70635 ± 0.00003	0.70631-0.70638
14999	Huaca Gallinazo	EIP	2	0.70588 ± 0.00006	0.70583-0.70592
15000	Huaca Gallinazo	EIP	4	0.70679 ± 0.00008	0.70670-0.70689
15001	Huaca Gallinazo	EIP	4	0.70502 ± 0.00004	0.70498-0.70506
15002	Huaca Gallinazo	EIP	4	0.70636 ± 0.00009	0.70623-0.70642
15003	Huaca Gallinazo	EIP	6	0.70559 ± 0.00002	0.70558-0.70563
15004	Huaca Gallinazo	EIP	6	0.70579 ± 0.00003	0.70575-0.70583
14917	Huaca Santa Clara	EIP	3	0.70847 ± 0.0001	0.70834-0.70854
14918	Huaca Santa Clara	EIP	4	0.70559 ± 0.00004	0.70553-0.70562
14919	Huaca Santa Clara	EIP	3	0.70687 ± 0.00007	0.70681-0.70695
14920	Huaca Santa Clara	EIP	2	0.70864 ± 0.00002	0.70862-0.70865
14921	Huaca Santa Clara	EIP	3	0.70707 ± 0.00003	0.70698-0.70703
14922	Huaca Santa Clara	EIP	4	0.70632 ± 0.00003	0.70628-0.70635
15021	Huaca Santa Clara	EIP	2	0.70598 ± 0.000007	0.70597-0.70598
15022	Huaca Santa Clara	EIP	3	0.70599 ± 0.00007	0.70593-0.70606
15023	Huaca Santa Clara	EIP	3	0.70504 ± 0.00002	0.70502-0.70505
15024	Huaca Santa Clara	EIP	1	0.70850 ± 0.000007	N/A
321 (Llama 2)	Huaca Santa Clara	LMH	3	0.70606 ± 0.00009	0.70599-0.70616
332 (Llama 6)	Huaca Santa Clara	LMH	3	0.70582 ± 0.00002	0.70581-0.70584
337 (Llama 8)	Huaca Santa Clara	LMH	1	0.70560 ± 0.000003	N/A
344 (Llama 12)	Huaca Santa Clara	LMH	2	0.70558 ± 0.00006	0.70553-0.70562
348 (Llama 15)	Huaca Santa Clara	LMH	2	0.70573 ± 0.00003	0.70571-0.70575
350 (Llama 16)	Huaca Santa Clara	LMH	1	0.70586 ± 0.000005	N/A
354 (Llama 18)	Huaca Santa Clara	LMH	2	0.70567 ± 0.00004	0.70564-0.70569
357 (Llama 19)	Huaca Santa Clara	LMH	2	0.70597 ± 0.00002	0.70595-0.70598

(*continued on next page*)

Table 3 (*continued*)

Sample ID	Site	Occupation	N Increments	$^{87}Sr/^{86}Sr$ (Mean ±1σ)	$^{87}Sr/^{86}Sr$ (Range)
361 (Llama 21)	Huaca Santa Clara	LMH	1	0.70556 ± 0.000003	N/A
363 (Llama 22)	Huaca Santa Clara	LMH	1	0.70617 ± 0.000007	N/A
366 (Llama 24)	Huaca Santa Clara	LMH	2	0.70581 ± 0.00001	0.70581-0.70581
368 (Llama 25)	Huaca Santa Clara	LMH	2	0.70580 ± 0.00002	0.70578-0.70581
373 (Llama 27)	Huaca Santa Clara	LMH	2	0.70615 ± 0.00007	0.70610-0.70620
1215	Huancaco	EIP	4	0.70650 ± 0.0004	0.70606-0.70679
1216	Huancaco	EIP	5	0.70602 ± 0.0003	0.70578-0.70644
1217	Huancaco	EIP	5	0.70712 ± 0.0001	0.70701-0.70725
1218	Huancaco	EIP	2	0.70626 ± 0.00004	0.70623-0.70628
14902	Huancaco	EIP	3	0.70766 ± 0.0001	0.70653-0.70680
14906	Huancaco	EIP	4	0.70726 ± 0.0001	0.70714-0.70739
14909	Huancaco	EIP	4	0.70519 ± 0.0003	0.70494-0.70558
1175 (Llama 4)	Huancaco	LMH	1	0.70739 ± 0.000007	N/A
1179 (Llama 2)	Huancaco	LMH	1	0.70737 ± 0.000003	N/A
1180 (Llama 1)	Huancaco	LMH	2	0.70727 ± 0.00002	0.70725-0.70728
1181 (Llama 3)	Huancaco	LMH	4	0.70727 ± 0.00004	0.70724-0.70732
1183 (Llama 6)	Huancaco	LMH	2	0.70752 ± 0.0002	0.70736-0.70768
1190 (Llama 6)	Huancaco	LMH	2	0.70775 ± 0.00002	0.70773-0.70776
1193 (Llama 9)	Huancaco	LMH	3	0.70709 ± 0.0002	0.70701-0.70736
1199 (Llama 10)	Huancaco	LMH	2	0.70649 ± 0.00002	0.70648-0.70651
1203 (Llama 13)	Huancaco	LMH	3	0.70739 ± 0.0003	0.70721-0.70774
1207 (Llama 11)	Huancaco	LMH	2	0.70618 ± 0.00004	0.70615-0.70620
1210 (Llama 2)	Huancaco	LMH	1	0.70619 ± 0.000004	N/A
14903 (Llama 2)	Huancaco	LMH	2	0.70719 ± 0.00001	0.70718-0.70720
14904 (Llama 5)	Huancaco	LMH	3	0.70644 ± 0.0002	0.70623-0.70662
14905 (Llama 1)	Huancaco	LMH	3	0.70737 ± 0.00003	0.70734-0.70739
14907 (Llama 3)	Huancaco	LMH	3	0.70725 ± 0.001	0.70716-0.70743
14908 (Llama 11)	Huancaco	LMH	3	0.70712 ± 0.00008	0.70704-0.70720
14910 (Llama 9)	Huancaco	LMH	2	0.70766 ± 0.000007	0.70765-0.70766
14911 (Llama 2)	Huancaco	LMH	1	0.70617 ± 0.000009	N/A
14912 (Llama 6)	Huancaco	LMH	1	0.70761 ± 0.000003	N/A
14913 (Llama 4)	Huancaco	LMH	1	0.70747 ± 0.000008	N/A
14914 (Llama 13)	Huancaco	LMH	1	0.70676 ± 0.000007	N/A
14915 (Llama 12)	Huancaco	LMH	2	0.70622 ± 0.000002	0.70619-0.70676
14916 (Llama 1)	Huancaco	LMH	1	0.70653 ± 0.000004	N/A

relative abundance of animals with local geographic origins differs among the three sites as well as the two time periods.

