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RESEARCH ARTICLE

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Scale of human mobility in the southern Andes (Argentina and Chile): A new framework based on strontium isotopes

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Abstract

Objectives: The goal of this article is to assess the scale of human paleomobility and ecological complementarity between the lowlands and highlands in the southern Andes during the last 2,300 years. By providing isotope results for human bone and teeth samples, we assess a hypothesis of "high residential mobility" suggested on the basis of oxygen isotopes from human remains.

Methods: We develop an isotopic assessment of human mobility in a mountain landscape combining strontium and oxygen isotopes. We analyze bone and teeth samples as an approach to life-history changes in spatial residence. Human samples from the main geological units and periods within the last two millennia are selected.

Results: We present a framework for the analysis of bioavailable strontium based on the combination of the geological data with isotope results for rodent samples. The $^{87}Sr/^{86}Sr$ values from human samples indicate residential stability within geological regions along life history. When comparing strontium and oxygen values for the same human samples, we record a divergent pattern: while $\delta^{18}O$ values for samples from distant regions overlap widely, there are important differences in $^{87}Sr/^{86}Sr$ values.

Conclusions: Despite the large socio-economic changes recorded, $^{87}Sr/^{86}Sr$ values indicate a persisting scenario of low systematic mobility between the different geological regions. Our results suggest that strontium isotope values provide the most germane means to track patterns of human occupation of distinct regions in complex geological landscapes, offering a much higher spatial resolution than oxygen isotopes in the southern Andes.

KEYWORDS
geology and bioavailable strontium, human life history, scale of human paleomobility, southern Andes, Trans-Andean interaction

1 | INTRODUCTION

Characterizing human tissues with strontium and oxygen isotopes has made a greater range of historical issues archeologically visible (Borić & Price, 2013; Copeland et al., 2016). These isotopic markers make it possible to assess place of origin, spatial scale of mobility, and migrations, within the interdisciplinary framework of human life histories (Kaplan, Hill, Lancaster, & Hurtado, 2000; Knudson & Torres-Rouff, 2014). Radiogenic strontium isotope values ($^{87}Sr/^{86}Sr$) vary according to bedrock age and initial rock composition, and can be used to determine the geographic sources of dietary strontium, and hence paleomobility (Bentley, 2006; Ericson, 1985; Faure, 1986; Grimstead, Nugent, & Whipple, 2017). Oxygen isotope values in water sources respond to a number of environmental factors including altitude, precipitation patterns, latitude, and temperature. They track the oxygen isotope signatures of the drinking water consumed by humans in the past (Bowen & Wilkinson, 2002; Craig, 1961; Pellegrini, Pouncett, Jay, Parker Pearson, & Richards, 2016; Sponheimer & Lee-Thorp, 1999).

The south-central Andes -southern Peru, western Bolivia, and northern Chile (16°–23°S)-, placed at the core of processes of animal and plant domestication and socio-political complexity during the last 3,000 years (Stanish, 2003), have been one of the hot spots in the development of this isotopic approach (Knudson, Goldstein, Dahlstedt, Somerville, & Schoeninger, 2014; Santana-Sagredo, Uribe, Herrera, Retamal, & Flores, 2015). In this article, we extend this approach southwards to a latitudinal band around 32° to 34°S in the southern Andes of Argentina and Chile (Fig. 1), seeking to assess a hypothesis of "high residential mobility" previously suggested on the basis of oxygen isotopes (Ugan et al., 2012). We present the first analysis for rodent and human bone and teeth remains directly dated to 2,300–300 years BP. In the future, this will contribute for the development of a comparative Andean approach.

Biogeographically, this latitudinal band of the Andes has the highest average altitude separating the Pacific and Atlantic slopes. In combination with climate patterns (Garreaud, 2009), topography dictates that areas located above 2,500 masl should be inhabitable mostly during the summer months, which in turn conditions patterns of trans-Andean human movement and interaction (Cornejo & Sanhueza, 2011). In this context of strong topographic variation, the goal of this article is *to assess the scale of paleomobility and ecological complementarity between the lowlands and highlands in both Andean slopes*. Was there a systematic connection between the eastern lowlands and the Andean highlands? From which side of the Andes were the highlands most often accessed? Considering that the structure of the landscape and socio-economic organization during the late Holocene displayed remarkable differences on both slopes, these questions are essential to

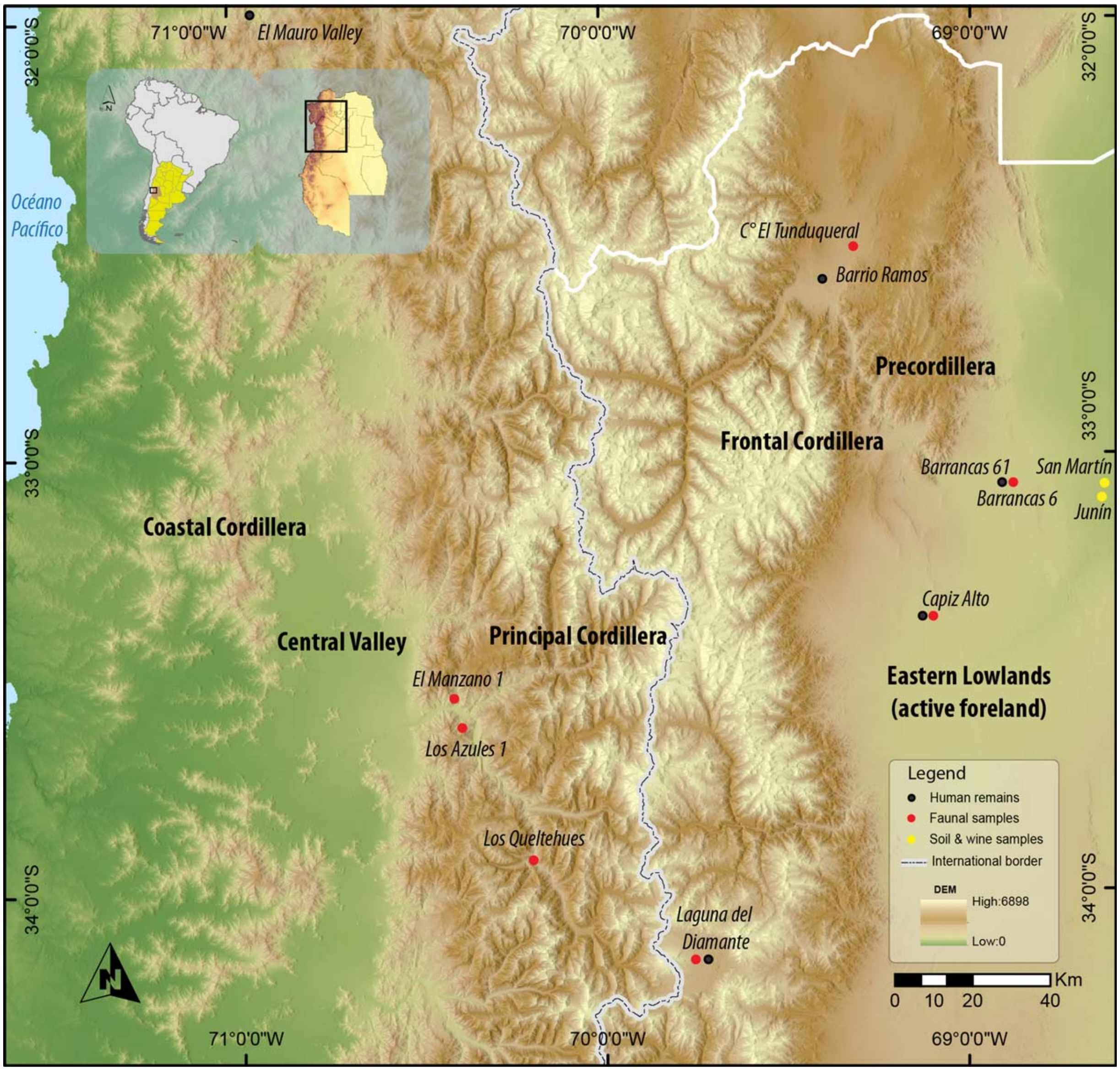

FIGURE 1 Study area and location of samples

understand the role of the highlands within wider social networks. Isotopic information from human remains provides the most direct means to advance our understanding of the spatial scale of human societies, particularly if combined with independent archeological studies such as obsidian sourcing and ceramic styles (Durán et al., 2017).