Many Andean archaeologists have relied heavily on the ethnohistoric accounts of camelid herding and have assumed that patterns from the Inca or the early colonial period (Murra, 1965, 1980) would have characterized earlier periods in Peruvian prehistory. In these accounts, which are also strongly influenced by the association between camelids and high-altitude habitats by the geographer Carl Troll (1958), camelids were raised in the highlands (*puna* and *altiplano*), with their presence at low altitude and coastal archaeological sites being explained as evidence of trade rather than local camelid husbandry.

During the introduction of European livestock, there was a drastic reduction in camelid range and quantity in the Andean region (Pozorski, 1976; Shimada and Shimada, 1985; Goepfert et al., 2020). Ethnohistoric accounts of camelid husbandry describe mobile pastoralists that were dispersed throughout the *puna* (Flannery et al., 1989; Flores-Ochoa, 1979; Tomka, 1992; McGreevy, 1984), with the reliance on camelids by traditional societies at lower altitudes being minimal (Browman, 1975; 1990). Because of this reliance of highland groups on camelids and the historic herding practices observed after the arrival of Eurasian domesticates, the connection between the domestic camelids and the *puna* is especially strong. On top of the highland pastoral history, it has been questioned whether the ruling coastal polities would have been able to maintain herds of camelids because of breeding issues, slower rates of wool growth, predisposition to disease, and adaptability issues on the coast, especially for alpacas (Topic et al., 1987; Cardich, 1980). Although some researchers have stated that camelid husbandry was possible on the coast (Shimada and Shimada, 1985; Bonavia, 2008), these have mainly focused on the llama which is apparently more adaptable (Franklin, 1982).

The previously published isotopic evidence that was interpreted to be consistent with coastal camelid husbandry (Szpak et al., 2018; Szpak et al. 2014; Szpak et al. 2015; Santana-Sagredo et al., 2020), however, remains equivocal. The results of this study more clearly demonstrate that some coastal sites relied predominantly, or possibly entirely, on local populations of camelids from at least the EIP. We explore the implications of the strontium isotope data at each of the three sites below.

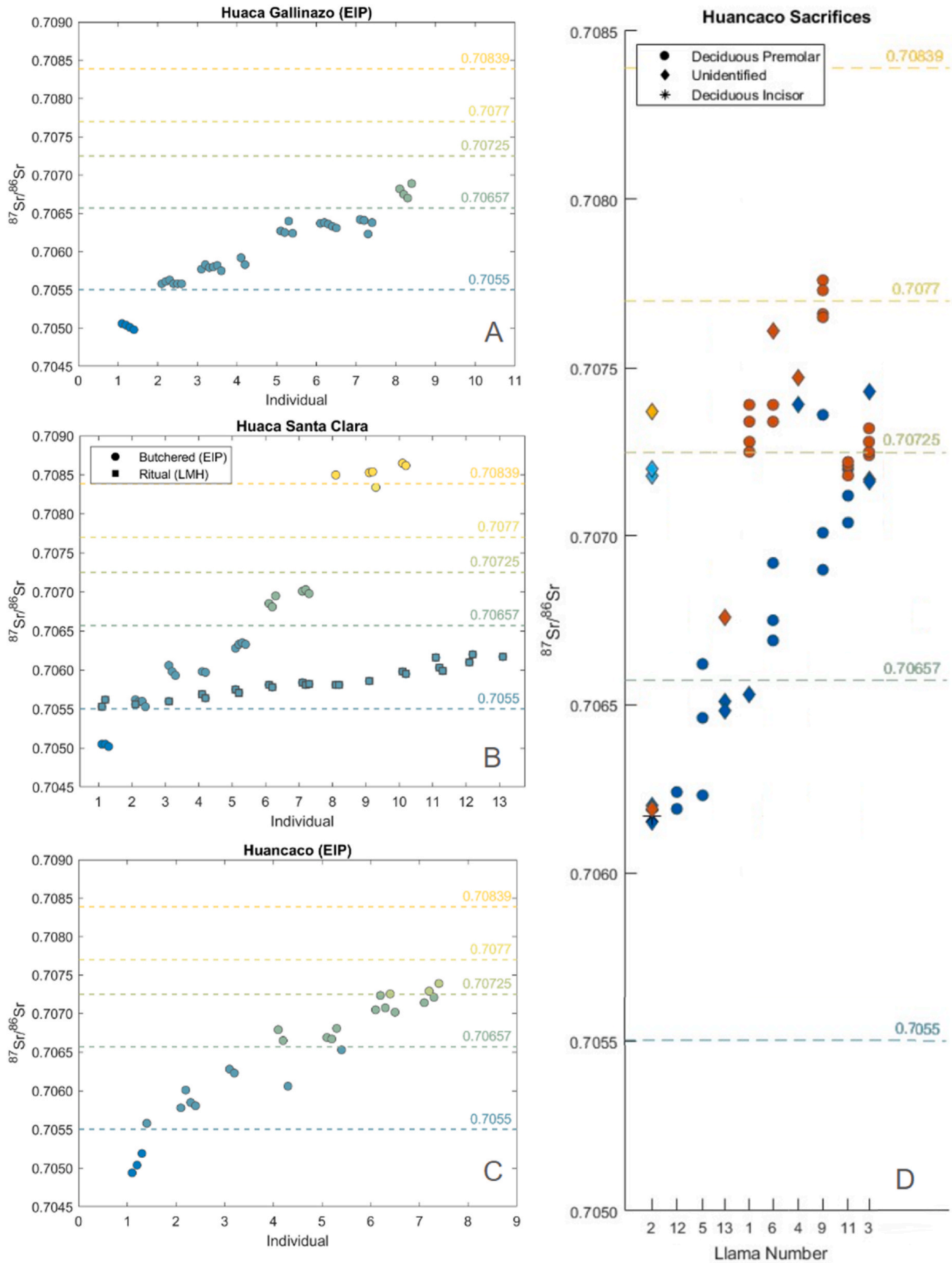

Fig. 4. Strontium isotope ratios for camelid tooth enamel from the Huaca Gallinazo EIP occupation (A), the Huaca Santa Clara EIP occupation (circles) and late MH sacrificial event (circles) (B), the Huancaco EIP occupation (C), and the Huancaco ritual sacrifice (D). In A, B, and C the color of each dot corresponds to the colored bands in the Sr isoscape generated by Scaffidi and Knudson (2020) represented in Fig. 2. In Panels A, B, and C the x-axis is an arbitrary number to differentiate individuals, which are sorted according to their $^{87}Sr/^{86}Sr$ values. The individuals listed in the Huancaco sacrifices are according to their burial number used in other publications (Szpak et al., 2016b). In panel D, the different colors correspond to different teeth that were sampled and the shape corresponds to the type of tooth (multiple teeth were sampled from some individuals). The camelid strontium isotope ratios from the three EIP occupations are presented on the same panel in Fig. S50. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