The specific goals of this article are: (a) to produce a geology-based regional map that provides a deductive framework for the characterization of bioavailable strontium (Price, Burton, & Bentley, 2002); (b) to compare results obtained from humans and faunal remains from the same locations to assess fidelity of humans to the local signatures defined on a preliminary basis; c) to compare bone and teeth values from the same individuals to explore life-history changes. On this basis, we will consider inter-regional variation, scale of paleomobility, and residential stability throughout life.

In the discussion, we integrate our results for strontium and oxygen isotopes with a wider database published for central Argentina and Chile (Gil, Neme, Ugan, & Tykot, 2014a; Gómez & Pacheco, 2016; Sanhueza & Falabella, 2010). We assess the spatial resolution provided by different isotopic markers and their capacity to track human mobility. In particular, we reevaluate the hypothesis of "high residential mobility" based on oxygen isotopes (Ugan et al., 2012) in light of our strontium data.

2 | BACKGROUND: GEOLOGY, ECOLOGY, AND ARCHEOLOGY

2.1 | Geology and ecology of the southern Andes of Argentina and Chile

The southern Andes of Argentina and Chile is a mountain belt formed at the convergent plate margin between the Nazca and South American plates. The study area is located in the transition zone between the "Pampean flat slab," a shallow subduction angle resulting in a volcanic gap between 27° and 33°S, and the normal subduction zone of central Chile and Argentina (Ramos & Folguera, 2009). This segment with normal subduction along 33° represents the northernmost active volcanism of the Southern Volcanic Zone. Between 32° and 34°S, the Andes comprise six major morpho-structural provinces (see units in Fig. 2), which are from west to east as follows: (1) Coastal Cordillera; (2) Central Depression -or Central Chilean Valley-; (3) Principal Cordillera (>6,000 masl); (4) Frontal Cordillera (6,000–5,000 masl), (5) Precordillera (north of 33°, <3,500 masl), and (6) the active foreland (south of 33°S). These macro geological units provide our basic framework for the analysis of bioavailable strontium.

The Coastal Cordillera (unit 1) has a Paleozoic-Triassic basement in the west and Jurassic-Cretaceous clastic and volcanoclastic intra-arc sequences in the east. These units extend to the western and middle Central Depression and are intruded by Upper Cretaceous igneous rocks of dioritic to monzodioritic composition. From the eastern flank of the Central Depression to the central Principal Cordillera of Chile, an extensional basin developed since late Eocene-Oligocene times (unit 2). This basin was filled by volcanic and volcanoclastic rocks (Charrier et al., 2002). During the early to mid-Miocene, calc-alkaline andesitic lava and acid pyroclastic flows of the Farellones Formation were deposited in the central part of the basin (Kurtz, Kay, Charrier, & Farrar, 1997).

The central and eastern zones of the Principal Cordillera (unit 3) in Argentina consist of sedimentary back-arc sequences and subordinated volcanoclastic rocks. The Jurassic to middle Cretaceous sedimentary rocks consist of marine evaporites, sandstones, claystones, and limestones, unconformably overlain by upper Cretaceous rocks (Giambiagi, Alvarez, Godoy, & Ramos, 2003; Uliana, Biddle, & Cerdán, 1989). The youngest geological units of the Cordillera Principal correspond to the active arc magmatism represented by Pliocene to Quaternary stratovolcanoes such as the Tupungato and Maipo.

The Frontal Cordillera (unit 4) has a Proterozoic-Triassic basement, which was strongly deformed by two orogenic episodes during the Mesozoic and uplifted by high angle-inverted faults during the late Miocene. This basement consists of a Precambrian igneous-metamorphic complex, lower Paleozoic sedimentary rocks intruded by Paleozoic calc-alkaline granitoids, upper Paleozoic sedimentary rocks that extend to the Precordillera of Mendoza (unit 5), and Permian-Triassic intermediate to acid volcanic and intrusive rocks. Finally, late Cenozoic foreland clastic deposits (unit 6) occur to the east of the Frontal Cordillera and reflect the progressive erosion of the Andes.

In this diverse geological setting, ecology and climate also vary strongly. Large-scale climate patterns are related to major atmospheric circulation patterns. The interaction of two large climatic systems that control precipitations, the tropical easterlies, and the southern Westerlies, and the orographic rain-shadow effect of the Andes, result in the major climatic and biogeographic areas on both sides of the Andes (Abraham et al., 2009; Muñoz-Schick, Moreira-Muñoz, Villagrán, & Luebert, 2000). Overall, the Andean highlands are characterized by large amounts of precipitation, which occurs mostly in winter as a result of the Pacific anticyclone (Garreaud, 2009). Despite rugged topography, the highlands offer localized wetlands and high quality pastures that attract camelid and bird communities seasonally. Laguna del Diamante, included in this article, offers one such example (Puig, Rosi, Videla, & Méndez, 2011). As altitude decreases, ecosystems become increasingly dry on both sides of the Andes.

Very dry summer seasons characterize the Pacific-dominated western slope. The combined variation in precipitation and temperature produces a succession of vegetation communities by altitude: open scrubland (1,000–1,500 masl), sub-Andean and Andean scrubland (1,500–2,700 masl), Andean steppe (2,700–3,300 masl), and Andean desert (>3,300 masl). These communities are dominated by shrubs in the lowlands and by an increase in the herbaceous stratum up to 3,300 masl (Muñoz-Schick et al., 2000). The eastern slope is also characterized by a progressive decrease in precipitation with decreasing altitude produced by the rain-shadow effect (Garreaud, 2009). As the influence of the Pacific anticyclone decreases eastwards, the influence of summer precipitation brought about by the Atlantic anticyclone increases (Garreaud, 2009). Andean steppe and scrubland associated to the Patagonia phytogeographical province (3,300–1,400 masl) are followed to the east by the dry scrublands of the Monte phytogeographical province (Abraham et al., 2009).