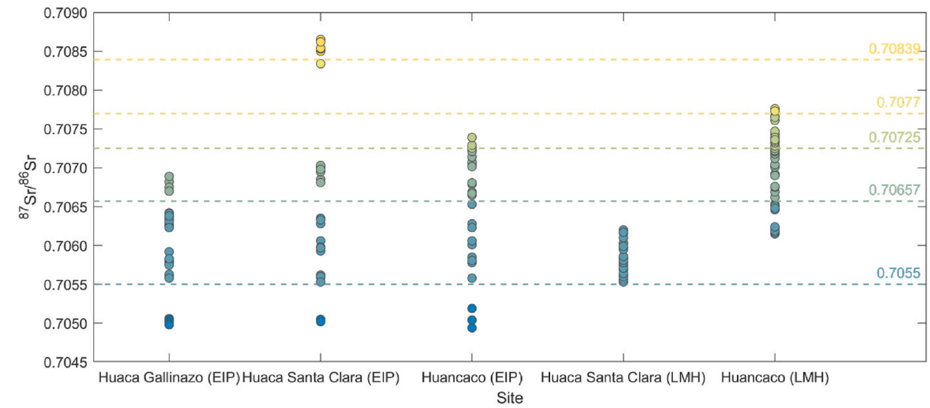

Fig. 5. Jitter plot of all strontium isotope ratios of camelid tooth enamel, demonstrating the distribution of strontium isotope ratios at each site and time period. The color of each dot corresponds to the colored bands in the Sr isoscape generated by Scaffidi and Knudson (2020) represented in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

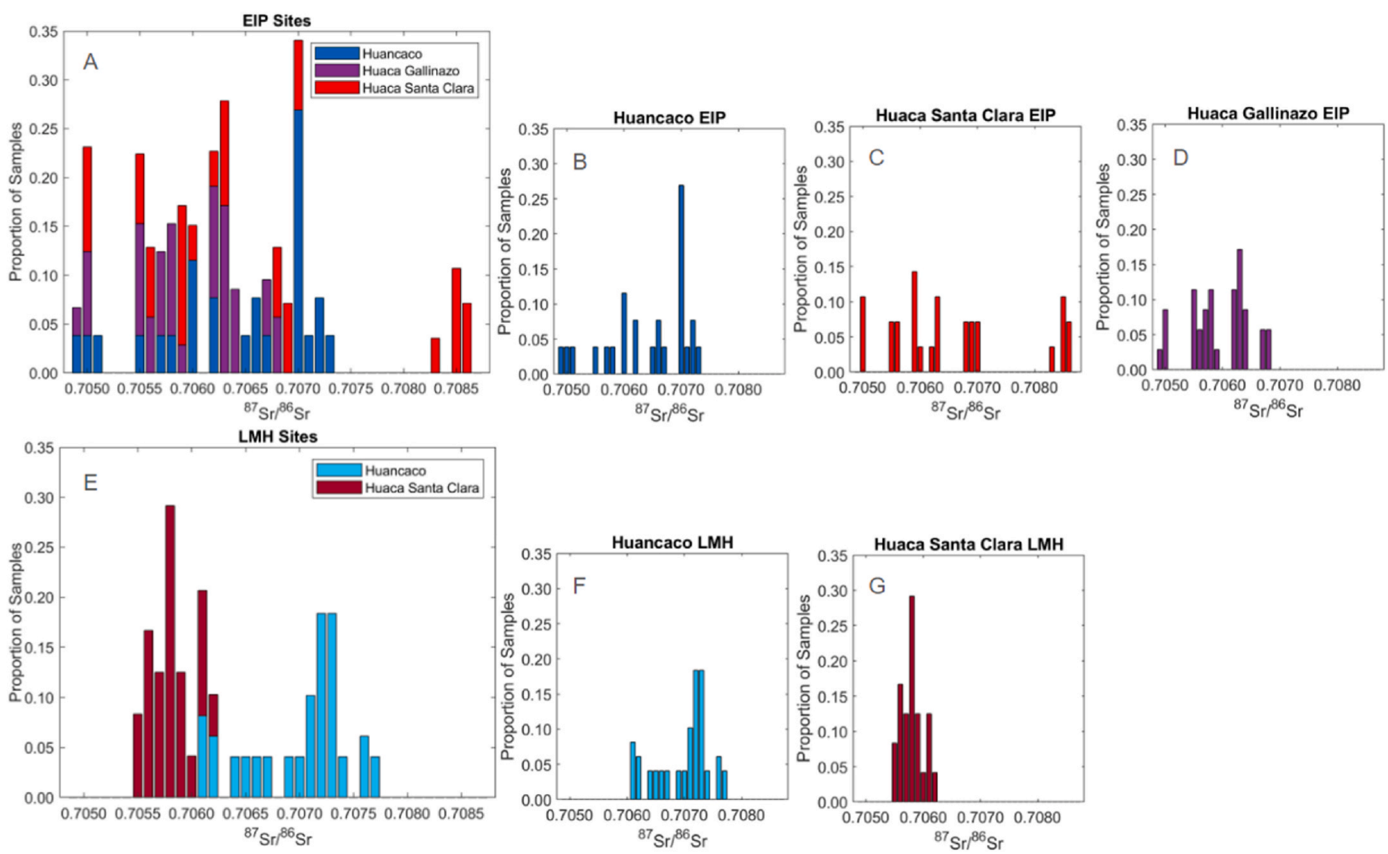

Fig. 6. Histograms of strontium isotope ratios by period (Panels A, E) and site (Panels B, C, D, F, G). These data are presented on a single histogram in Fig. S49.

4.1. Huaca Gallinazo

All of the camelids analyzed from Huaca Gallinazo have strontium isotope ratios consistent with these animals being raised locally. Being the capital of the Virú polity, Huaca Gallinazo had an abundance of resources and highly developed trade networks with other groups (Millaire, 2010b). We initially expected that because of this, and the earlier date for the EIP occupation at this site relative to the other contexts, Huaca Gallinazo would have camelids that were from a variety of areas, but little isotopic variability is observed, suggesting a consistently local origin (Fig. 7). Intra-tooth variation in strontium isotope ratios suggests that individuals remained in one area during the time of tooth formation. Though these data show that nearly all animals at this site were local, this does not imply that all animals were herded at Huaca Gallinazo. The presence of such a high proportion of local camelids at Huaca Gallinazo suggests the practice of herding animals on the coast was well established by at least the EIP. Limited evidence exists to speak to the origins of coastal camelid husbandry, but Szpak et al. (2016a) suggested that there may have been some local camelid husbandry during the Early Horizon further south in the Nepeña Valley based on stable carbon and nitrogen isotope data. While the Virú polity engaged in trade with neighboring groups as evidenced by ceramics sourced from the highlands and a belt made of braided grass from the Amazon (Szpak et al., 2015), they do not appear to have relied heavily on traded camelid livestock with highland groups.