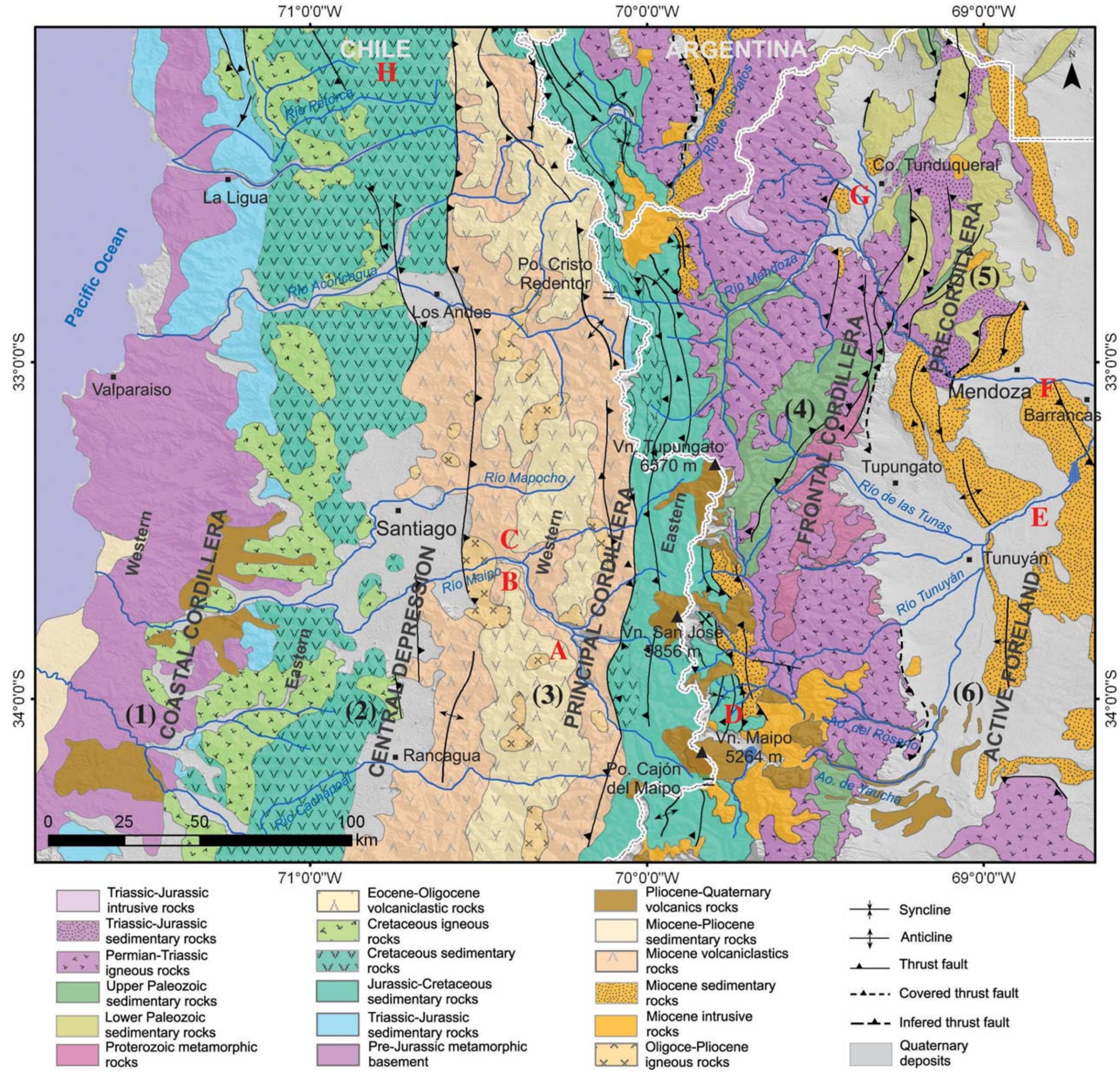

FIGURE 2 Main geological units and location of the samples. References: A. Los Queltehues (rodent); B. Los Azules 1 (rodent); C. El Manzano 1 (rodent); D. Laguna del Diamante (rodent and humans); E. Capiz Alto (rodent and humans); F. Barrancas (rodent and humans); G. Uspallata (rodent and humans); H. El Mauro (humans)

2.2 | Archeology of central western Argentina and central Chile: Main trends

Humans have occupied the coastal and mountain environments of central Chile and central-western Argentina since the late Pleistocene (García, 2003; Méndez & Jackson, 2015). For most of the Holocene, mobile foraging was the dominant way of life, documented by a variety of hunting weapon systems, the consumption of diverse plant and animal taxa, including algarrobo (*Prosopis* sp.) and the region's top-ranked prey, the guanaco (*Lama guanicoe*) (Bárcena, 2001; Cortegoso, 2006; Frigolé & Gasco, 2016; Llano, 2015). By the early late Holocene, foragers had access to domestic plants such as quinoa (*Chenopodium* spp.), beans (*Phaseolus vulgaris*), and squash (*Cucurbita* spp.) (Gambier, 1988; Planella, Scherson, & McRostie, 2011). However, there is still debate on the reliability of these early contexts and dates, and whether they represent incipient agriculture, horticulture, or exchange, and to what degree they are associated with reduced mobility (Bárcena, 2001; Gil, 1997, 1998).

There are indications of a major regional shift in human adaptations and practices starting before 2,000 years BP. First, domestic plants became a clear component of the material record, including maize (*Zea mays*) (Gil, Tykot, Neme, & Shelnut, 2006; Lagiglia, 2001). Second, the earliest pottery appeared (Sanhueza & Falabella, 2000). Third, there seems to be the beginning of a demographic increase that becomes much clearer in the following centuries. Fourth, burial practices became more elaborate (Novellino et al., 2013) and there are many more burials dated to these centuries. This macro change in practices may be part of novel responses to increased environmental

TABLE 1 Elemental and isotopic data from modern and archaeological faunal remains

Locality	Landscape unit	Geological setting	Site	Material	Sample	Lab code	Ca/P	U/Ca	$^{87}Sr/^{86}Sr$
San Carlos (Argentina)	Eastern foreland (6)	Quaternary sediments	COINCE	Dasypodidae sp. (modern)	bone	ACL-5425	1.9	1.25E-08	0.70732
Laguna del Diamante (Argentina)	Frontal cordillera (4)	Jurassic-Cretaceous	Gendarmería	Rodentia (modern)	bones	ACL-5426	NA	2.88E-07	0.70655
Barrancas (Argentina)	Eastern foreland (6)	Quaternary sediments	B.61	Rodentia (archaeological)	bones	ACL-5427	2.1	6.01E-06	0.70666
Uspallata (Argentina)	Precordillera-Frontal cordillera (5, 6)	Lower Paleozoic sediments/ Permo-Triassic volcanic	Cerro Tunduqueral. Alero 1	*Ctenomys* sp. (archaeological)	bones	ACL-5428	2.0	5.24E-07	0.70864
Maipo Basin (Chile)	Principal cordillera (2)	Miocene volcaniclastic	Los Azules 1	Rodentia (archaeological)	bone	ACL-5429	1.9	4.59E-07	0.70393
Maipo Basin (Chile)	Principal cordillera (2)	Miocene volcaniclastic	Manzano 1	Rodentia (archaeological)	bone	ACL-5430	1.9	1.43E-07	0.70396
Upper Maipo basin (Chile)	Principal cordillera (2)	Miocene volcaniclastic	Los Queltehues	Rodentia (archaeological)	bone	ACL-5431	2.0	9.62E-06	0.70401

instability as ENSO activity became more intense at this time (Rein et al., 2005). Data on this shift remain sparse and may not have affected all groups living in the region. However, taken together, this evidence marks an enduring change from previous practices and foreshadows ensuing developments.

Beginning around 1,500 years BP, previous trends became much more pronounced and widespread. By this time, most sites include a range of domestic plants and at some sites there were multiple varieties of maize (Bárcena, 2001; Cortegoso, 2006). Variable intensities of maize consumption may have been linked to climatic changes (Gil et al., 2014b). Changes in cranio-facial morphology suggest a population replacement or migration during this period (Menéndez et al., 2014). Ground stone became more commonly used and, in some areas, people built and used agricultural fields, canal-fed circular basins with raised borders (Gambier, 1988). Domestic camelids were now present in the faunal record of multiple sites (Gasco, 2013). Camelids were part of the region's engraved rock art repertoire, most of which is attributed to this period and is found at numerous sites (Schobinger, 2009; Troncoso, 2012). People made much larger ceramic vessels and decorated pottery; there were different styles in different regions that were sometimes exchanged. Mobility may have been significantly reduced as people built thatched pit houses in similar styles at multiple sites (Cortegoso, 2006). For at least a millennium, people had an agropastoral lifeway that included farming, herding, hunting, and gathering. It was a resilient subsistence strategy that persisted because it effectively mitigated risk from environmental instability. The Inca Empire arrived from the north at around 550 BP, but its impact was not pronounced (Raffino & Stehberg, 1999). At Spanish contact, population density and social complexity was relatively low compared to other areas of the Andes.

3 | MATERIALS AND METHODS

3.1 | Sample selection and archeological contexts

The sample analyzed is composed of seven rodent samples from four localities in Argentina and three localities in Chile (Fig. 1, Table 1) and 18 human bone and teeth samples from nine individuals that were sampled in duplicate to assess life history changes in enamel and bone that formed at different times (Table 2). The human and rodent samples were identified to taxon using reference collections. The rodent samples from the western slope of the Andes (Chile) come from Los Azules (2,000 masl), Los Queltehues (1,900 masl), and El Manzano 1 (1,020 masl), while those from the eastern slope (Argentina) come from Laguna del Diamante (3,300 masl), Cerro Tunduqueral-Uspallata (2,000 masl), COINCE-San Carlos (920 masl), and Barrancas (760 masl) (Fig. 1). The human samples come from four archeological sites in Mendoza Province. They were selected so they would cover the altitudinal range of the Andes from the eastern lowlands to the Andean highlands (Fig. 1). They were also selected to include contexts distributed along the last 2,300 calibrated years, which is a key period of subsistence and mobility change in the macro-region. These samples allow a first exploration of spatial and temporal variation in human paleomobility, including changes between childhood and adulthood.

The site B6 in Barrancas is located in the eastern lowlands (760 masl). It includes the earliest sample directly dated to 2,350–2,090 cal years BP (individual B19). Another similar date from an adjacent skeleton confirmed the date of the context (Fig. 3). The site is a cemetery with a minimum number of 33 individuals deposited in primary and secondary burials (Novellino et al., 2013). Carbon and nitrogen isotope studies indicate diets based on wild resources with animal protein

TABLE 2 Contextual and isotope data for archaeological human remains from Mendoza Province (Argentina).

Locality and landscape unit	Geological setting	Site and individual	Element (+)	Sex	Age	Violence	^{14}C date	Cal. date BP (95%)	Lab code	Ca/P	U/Ca	^{87}Sr/^{86}Sr	δ^{18}O$_{carb}$ (VPDB)	δ^{18}O dw$_{(SMOW)}$ (1)	δ^{18}O dw$_{(SMOW)}$ (2)
Uspallata (eastern valleys)	Paleozoic sediments/ Permo-Triassic volcanic	Barrio Ramos/2	LC (0.3–7 years)	M	40–50	cranial trauma	583 ± 43* (AA-98708)	640–500	ACL-5436	2.0	5.24E-07	0.70901	−6.6	−9.7	−10.3
Uspallata (eastern valleys)	Paleozoic sediments/ Permo-Triassic volcanic	Barrio Ramos/ 2	rib	M	40–50	cranial trauma	583 ± 43*	640–500	ACL-5437	1.9	1.12E-07	0.70953	−9.6	−13.6	−15.2
Uspallata (eastern valleys)	Paleozoic sediments/ Permo-Triassic volcanic	Barrio Ramos/3	LI2 (0.8–5 years)	F	>40	-	583 ± 43 #	640–500	ACL-5438	2.0	2.14E-07	0.70865	−6.7	−9.8	−10.4
Uspallata (eastern valleys)	Paleozoic sediments/ Permo-Triassic volcanic	Barrio Ramos/3	rib	F	>40	-	583 ± 43 #	640–500	ACL-5439	2.1	4.84E-08	0.70922	−8.3	−11.9	−13.1
Barrancas (eastern lowlands)	Quaternary sediments	B.6/19	LI2 (0.8–5 years)	M	>45	projectile in sternum	2251 ± 49* (AA-98707)	2350–2090	ACL-5440	1.9	1.24E-06	0.70754	−2.9	−4.9	−4.2
Barrancas (eastern lowlands)	Quaternary sediments	B.6 /19	rib	M	>45	projectile in sternum	2251 ± 49*	2350–2090	ACL-5441	2.1	6.15E-05	0.70665	−8.7	−12.4	−13.7
Barrancas (eastern lowlands)	Quaternary sediments	B.6/25	PM1 (1.5–6 years)	M	35–40	-	2251 ± 49 #	2350–2090	ACL-5442	1.9	1.46E-06	0.70697	−6.8	−10	−10.6
Barrancas (eastern lowlands)	Quaternary sediments	B.6/25	rib	M	35–40	-	2251 ± 49 #	2350–2090	ACL-5443	2.1	7.13E-05	0.70661	−11.2	−15.7	−17.8
San Carlos (eastern lowlands)	Quaternary sediments	Cápiz Alto/2	PM2 (2–7 years)	F	40–45	-	246 ± 44* (AA-101145)	440-Modern	ACL-5444	1.9	2.54E-08	0.70709	−5.8	−8.7	−8.9
San Carlos (eastern lowlands)	Quaternary sediments	Cápiz Alto/2	rib	F	40–45	-	246 ± 44*	440-Modern	ACL-5445	1.9	1.83E-07	0.70724	−8.6	−12.3	−12.6
San Carlos (eastern lowlands)	Quaternary sediments	Cápiz Alto/6	M1 (0–3 years)	M	35–45	-	423 ± 41* (AA-101146)	510–320	ACL-5446	1.9	1.22E-08	0.70807	−7.1	−10.3	−11.1
San Carlos (eastern lowlands)	Quaternary sediments	Cápiz Alto/6	rib	M	35–45	-	423 ± 41*	510–320	ACL-5447	2.0	3.66E-06	0.70731	−11.2	−15.7	−17.8
San Carlos (eastern lowlands)	Quaternary sediments	Cápiz Alto/18	UC (0.3–7 years)	M	45–49	-	423 ± 41 #	510–320	ACL-5448	1.9	2.49E-08	0.70795	−6.0	−8.9	−9.3
San Carlos (eastern lowlands)	Quaternary sediments	Cápiz Alto/18	rib	M	45–49	-	423 ± 41 #	510–320	ACL-5449	1.9	5.01E-08	0.70748	−10.4	−14.6	−16.5

(Continues)

TABLE 2 (Continued)

Locality and landscape unit	Geological setting	Site and individual	Element (+)	Sex	Age	Violence	^{14}C date	Cal. date BP (95%)	Lab code	Ca/P	U/Ca	$^{87}Sr/^{86}Sr$	$\delta^{18}O_{carb}$ (VPDB)	$\delta^{18}O$ dw(SMOW) (1)	$\delta^{18}O$ dw(SMOW) (2)
Laguna del Diamante (highlands)	Jurassic-Cretaceous sedimentary	LDS 13 / 1	LC (0.3–7 years)	ND	35–49	-	1561 ± 44 #	1520–1310	ACL-5432	1.8	3.43E-08	0.70497	−7.1	−10.3	−11.1
Laguna del Diamante (highlands)	Jurassic-Cretaceous sedimentary	LDS 13 / 1	maxilla	ND	35–49	-	1561 ± 44 #	1520–1310	ACL-5433	1.8	3.73E-08	0.70545	−8.7	−12.4	−13.7
Laguna del Diamante (highlands)	Jurassic-Cretaceous sedimentary	LDS 13 / 2	PM2 (2–7 years)	ND	35–49	-	1561 ± 44* (AA-103146)	1520–1310	ACL-5434	1.8	1.65E-08	0.70556	−6.4	−9.4	−9.9
Laguna del Diamante (highlands)	Jurassic-Cretaceous sedimentary	LDS 13 / 2	maxilla	ND	35–49	-	1561 ± 44*	1520–1310	ACL-5435	1.8	6.79E-08	0.70554	−9.3	−13.2	−14.7

Reference: +. age range of tooth mineralization (Hillson, 2005); *. direct date on the human remains; #. date based on contextual association; (1) following equations in Knudson (2009); (2) following equation 6 in Chenery et al. (2012).

figuring prominently (Gil et al., 2014b). Teeth and bone samples from two individuals were analyzed. Individual B19 was an adult male (>45 years) whose skeleton included a projectile point lodged in a vertebra, which would have been the cause of death. The second sample from this site was from individual B25, who was also an adult male (35–40 years).