Huaca Gallinazo has been relatively well-studied in the context of

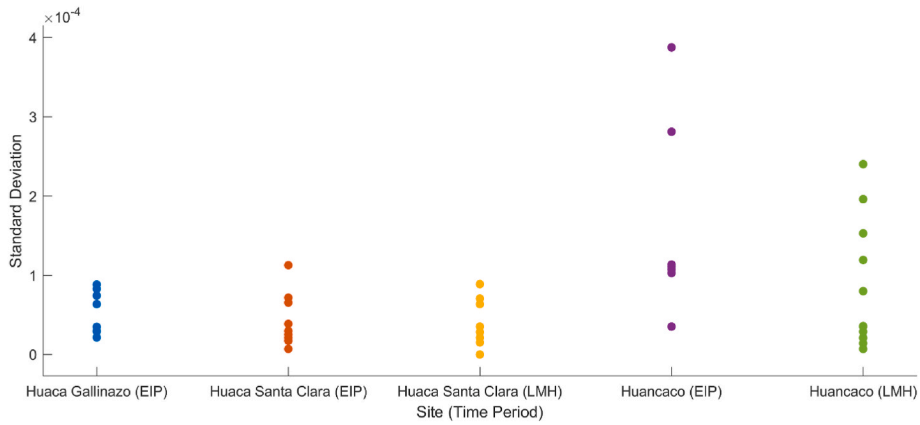

Fig. 7. Jitter plot of the standard deviation within serial samples of individual camelid teeth from each site. Teeth that were sampled in bulk are not included in this figure.

early-state development. Though the organization and size of the Virú polity are debated, it appears to have had a similar structure to other archaic states (Millaire, 2010b). The extent to which Huaca Gallinazo exerted control over animal husbandry or relied on trade with highland groups for camelids and camelid products, has been relatively unclear though camelids were the most abundant mammalian taxon identified at the site (Johns, 2017). Based on this study, it is clear that local camelid husbandry was an important activity within or in the area around the capital. This, however, does not imply that the ruling elites at Huaca Gallinazo did not require some form of local camelid tributes from nearby sites that had a similar strontium isotope baseline. Further, it is possible that some camelids were acquired via trade with the highlands, but the data collected in this study suggest that if this did happen, the relative importance of imported camelids was lesser than the reliance of locally-raised animals.

4.2. Huaca Santa Clara

EIP camelids at Huaca Santa Clara show diverse strontium isotope values. Out of the ten butchered individuals in this sample, three show strontium isotope ratios consistent with a highland origin, suggesting trade between Huaca Santa Clara and highland groups involving the movement of live camelids to the lower Virú Valley. Two camelids demonstrate strontium isotope values that appear non-local but correspond with strontium isotope values present in the upper valley or intermediate zones (*yunga,* or *quechua*). The presence of these two individuals suggests that there was trade with the upper valley and camelid husbandry may have existed not only in the highlands and on the coast, but in a variety of environments in the Andes during the EIP. It is therefore likely that camelids were distributed widely throughout the elevational zones in the central Andes, but additional isotopic data from sites associated with these intermediate altitudes would be highly useful. Half of the EIP camelids at Huaca Santa Clara have strontium isotope values that are consistent with the local range according to Scaffidi and Knudson's (2020) isoscape. Therefore, there must have been some effort directed towards raising camelids locally at the site or a nearby location in the lower valley (Fig. 4). Tooth enamel from these camelids does not show a large amount of intra-tooth variation, suggesting these individuals stayed in one area with a consistent strontium isotope baseline during the time of enamel formation (Fig. 7). Even though there is clear evidence of coastal camelid husbandry at Huaca Gallinazo, elites at Huaca Santa Clara must have found trade with highland or upper valley groups beneficial because they maintained these connections. These elites at Huaca Santa Clara may have acted as middlemen in exchange that occurred between the coastal and highland regions. Strontium isotope data suggesting the presence of highland camelids at Huaca Santa Clara are consistent with textiles manufactured using foreign (i.e., highland) styles and fibers with isotopic compositions suggestive of a highland origin found at the site (Millaire, 2015; Szpak et al., 2015).

The ritually sacrificed camelids at Huaca Santa Clara all had tooth enamel with a local strontium isotope signature, similar to the EIP camelids at Huaca Gallinazo. This ritual was part of a larger complex of ritual sacrifices that occurred across the north coast of Peru during this time (Millaire et al. 2009; Prieto et al., 2019; Szpak et al., 2014, 2016b). The camelid sacrifices at Huaca Santa Clara were all under 6 months old and the majority were under 3 months old. The local strontium isotope signature of these animals suggests that they would not have been moved to the site from the highlands, *yungas*, or *quecha* zones while still in utero as the deciduous camelid teeth used in this analysis form before birth (Wheeler, 1982; Takigami et al., 2020). The local strontium isotope signature in these individuals demonstrates that the mothers lived in the lower Virú Valley while they were pregnant (Fig. 4), further confirming the presence of a local, stable population of camelids. Coastal husbandry was productive enough in this region such that many animals could be destined for sacrifice and were not used to sustain the local subsistence or political economy through their primary and secondary products. If camelid herding was a marginal activity on the north coast, it is difficult to explain the sacrifices that consisted of these young individuals born from local mothers.

4.3. Huancaco

The butchered EIP camelids at Huancaco have strontium isotope values that suggest both local and non-local origins, possibly associated with the upper valley or intermediate zones between the coast and highlands (Fig. 4). The lack of elevated strontium isotope ratios that reflect highland origins suggests variable patterns of camelid in the Virú Valley. During the EIP occupation at Huancaco, it is likely that trade with the upper valley or *yungas* zone was prioritized over trade with the highlands. It suggests that local camelid herding was not the primary focus at Huancaco during its short occupation, which contrasts with the pattern of local husbandry observed at Huaca Gallinazo. Some individuals from Huancaco also showed a high amount of strontium isotopic variation during the EIP, which suggests that during the time of tooth formation, these camelids were moving throughout the valley (Fig. 7). The majority of the teeth sampled were molars (M2 or M3) which erupt between 1.5 and 4 years (Wheeler, 1982). This, combined with the high intra-tooth variation in some of these animals, suggests that these particular individuals may have been used in caravans and were eventually brought to Huancaco to be butchered as the strontium isotope ratios do not present consistent patterns of variation.