Laguna del Diamante 13 site is a double burial in a small rock shelter formed by two large boulders. One of the individuals was dated to 1,520–1,310 cal years BP (Durán et al., 2017). This site is located in a wetland environment in the Andean highlands (3,300 masl) that is only available for human use and circulation during the summer months, making it a key spot to test seasonal paleomobility. This highland locality presents two chemically distinct obsidian sources that have been used to trace mobility (Cortegoso, Barberena, Durán, & Lucero, 2016). Bones and teeth from both individuals were sampled.

Barrio Ramos site is located in the Uspallata inter-mountain valley (1,900 masl). One of the individuals was directly dated to 640–500 cal years BP (Gil et al., 2014b). This individual died during the Inca occupation of the valley or perhaps slightly before (Marsh, Kidd, Ogburn, & Durán, 2017). The burial is composed of six individuals of different ages deposited in an unknown number of events (Bárcena, 1998). These were agro-pastoral societies in which maize may have been an important staple, though there is inter-individual variation (Gil et al., 2014b; cf. Bernal, González, Gordón, & Pérez, 2016). There were grave goods as well as evidence of violent trauma to the cranium of individual 2. We sampled bone and teeth for two individuals.

Finally, Capiz Alto site is a multiple burial with a minimum number of 20 individuals located in the eastern lowlands (925 masl). The context dates to the 16–17th centuries, based on the ceramics, metal artifacts, and radiocarbon dates of bones from individuals 2 and 6 (510–320 and 440–modern cal years BP, respectively; Fig. 4). This was the period of contact between the indigenous Huarpe communities and Spanish colonies (Durán & Novellino, 2003). The local societies experienced a dramatic demographic collapse due to European diseases and forced resettlement over the Andes to Central Chile. We analyzed bone and teeth samples for three individuals.

3.2 | Methods

The samples were processed at the Archeological Chemistry Laboratory in the School of Human Evolution and Social Change, Arizona State University. The outermost layers were removed, since they are the most susceptible to diagenetic contamination (Budd, Montgomery, Barreiro, & Thomas, 2000). Strontium isotope sample preparation and analysis were performed at the W.M. Keck Foundation Laboratory for Environmental Biogeochemistry at Arizona State University. The strontium was separated from the sample matrix using EiChrom SrSpec resin based on published methodologies (Knudson & Price, 2007). The enamel samples were analyzed with the Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS). On June 4, 2015, strontium carbonate standard SRM-987 yielded a value of $^{87}Sr/^{86}Sr = 0.710263 \pm 0.000019$ (2σ, $n = 15$). These values agree with analyses of SRM-987 using a thermal ionization mass

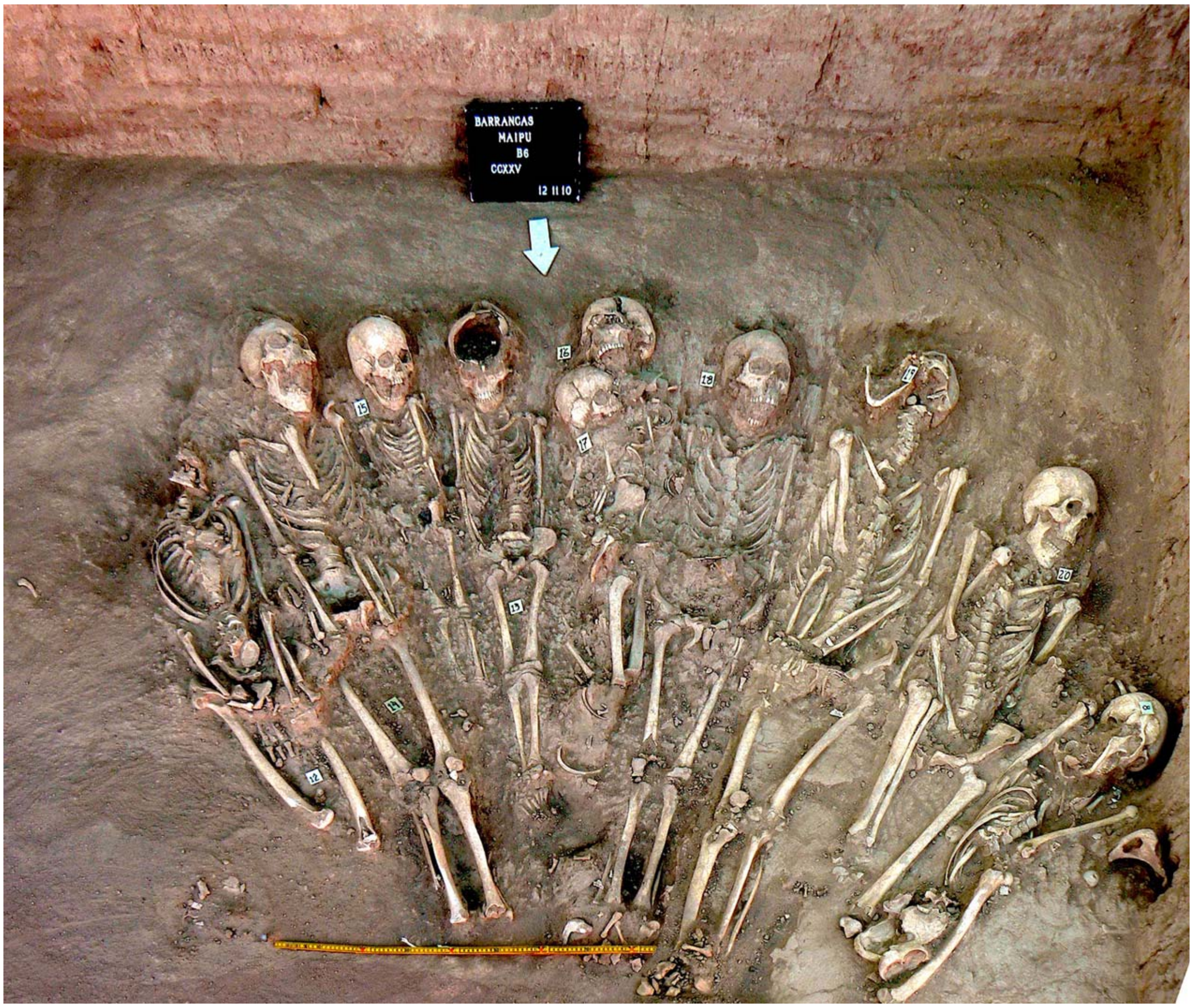

FIGURE 3 Partial view of the cemetery in Barrancas, site B6 (credit: Diego Estrella). Note: individual B18 is the third from the right. Individual B25 is not pictured here; it is located slightly to the west of the photo

spectrometer, where $^{87}Sr/^{86}Sr = 0.710263 \pm 0.000016$ (2σ) (Stein et al., 1997), and analyses of SRM-987 using an identical MC-ICP-MS, where $^{87}Sr/^{86}Sr = 0.710251 \pm 0.000006$ (2σ) (Balcaen, Schrijver, Moens, & Vanhaecke, 2005). For the analysis of elemental concentration, ten milligrams of tooth enamel powder or chemically cleaned bone ash were dissolved in 0.64 mL of 5 M HNO_3, and diluted with 9.36 mL of Millipore H_2O. Internal standards CUE-0001 exhibited mean $Ca/P = 2.06 \pm 0.07$ (1σ, $n = 10$) and $Ba/Sr = 0.45 \pm 0.02$ (1σ, $n = 10$). Bone carbonate standard NIST-1400 exhibited mean $Ca/P = 2.25 \pm 0.04$ (1σ, $n = 9$) and $Ba/Sr = 0.97 \pm 0.02$ (1σ, $n = 9$). Sample concentrations were analyzed by a Thermo Scientific iCAP Qc quadrupole ICPMS with a 100 microliter per minute nebulizer and a Peltier cooler. Internal standards CUE-0001 exhibited mean $Ca/P = 1.88 \pm 0.05$ (2σ, $n = 8$) and $U/Ca = 1.3 \times 10{-}07 \pm 3.2 \times 10{-}07$ (2σ, $n = 8$). Bone carbonate standard NIST-1400 exhibited mean $Ca/P = 1.82 \pm 0.04$ (2σ, $n = 8$) and $U/Ca = 1.9 \times 10{-}07 \pm 2.0 \times 10{-}08$ (2σ, $n = 8$).