The sacrificed individuals show a similar pattern to the EIP camelids at this site (Fig. 4). Though there are local camelids at this site, many of these sacrificed camelids have origins that are suggestive of the upper valley. These sacrificed camelids were all under 9 months old, and the majority of the teeth taken from these individuals were deciduous premolars. Such young animals are characterized by high mortality rates in caravans (Davis et al., 1998), so it is unlikely that these animals were being used for this purpose. Additionally, because the majority of these teeth were already formed at birth, these teeth likely show the strontium isotope composition of the individual while they were in utero (Wheeler, 1982; Takigami et al., 2020). The high variation between some of the deciduous teeth demonstrates that some of these individuals may have been transported while they were still growing in a fetal state and their mothers were moved prior to the individual's birth. However, in both modern and historical accounts, camelids were only used to caravan if they were over 2 years old, male, and castrated (Browman, 1974, 1975, 1990; Frigolé and Gasco, 2016). Though there are no accounts of female llamas being used to caravan, the isotopic evidence presented here demonstrates that some of these mothers would have been moving around the valley during the time of fetal tooth formation (Fig. 7). Based on these strontium isotope data, some pregnant camelids were moving relatively long distances, likely in an east-west fashion in accordance with the local isoscape (Fig. 2), potentially as a part of caravans or to be traded as livestock. There may have been a particular demand for very young camelids to be used in ritual events on the north coast where local camelid husbandry does not seem to have been especially prominent, such as at Huancaco relative to Huaca Gallinazo. These camelids that were sacrificed at Huancaco were likely sourced well before the event.

4.4. Camelid husbandry on the north coast of Peru

The EIP modes of camelid husbandry associated with the Virú polity and the Huancaco tradition persisted despite the rise and fall of the larger political organizations and elite material cultural traditions indicating that camelid husbandry was likely independent of these political organizations. Camelid husbandry was likely dependent on family organizations that persisted despite the change in overarching political and cultural traditions. This demonstrates that small-scale or household camelid husbandry likely occurred on the coast (Szpak et al., 2014) while large-scale camelid herding strategies may have been more common in the highlands. Despite the presence of local camelid husbandry on the coast, the strontium isotope data demonstrate that camelids were an important part of connections between the coast and other higher altitude zones.

Stable carbon and nitrogen isotope data collected from camelids associated with the EIP occupations at Huaca Gallinazo and Huaca Santa Clara were indistinguishable from one another (Szpak et al., 2014). The strontium isotope data demonstrate that despite this similarity, the two sites were characterized by different patterns of geographic origins for these camelids. Furthermore, an alternative explanation for the highly variable $\delta^{13}C$ and $\delta^{15}N$ values for camelids at Huaca Gallinazo would be diverse geographic origins, but the strontium isotope data suggest that all animals originated in the same geographic region. Taken together, these two lines of isotopic evidence can provide insight into both the geographic origin of the camelids and the nature of the animal management practice, specifically related to diet. In the case of butchered camelids, we cannot directly compare the strontium isotope ratios with the stable carbon and nitrogen isotope compositions because the collagen (derived from phalanges) and tooth enamel cannot be confirmed to be from the same individual. However, for the sacrificed camelids, it is possible to compare the strontium isotope ratios to the stable carbon and nitrogen isotope data from bone collagen (Fig. 8). For the sacrificed individuals from Huaca Santa Clara, all individuals have a local strontium isotope signature, yet they have a large range of carbon and nitrogen isotope signatures (Szpak et al., 2014). While the Huancaco camelids had less variation in the carbon and nitrogen isotope values, they had more variation in the strontium isotope ratios. These differences demonstrate that the variation in carbon and nitrogen isotope values is not a good predictor of the diversity of geographic origins.

Previous studies have also included information about people who were buried at Huaca Gallinazo (EIP) and Huaca Santa Clara (EIP and LMH), including their geographic origins (Hyland et al., 2021). The strontium isotope ratios of tooth enamel from M2s and M3s from these individuals were found to be representative of both local and non-local origins in all three contexts (Fig. 9). Burial 2 from the EIP occupation of Huaca Gallinazo as well as burials 4, 5, and 6 from the LMH sacrifice of Huaca Santa Clara included camelids (Dillon, 2015). The sacrificed human burials that included camelid remains were not from one unique region, but instead had isotopic compositions that suggested geographic origins on the coast, the upper valley, and the highlands. Despite predominately local animals, interactions between the coast and other regions were still occurring. These sacrificial burials show that the people at these sites likely came from a much wider geographic range than the camelids would have.

5. Conclusion

Strontium isotope measurements of camelid tooth enamel from the Virú Valley demonstrate that local husbandry of camelids in the lower valley occurred from at least the Early Intermediate Period. Considering the diversity in carbon and nitrogen isotope compositions, these animals had very different diets, despite originating in the same region. This pattern of isotopic variation is consistent with small-scale camelid

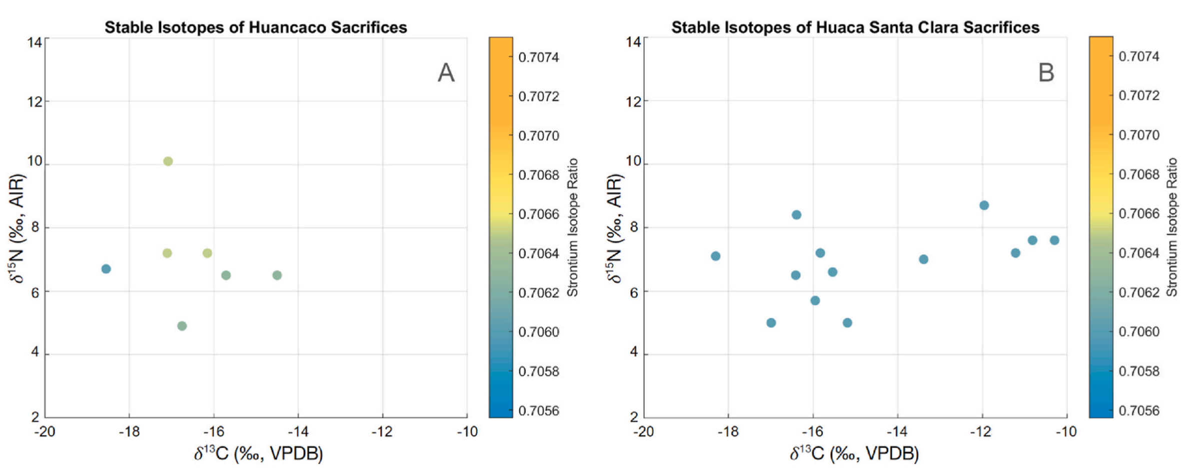

Fig. 8. Stable carbon and nitrogen isotope compositions of sacrificed camelids from Huancaco (Panel A) and Huaca Santa Clara (Panel B) (data from Szpak et al., 2014, 2016b). The color of each data point corresponds to the average strontium isotope ratio. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

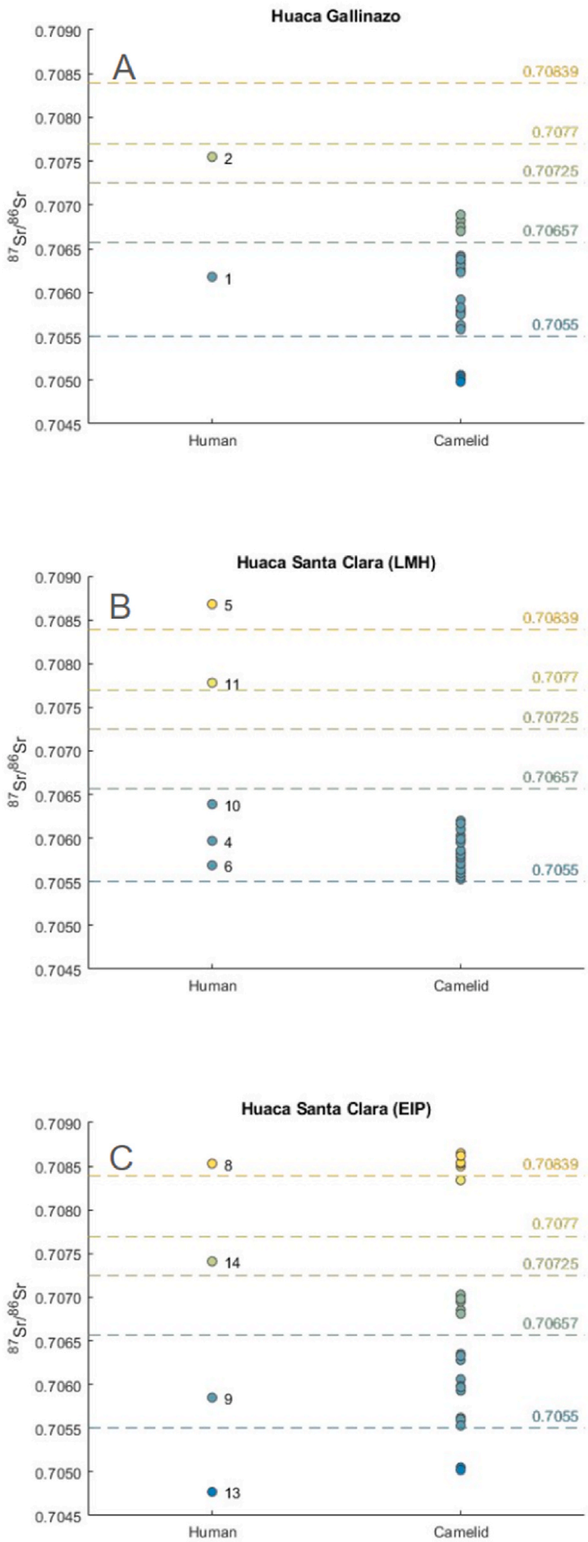

Fig. 9. Strontium isotope signatures of human tooth enamel and camelid tooth enamel from Huaca Gallinazo (Panel A) and Huaca Santa Clara (Panel B and C). Human strontium isotope values were generated by Hyland et al. (2021) The color of each dot corresponds to the colored bands in the Sr isoscape generated by Scaffidi and Knudson (2020). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

husbandry organized around households where different animals are provided with isotopically variable fodder from local agricultural produce. The geographic origins of camelids varied among the three sites and two time periods studied. Camelids with strontium isotope ratios consistent with a non-local origin were.

- Absent at Huaca Gallinazo during the EIP
- Uncommon at Huaca Santa Clara during the EIP
- Abundant at Huancaco during the EIP
- Absent among sacrificed individuals at Huaca Santa Clara in the late Middle Horizon
- Abundant among sacrificed individuals at Huancaco in the late Middle Horizon

Additional systematic studies of strontium isotope camelids from sites throughout the north coast region will provide more insight into the variability in the importance of local camelid husbandry. Expanding these analyses into earlier periods is also necessary to determine when and where these practices may have originated.

CRediT authorship contribution statement

Nicole Hultquist: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Jean-Francois Millaire:** Writing – review & editing, Conceptualization. **Paul Szpak:** Writing – review & editing, Supervision, Resources, Funding acquisition, Formal analysis, Conceptualization.

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.

Acknowledgements

The authors would like to thank Karla Newman at the Trent Water Quality Centre for her technical assistance. This research was supported by the Social Science and Humanities Research Council Canada through an Insight Grant [435-2019-0657].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2024.106142.

References

Bauer, B.S., Covey, R.A., 2002. Processes of state formation in the Inca heartland (Cuzco, Peru). Am. Anthropol. 104 (3), 846–864.
Bennett, W.C., 1950. The Gallinazo Group, Virú Valley, Peru. Yale University Publications in Anthropology.
Benson, E.P., 1972. The Mochica: A Culture of Peru. Praeger Publishers, New York.
Bentley, R.A., 2006. Strontium isotopes from the earth to the archaeological skeleton: a review. J. Archaeol. Method Theor 135–187.
Bonavia, D., 2008. The South American camelids. Translated by Javier Flores Espinoza. Cotsen Institute of Archaeology, Los Angeles.
Bourget, S., 2010. Cultural assignations during the early Intermediate Period: the case of Huancaco, Virú Valley. In: Quilter, J., Castillo, L.J. (Eds.), New Perspectives on Moche Political Organization. Dumbarton Oaks, Washington, D.C., pp. 201–222
Browman, D.L., 1974. Pastoral nomadism in the Andes. Curr. Anthropol. 15 (2), 188–196.
Browman, D.L., 1975. Trade patterns in the central highlands of Peru in the first millennium BC. World Archaeol. 6 (3), 322–329.
Browman, D.L., 1990. High Altitude Camelid Pastoralism of the Andes. Belhaven Press, pp. 323–353.
Cardich, A.R., 1980. Fluctuaciones de los límites superiores del cultivo de los Andes, vol. 14. Relaciones de la Sociedad Argentina de Antropología.
Davis, R., Keeble, E., Wright, A., Morgan, K.L., 1998. South American camelids in the United Kingdom: population statistics, mortality rates and causes of death. Vet. Rec. 142 (7), 162–166.

Dillon, Rebecca A., 2015. Ritual Violence and Times of Transition: A Bioarchaeological Analysis of Burials from Huaca Santa Clara and Huaca Gallinazo in the Virú Valley, Peru. *Electronic Thesis and Dissertation Repository*. 2724.

Donnan, C., 2009. The Gallinazo illusion. In: Millaire, J.-F., Morlion, M. (Eds.), Gallinazo: an Early Cultural Tradition on the Peruvian North Coast. Cotsen Institute of Archaeology Press, Los Angeles, pp. 17–32, 2009.

Driessens, F.C., Verbeeck, R.K., 1990. Biominerals. CRC press.

Dufour, E., Goepfert, N., Le Neün, M., Prieto, G., Verano, J.W., 2018. Life history and origin of the camelids provisioning a mass killing sacrifice during the Chimú Period: insight from stable isotopes. Environ. Archaeol. 25 (3), 310–324.