Sample preparation for oxygen isotope analysis of archeological hydroxyapatite carbonate ($\delta^{18}O_{carbonate}$) followed Koch, Tuross, and Fogel (1997). Samples prepared at ASU were then analyzed at the Colorado Plateau Stable Isotope Laboratory at Northern Arizona University, using a Delta V Advantage isotope ratio MS equipped with a Gas Bench II. International standards NBS-18 and NBS-19 were used to create the calibration curve. External and internal laboratory standards (NBS-18, NBS-19, Joplin calcite, and an internal laboratory calcium carbonate [$CaCO_3$] standard) were reproducible within ±0.2‰ for $\delta^{18}O_{carbonate(VPDB)}$. Accuracy was within ±0.2‰ for $\delta^{18}O_{carbonate(VPDB)}$. Analyses of working standard Joplin calcite yielded a value of mean $\delta^{18}O_{carbonate(VPDB)} = -23.41 \pm 0.19‰$ ($n = 19$, 1σ); long-term reproducibility of Joplin CC at the Colorado Plateau Stable Isotope Laboratory is ±0.16‰ for $\delta^{18}O$. In addition, mean $\delta^{18}O_{carbonate(VPDB)} = -13.01 \pm 0.14‰$ ($n = 19$, 1σ) for an internal laboratory $CaCO_3$ standard at the Colorado Plateau Stable Isotope Laboratory. Oxygen isotope ratios are reported relative to the V-PDB carbonate standard and are expressed in parts per mil (‰). The values of $\delta^{18}O_{carbonate(VPDB)}$ were utilized to calculate the average value of drinking water ($\delta^{18}O_{dw}$) following the alternative regression equations detailed by Knudson (2009) and Chenery, Pashley, Lamb, Sloane, and Evans (2012). However, it must be considered that the best procedures for the reconstruction of

FIGURE 4 Capiz Alto site: (a) grave goods associated with burial 4 (bronze head adornment, ceramic bowl, and beads on marine snail beads); (b) burial 2

drinking water values are still subject of debate (Chenery et al., 2012; Pollard, Pellegrini, & Lee-Thorp, 2011).

4 | RESULTS

4.1 | Bioavailable strontium: A preliminary framework integrating geology and ecology

We processed seven rodent samples from Argentina and Chile for $^{87}Sr/^{86}Sr$ values (Table 1, Fig. 1). While we recognize that this is a small sample, each rodent incorporates bioavailable strontium from a wider area and is a proxy for spatial variation in bioavailable strontium. When utilized in combination with the geological background, these values allow building a preliminary framework that will be improved in forthcoming research. Element concentration data were analyzed for the faunal bone samples. In biogenic bone, $Ca/P = 2.1$. For all the faunal samples analyzed, Ca/P values range from $Ca/P = 1.9$ to 2.1 (Table 1). Another way to identify and monitor diagenetic contamination in archeological samples is to examine the amount of uranium present. Here, U/Ca values for enamel and bone are consistent with little diagenetic contamination in all the faunal samples (Table 1).

Two of the rodent samples come from the lowlands of the eastern foreland (Quaternary sediments), one from inter-mountain valleys in the eastern slope (Paleozoic and Mesozoic rocks associated to the Frontal Cordillera and Precordillera units), one from the Frontal cordillera in the highlands (Cretaceous-Permian), and three from inter-mountain valleys in the western slope associated to the Principal cordillera unit (Miocene volcaniclastic setting). There are interesting differences between the values recovered from these different geological regions. The western inter-mountain valleys (Chile) present the lowest radiogenic strontium isotope values with a very small dispersion: mean $^{87}Sr/^{86}Sr = 0.70396 \pm 0.00004$. Their geological setting corresponds to volcaniclastic rocks of Tertiary age from the Miocene and Eocene/Oligocene (Fig. 2). The sample from the Andean highlands comes from a Jurassic-Cretaceous setting and presents a value of $^{87}Sr/^{86}Sr = 0.70655$. The eastern inter-mountain valleys (Argentina) are delimited by the Cordillera Frontal to the west, composed of Lower Paleozoic and Permo-Triasic rocks, and the Precodillera to the east, composed of Lower Paleozoic sedimentary rocks (Fig. 2). All of these rocks, and those associated with the Precodillera in particular, are characterized by high $^{87}Sr/^{86}Sr$ values with an average of $^{87}Sr/^{86}Sr = 0.70937 \pm 0.00024$ ($n = 10$) (Naipauer, Cingolani, Valencio, Chemale, & Vujovich, 2005). Accordingly, the faunal sample from this valley had the highest $^{87}Sr/^{86}Sr$ value $= 0.70864$. Finally, the two rodent samples from the eastern lowlands that are associated with Quaternary sediments derived from the Andean mountain range display values of $^{87}Sr/^{86}Sr = 0.70666$ and 0.70732.