Ericson, J.E., West, M., Sullivan, C.H., Krueger, H.W., 1989. The development of maize agriculture in the Virú Valley, Peru. The Chemistry of Prehistoric Human Bone. Cambridge University Press, Cambridge, pp. 68–104.

Faure, G., Powell, J.L., 2012. Strontium Isotope Geology, vol. 5. Springer Science & Business Media.

Flannery, K.V., Marcus, J., Reynolds, R.G., 1989. The Flocks of Wamani: A Study of the Llama Herders on the Punas of Ayacucho. Academic Press, Peru. San Diego.

Flores-Ochoa, J.A., 1979. *Pastoralists Of the Andes: The Alpaca Herders of Paratía*. Institute for the Study of Human Issues. Philadelphia.

Franklin, W.L., 1982. Biology, ecology and relationship to man of the South American camelids. In: Mares, M.A., Genoways, H.H. (Eds.), Mammalian Biology in South America. University of Pittsburgh Pymatuning Laboratory of Ecology Special Publication Series VI, Pittsburgh, pp. 457–489.

Fogel, M.L., Cifuentes, L.A., 1993. Isotope fractionation during primary production. In: In Organic Geochemistry. Springer, Boston, MA, pp. 73–98.

Fogel, H.P., 1993. Settlements in Time: A Study of Social and Political Development during the Gallinazo Occupation of the North Coast of Perú. Department of Anthropology. Yale University, New Haven, p. 421.

Frigolé, C., Gasco, A., 2016. Potters and herders at the southern edge of the Andean world: risk management and mobility in Northwestern Mendoza, Argentina. Quat. Int. 422, 152–162.

Goepfert, N., Dufour, E., Prieto, G., Verano, J., 2020. Herds for the gods? Selection criteria and herd management at the mass sacrifice site of Huanchaquito-Las Llamas during the Chimú period, northern coast of Peru. Environ. Archaeol. 25 (3), 296–309.

Hewitt, B.R., 2013. Foreigners Among the Dead at Túcume, Peru: Assessing Residential Mobility Using Isotopic Tracers. The University of Western Ontario (Canada).

Horwitz, E.P., Dietz, M.L., Fisher, D.E., 1991. Separation and preconcentration of strontium from biological, environmental, and nuclear waste samples by extraction chromatography using a crown ether. Anal. Chem. 63 (5), 522–525.

Hoppe, K.A., Koch, P.L., Furutani, T.T., 2003. Assessing the preservation of biogenic strontium in fossil bones and tooth enamel. Int. J. Osteoarchaeol. 13 (1-2), 20–28.

Horn, P., Müller-Sohnius, D., 1999. Comment on mobility of bell beaker people revealed by strontium isotope ratios of tooth and bone: a study of southern Bavarian skeletal remains. Appl. Geochem. 14 (2), 263–270.

Hogg, A.G., Heaton, T.J., Hua, Q., Palmer, J.G., Turney, C.S.M., Southon, J., Bayliss, A., Blackwell, P.G., Boswijk, G., Bronk Ramsey, C., Pearson, C., Petchey, F., Reimer, P., Reimer, R., Wacker, L., 2020. SHCal20 southern hemisphere calibration, 0–55,000 Years cal BP. Radiocarbon 62, 759–778. https://doi.org/10.1017/RDC.2020.59.

Hyland, C., Millaire, J.-F., Szpak, P., 2021. Migration and maize in the Virú Valley: understanding life histories through multi-tissue carbon, nitrogen, sulfur, and strontium isotope analyses. Am. J. Phys. Anthropol. 176 (1), 21–35.

Johns, A.M., 2017. The Richness of Food: a Zooarchaeological Analysis of Huaca Santa Clara and Huaca Gallinazo, North Coast of Peru. *Electronic Thesis and Dissertation Repository*. 4899.

Klerkx, J., Deutsch, S., Pichler, H., Zeil, W., 1977. Strontium isotopic composition and trace element data bearing on the origin of Cenozoic volcanic rocks of the central and southern Andes. J. Volcanol. Geoth. Res. 2 (1), 49–71.

MacGregor, M.H., Wiedenbeck, M.L., 1952. The decay of rubidium 87. Phys. Rev. 86 (3), 420.

Malpass, M.A., 2016. Ancient People of the Andes. Cornell University Press.

Martinez De La Torre, H.A., Reyes, A.V., Zazula, G.D., Froese, D.G., Jensen, B.J.L., Southon, J.R., 2019. Permafrost-preserved wood and bone: radiocarbon blanks from Yukon and Alaska. Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 455, 154–157. https://doi.org/10.1016/j.nimb.2018.12.032.

McGreevy, T.H., 1984. The role of pastoralism in prehispanic and modern huamachuco. Department of Anthropology. Trent University. Peterborough.

Miller, A.V., Fernandes, R., Janzen, A., Nayak, A., Swift, J., Zech, J., Boivin, N., Roberts, P., 2018. Sampling and pretreatment of tooth enamel carbonate for stable carbon and oxygen isotope analysis. J. Vis. Exp. 138.

Millaire, J.-F., Morlion, M. (Eds.), 2009. Gallinazo: an Early Cultural Tradition on the Peruvian North Coast. Cotsen Institute of Archaeology Press, Los Angeles.

Millaire, J.-F., Eastaugh, E., 2011. Ancient urban morphology in the Virú Valley, Peru: remote sensing work at the Gallinazo group (100 BC–AD 700). J. Field Archaeol. 36 (4), 289–297.

Millaire, J.-F., 2010a. Moche political expansionism as viewed from Virú: recent archaeological work in the close periphery of a hegemonic city-state system. New Perspectives on Moche Political Organization 221–249.

Millaire, J.-F., 2010b. Primary state formation in the Virú Valley, north coast of Peru. Proc. Natl. Acad. Sci. USA 107 (14), 6186–6191.

Millaire, J.-F., 2015. The sacred character of ruins on the Peruvian north coast. In: Shimada, Izumi, Fitzsimmons, James L. (Eds.), Living with the Dead in the Andes, edited by. University of Arizona Press, pp. 50–75.

Millaire, J.-F., Prieto, G., Surette, F., et al., 2016. Statecraft and expansionary dynamics: a Virú outpost at Huaca prieta, chicama valley, Peru. Proc. Natl. Acad. Sci. USA 113, 6016–6025.

Murra, J.V., 1965. Herds and herders in the Inca state. In: Leeds, A., Vayda, A.P. (Eds.), Man, Culture, and Animals: the Role of Animals in Human Ecological Adjustments. American Association for the Advancement of Science, Washington, D.C., pp. 185–215

Murra, J.V., 1972. El control vertical de un máximo de pisos ecológicos en la economía de las sociedades andinas. In: Iñigo Ortiz de Zúñiga, *Visita de la Provincia de León de Huánuco en 1562*. Universidad Nacional Hermilo Valdizán, Huánuco, pp. 429–476.

Murra, J.V., 1980. *The Economic Organization Of the Inka State*. CT: JAI, Greenwich.

Murra, J.V., 1985. El archipiélago vertical. In: Masuda, Shozo, Shimada, Izumi, Morris, Craig (Eds.), Ecology and Civilization: an Interdisciplinary Perspective on Andean Ecological Complementarity, edited by. University of Tokyo Press, pp. 3–13.

Nelson, B.K., DeNiro, M.J., Schoeninger, M.J., DePaolo, D.J., Hare, P.E., 1986. Effects of diagenesis on strontium, carbon, nitrogen, and oxygen concentration and isotopic composition of bone. Geochimica et Cosmogeochimica Acta 50, 1941–1949.

Pankhurst, R.J., 1982. Rb-Sr geochronology of graham land, Antarctica. J. Geol. Soc. 139 (6), 701–711.

Pozorski, S.G., 1976. Prehistoric Subsistence Patterns and Site Economics in the Moche. The University of Texas, Valley, Peru. Austin.

Price, T.D., Burton, J.H., Bentley, R.A., 2002. The characterisation of biologically-available strontium isotope ratios for investigation of prehistoric migration. Archaeometry 44, 117–135.

Prieto, G., Verano, J.W., Goepfert, N., Kennett, D., Quilter, J., LeBlanc, S., et al., 2019. A mass sacrifice of children and camelids at the Huanchaquito-Las Llamas site, Moche Valley, Peru. PLoS One 14 (3), e0211691.

Pulgar Vidal, J., 1996. Geografia del Peru: las ocho regiones naturales. PEISA, Lima, Peru.

Rostworowski de Diez Canseco, M., 1970. Mercaderes del Valle de Chincha en la época prehispánica: un documento y unos comentarios. Revista Espa~nnola de Antropologia Americana 5, 135–177.

Salda, L.D., Cingolani, C., Varela, R., 1992. Early paleozoic orogenic belt of the Andes in southwestern south America: result of laurentia-gondwana collision? Geology 20 (7), 617–620.

Shimada, M., Shimada, I., 1985. Prehistoric llama breeding and herding on the north coast of Peru. Am. Antiq. 50 (1), 3–26.

Santana-Sagredo, F., Dufour, E., Goepfert, N., Zazzo, A., Franco Jordán, R., Vásquez Sánchez, S., 2020. New bioarchaeological evidence and radiocarbon dates from the Lambayeque/Sicán culture camelids from the El Brujo complex (northern coast of Peru): Implications for funerary and herd management practices. Environ. Archaeol. 25 (3), 333–352.

Scaffidi, B.K., Knudson, K.J., 2020. An archaeological strontium isoscape for the prehistoric Andes: understanding population mobility through a geostatistical meta-analysis of archaeological 87Sr/86Sr values from humans, animals, and artifacts. J. Archaeol. Sci. 117, 105121.

Strong, W.D., Evans, C., 1952. Cultural Stratigraphy in the Viru Valley Northern Peru. Columbia University Press, New York.

Stuiver, M., Reimer, P.J., 1993. Extended 14C database and revised CALIB 3.0 14C age calibration program. Radiocarbon 35 (1), 215–230.

Szpak, P., Millaire, J.-F., White, C.D., Longstaffe, F.J., 2014. Small scale camelid husbandry on the north coast of Peru (Virú Valley): insight from stable isotope analysis. J. Anthropol. Archaeol. 36, 110–129.

Szpak, P., Millaire, J.-F., White, C.D., Lau, G.F., Surette, F., Longstaffe, F.J., 2015. Origins of prehispanic camelid wool textiles from the north and central coasts of Peru traced by carbon and nitrogen isotopic analyses. Curr. Anthropol. 56 (3), 449–459.

Szpak, P., Chicoine, D., Millaire, J.-F., White, C.D., Parry, R., Longstaffe, F.J., 2016a. Early Horizon camelid management practices in the Nepeña Valley, north-central coast of Peru. Environ. Archaeol. 21 (3), 230–245.

Szpak, P., Millaire, J.-F., White, C.D., Bourget, S., Longstaffe, F.J., Klaus, H.D., 2016b. Life histories of sacrificed camelids from Huancaco (Virú Valley). Reconstructing Sacrifice on the North Coast of Peru: Archaeological Studies of Ritual Violence in the Ancient Andes, pp. 319–341.

Szpak, P., Millaire, J.F., White, C.D., Donnan, C.B., Longstaffe, F.J., 2018. Stable isotope sourcing of wool from textiles at pacatnamú. Archaeometry 60, 612–627. https://doi.org/10.1111/arcm.12342.

Szpak, P., Millaire, J.F., Chapdelaine, C., White, C.D., Longstaffe, F.J., 2020. An integrated isotopic study of early Intermediate Period camelid husbandry in the Santa valley, perú. Environ. Archaeol. 25, 279–295. https://doi.org/10.1080/14614103.2019.1583302.

Thornton, E.K., Defrance, S.D., Krigbaum, J., Williams, P.R., 2011. Isotopic evidence for middle Horizon to 16th century camelid herding in the osmore valley, Peru. Int. J. Osteoarchaeol. 21 (5), 544–567.

Trickett, M.A., Budd, P., Montgomery, J., Evans, J., 2003. An assessment of solubility profiling as a decontamination procedure for the 87Sr/86Sr analysis of archaeological human skeletal tissue. Appl. Geochem. 18 (5), 653–658.

Takigami, M., Uzawa, K., Seki, Y., Chocano, D.M., Yoneda, M., 2020. Isotopic evidence for camelid husbandry during the Formative Period at the Pacopampa site, Peru. Environ. Archaeol. 25 (3), 262–278.

Tomka, S.A., 1992. Vicuñas and llamas: parallels in behavioral ecology and implications for the domestication of andean camelids. Hum. Ecol. 20, 407–433.

Topic, T.L., McGreevy, T.H., Topic, J.R., 1987. A comment on the breeding and herding of llamas and alpacas on the north coast of Peru. Am. Antiq. 832–835.

Troll, C., 1958. Las Culturas Superiores Andinas Y El Medio Geográfico. Publicaciones del Instituto de Geografía, Facultad de Letras, Universidad Nacional Mayor de San Marcos, Lima, Peru.

Willey, G.R., 1953. Prehistoric Settlement Patterns in the Virú Valley, Perú. Smithsonian Institution, Washington, D.C.

West, M., 1981. Agricultural resource use in an Andean coastal ecosystem. Human Ecol. 9, 47–78.

Wheeler, J.C., 1982. Aging llamas and alpacas by their teeth. Llama World 1 (2), 12–17.