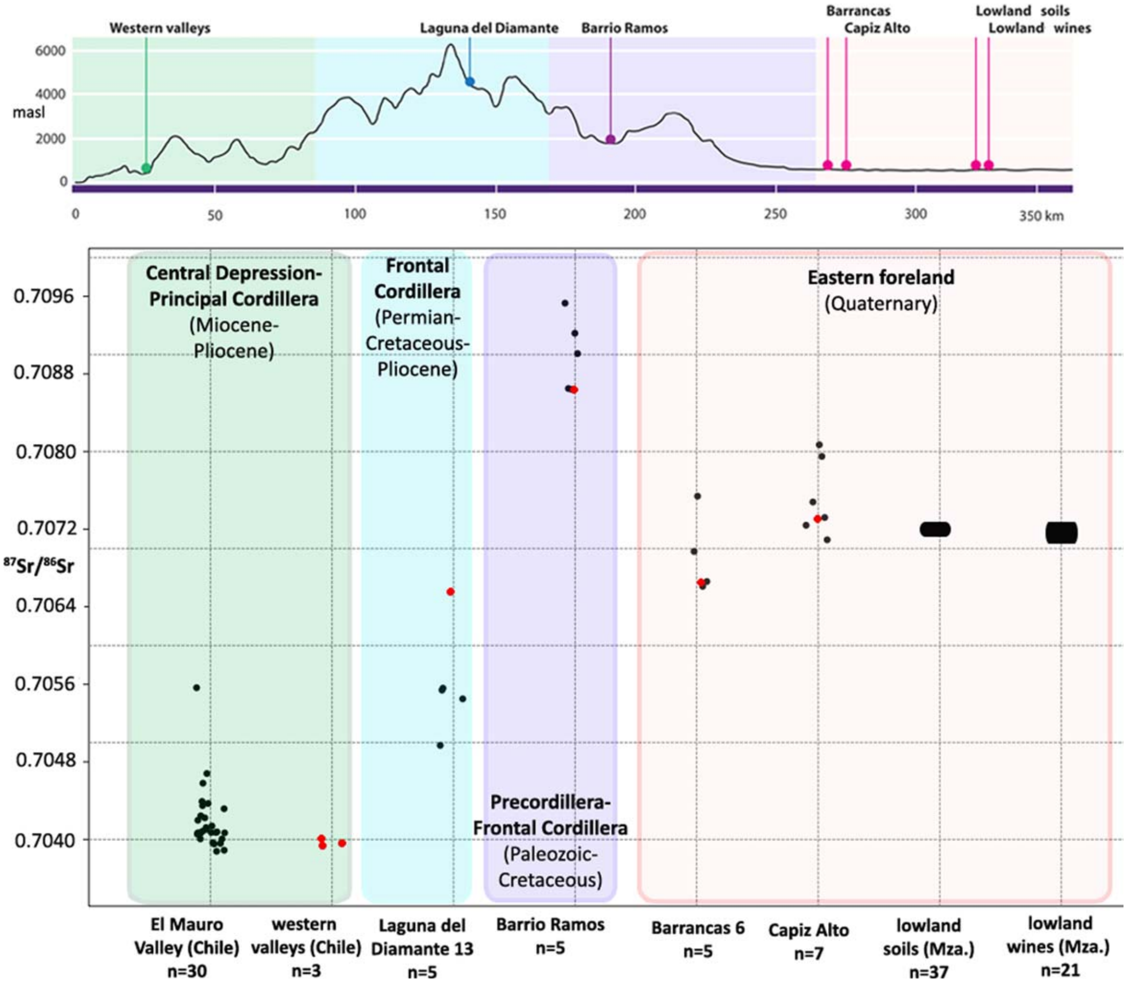

FIGURE 5 $^{87}Sr/^{86}Sr$ values for fauna, human remains, soil, and wine samples. *References*: Red dots indicate rodent samples; soil and wine samples are depicted as a range (source: Di Paola-Naranjo et al., 2011); values for the El Mauro Valley, Chile, are from Gómez and Pacheco (2016)

In synthesis, the western slope of the Andes, composed of relatively young Tertiary volcaniclastic rocks has the lowest values, while the eastern intermountain valleys, where the rocks are the oldest (Mesozoic and Paleozoic), have the highest values. Since ^{87}Sr is a radiogenic isotope formed over time by the β-decay of ^{87}Rb (half-life = 4.88 × 1010 years), these current isotopic endpoints seem to reflect the very different ages of these rocks, in addition to compositional differences. The highland sample from Laguna del Diamante has a value that is considerably higher than those from the Chilean valleys, which is compatible with the Jurassic-Cretaceous age of the bedrock dominant in the area (Fig. 2). In the future, it will be necessary to assess the incidence in bioavailable strontium values of the volcanic rocks of Pliocene-Quaternary age that outcrop locally. Finally, as mentioned above, the values of the two samples from the eastern foreland fall between the extremes from the eastern and western intermountain valleys. This is expected, since the lowlands function as a sedimentary basin for sediments derived from different Andean outcrops.

The values from the eastern lowlands are confirmed by published strontium values for soil and wine samples from the same geological setting -Junín and San Martín Departments, Mendoza Province- (Fig. 1). Thirty-seven soil samples produce a value of $^{87}Sr/^{86}Sr = 0.7072 \pm 0.0004$, while 21 wine samples produce values contained within $^{87}Sr/^{86}Sr = 0.7073 - 0.7071$ (Di Paola-Naranjo et al., 2011). There is a full overlap of the values obtained for soil and wine samples from the eastern lowlands, which together with our faunal data provide a reliable preliminary isotope signature of this geological area (Fig. 5).

4.2 | Oxygen and strontium isotope results for human bone and teeth samples

The human enamel and bone samples from Mendoza Province have a mean value of $\delta^{18}O_{carbonate(V\text{-}PDB)} = -7.8‰ \pm 2.1‰$ ranging from $\delta^{18}O_{carbonate(V\text{-}PDB)} = -11.2‰$ to $-2.9‰$ (Tables 2, 3). The enamel subsample has a mean oxygen isotope value of $\delta^{18}O_{carbonate(V\text{-}PDB)} = -6.1‰ \pm 1.3‰$ ($n = 9$) with a range from $\delta^{18}O_{carbonate(V\text{-}PDB)} = -7.1‰$ to $-2.9‰$, while the bone subsample has a mean $\delta^{18}O_{carbonate(V\text{-}PDB)} = -9.5‰ \pm 1.1‰$ ($n = 9$) with a range extending from $\delta^{18}O_{carbonate(V\text{-}PDB)} = -11.2‰$ to $-8.3‰$. The mean difference in $\delta^{18}O$ values for enamel and bone

TABLE 3 Descriptive statistics of $\delta^{18}O_{carbonate(VPDB)}$ and $^{87}Sr/^{86}Sr$ in human remains

	$\delta^{18}O_{carbonate(VPDB)}$				
Site	**N**	**Mean**	**SD**	**Max**	**Min**
Barrio Ramos	4	−7.8	1.4	−6.6	−7.8
Barrancas 6	4	−7.4	3.5	−2.9	−11.2
Capiz Alto	6	−5.9	2.3	−5.8	−11.2
Laguna del Diamante 13	4	−7.8	1.3	−6.4	−9.3
Total	18	−7.8	2.1	−2.9	−11.2
	$^{87}Sr/^{86}Sr$				
Barrio Ramos	4	0.7091	0.0003	0.70953	0.70865
Barrancas 6	4	0.70694	0.0004	0.70754	0.70661
Capiz Alto	6	0.70752	0.0003	0.70807	0.70709
Laguna del Diamante 13	4	0.70538	0.0002	0.70556	0.70497
Total	18	0.70726	0.0013	0.70953	0.70497

samples from the same individuals is $\delta^{18}O_{carbonate(V\text{-}PDB)} = 3.4‰ \pm 1.4‰$ ($n = 18$) and there is no overlap between the range of values for enamel and bone samples.

Our samples show a larger inter-tissue difference for the same individuals than between individuals. This is unexpected since a larger sample ($n = 46$) for the same region had a mean inter-tissue difference of only 1.4‰, suggesting that "…people in the region appear to have exploited water resources as adults in much the same fashion that they did as juveniles" (Ugan et al., 2012, pp. 2761). This does not seem to be the case in our dataset. A fundamental aspect is the age span represented in each tooth sample, and whether it reflects isotopic enrichment due to the consumption of breast milk before and during the weaning process (White, Spence, Longstaffe, & Law, 2004).

In Table 2 we present the age range of tooth mineralization, which is the period that would be represented in the isotopic value observed in enamel (Hillson, 2005). Two of the nine teeth analyzed mineralize between 2 and 7 years, one between 1.5 and 6 years, three between 0.3 and 7 years, two between 0.8 and 5 years, and one between 0 and 3 years old (Table 2). Considering global averages for weaning, which occurs consistently between 2 and 3 years of age (Robson, van Sachik, & Hawkes, 2006) but can vary widely, the enamel sample of individual 6 from Capiz Alto may show enrichment due to the consumption of breast milk, which is ^{18}O-enriched. Considering that "values of bone in children under 3 years of age and of deciduous second molars and permanent first molars … [are] adjusted downward by 0.7‰, and by 0.35‰ in canines and premolars because they contain both pre- and post-weaning enamel" (White et al., 2004, pp. 394), these would not alter the overall patterns in the data.

The analysis of $\delta^{18}O_{carbonate}$ by region shows an overlapping of the values from the sites representing the Andean highlands, eastern intermountain valleys, and eastern lowlands (Table 3, Fig. 6).

Element concentration data were analyzed for the human bone and enamel samples. In biogenic human bone, Ca/P= 2.1. For all enamel and bone samples, Ca/P values range from Ca/P = 1.8 to Ca/P = 2.1, and mean Ca/P = 1.9 ± 0.1 (1σ, $n = 18$). Some samples exhibit lower Ca/P values, which may indicate the possibility of some diagenetic alteration (Table 2). Another way to identify and monitor diagenetic contamination in archeological samples is to examine the amount of uranium present. Here, U/Ca values for enamel and bone are consistent with little diagenetic contamination (Table 2).

Strontium isotope values for the human dataset range from $^{87}Sr/^{86}Sr = 0.70497$ to 0.70953 with a mean of 0.70726 ± 0.00134 (Table 3, Fig. 5). The enamel subsample has a mean $^{87}Sr/^{86}Sr$ value of 0.70737 ± 0.00152 ($n = 9$) with a range from 0.70901 to 0.70497, while the bone samples have a mean $^{87}Sr/^{86}Sr$ value= 0.70722 ± 0.00141 ($n = 9$) with a range extending between 0.70953 and 0.70545. These ranges overlap considerably.

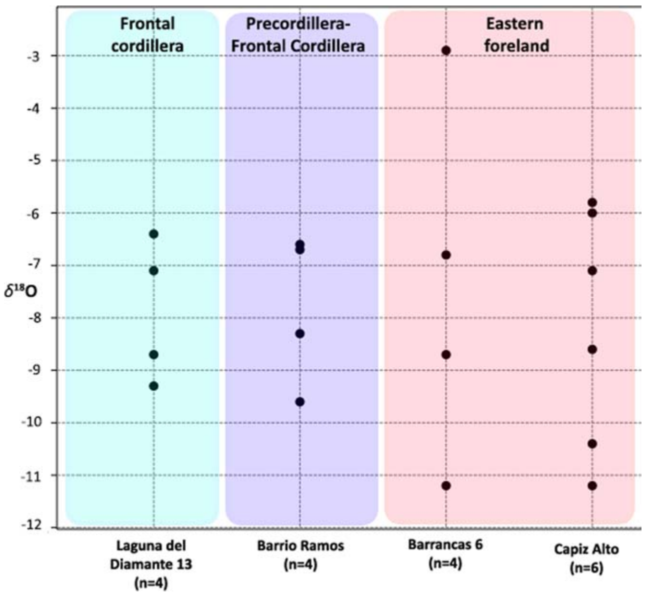

FIGURE 6 $\delta^{18}O$ values from human samples from Mendoza Province, Argentina

An exploratory comparison of the $^{87}Sr/^{86}Sr$ values from the different regions shows interesting preliminary patterns. First, in all regions there is a tight clustering of the values from enamel and bone from the same individuals, indicating that there were no significant spatial relocations between geological areas when comparing childhood and adulthood. Second, the human samples from the Andean highlands, eastern intermountain valleys, and eastern lowlands can be clearly differentiated between each other. The two sites from the lowlands (Barrancas B6, Capiz Alto) show the most similar values. Finally, there is a tight clustering of the human samples and local faunal samples, with the exception of the four human samples from Laguna del Diamante 13, located in the highlands, which have values that are considerably lower than the local rodent sample (Fig. 5).

5 | DISCUSSION

5.1 | Inter-regional variation: Comparing isotopic tracers of human mobility

A comparison of the $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values shows divergent patterns. Figure 5 reveals wide overlap of $\delta^{18}O$ values for individuals buried in the Andean highlands, the eastern intermountain valleys, and the eastern lowlands. Hence it seems that $\delta^{18}O$ values have a very limited potential for differentiating the geographic location of human samples - with the exception of an enriched enamel value from Barrancas 6 ($-2.9‰$) that sets it apart from the rest of the cases. Working with a larger dataset that includes this region, Ugan et al. (2012, pp. 2761) report "Individuals from most areas have a similar range of $\delta^{18}O$ values, averaging about -7 VPDB". Their average value is similar to ours = $-7.8‰$ (Table 3). A comparison of our data (Fig. 6) with that from Ugan et al. (2012, Fig. 6) shows a similar pattern of isotopic similarity between regions, with the samples most enriched in ^{18}O coming from the driest parts of the lowlands (see also Berón, Luna, and Barberena, 2013). Based on this pattern of geographical homogeneity, the authors infer that "The movement implied by the underlying oxygen isotope data and inherent in either pattern of resource exploitation, whether upland to lowland or within the lowland, continues to support the previous analysis and suggests a high degree of residential mobility throughout much of the region" (Ugan et al., 2012, pp. 2761; see also Gil et al., 2014a). In order to account for the isotopic pattern, the logic underlying this scenario implies not only *high mobility* (i.e., a high number of annual movements), but also a large *spatial scale of mobility* connecting different landscape areas.

Our article provides the first set of strontium values for human remains in the southern Andes (Dantas & Knudson, 2016 present data for camelids from northwestern Argentina). Since oxygen isotopes were measured for the same set of samples, we can compare the spatial resolution provided by the two isotope tracers. Radiogenic strontium values allow differentiating the faunal and human samples recovered from the western intermountain valleys in Chile (Miocene rocks of Cordillera Principal), the Andean highlands (Jurassic-Cretaceous sedimentary rocks), the eastern intermountain valleys in Argentina (Paleozoic-Permian-Triassic igneous and sedimentary rocks) and, to a lesser extent, the eastern foreland (Quaternary sediments) (Fig. 5). This preliminary dataset shows a relationship between the age of the bedrock and $^{87}Sr/^{86}Sr$ values. This finding highlights the enormous potential of strontium isotopes in the southern Andes, since they would allow discriminating both Andean slopes and the highlands.

The two extremes of the distribution are provided by the Cordillera Principal unit (Fig. 2: unit 3), which is formed by young rocks of Miocene age outcropping in Chile and presents the lowest $^{87}Sr/^{86}Sr$ values ($\mu = 0.70396$), and the Precordillera unit in the eastern valleys in Argentina (Fig. 2: units 4 and 5), in a setting composed by Paleozoic-Permian-Triassic rocks that presents the highest strontium values as recorded in rock samples ($\mu = 0.70937$; Naipauer et al., 2005). The highlands in between these units, of Cretaceous-Jurassic age, have one intermediate faunal value ($^{87}Sr/^{86}Sr = 0.70655$). Finally, the largest number of rodent, human, soil, and wine samples are from the eastern lowlands (Fig. 5). They have relatively similar values, despite being far from each other; therefore supporting the expectation that samples from the same geologic areas should have similar values.

Based on this preliminary analysis, we suggest that strontium isotopes offer a much higher spatial resolution than oxygen isotopes for the southern Andes. Information currently available from different sources allows suggesting the following hypothesis:

> *Human home ranges did not encompass the different landscape macro-units (Principal cordillera, Frontal cordillera, Precodillera, and Eastern foreland) systematically*.

This does not necessarily imply that mobility was reduced, since there are many possible forms of mobility within homogeneous geological areas that may not be reflected in $^{87}Sr/^{86}Sr$ values. Equally, the hypothesis does not imply lack of connectivity or interaction between these areas, since there are diverse archeological proxies that document these interactions during the late Holocene (Cortegoso, Neme, Giesso, Durán, & Gil, 2012). The world ethnographic record offers information on several mechanisms of interaction beyond the scale of daily movements –more likely to be represented in the averaged isotopic record- that may explain this situation (Binford, 1983; MacDonald & Hewlett, 1999). In order to account for the lack of regional distinctiveness in $\delta^{18}O$ in samples that can be differentiated on the basis of $^{87}Sr/^{86}Sr$ values, we turn to the chemistry of the main water sources in the province of Mendoza:

a. Snowmelt-derived water associated with air masses coming from the Pacific Ocean and precipitating in the highlands during winter (Garreaud, 2009). Available information indicates values depleted in ^{18}O ($\delta^{18}O_{vsmow} = -21/-15‰$; Hoke, Aranibar, Viale, Araneo, & Llano, 2013; Ugan et al., 2012; Vogel, Lerman, & Mook, 1975). This water source feeds the main rivers draining the Andes and traversing the eastern plains, where isotopic enrichment due to fractionation occurs. Hoke et al. (2013) have measured the isotopic variation along the basin (4500–1000 masl) of the main rivers in northern Mendoza, which show significant inter-annual variation: in 2002, values varied between

-19.2 and $-10.7‰$ and in 2007 between -16.8 and $-8.3‰$ (Hoke et al., 2013).

b. Precipitation that originates in the Atlantic Ocean that falls during summer, largely in the eastern foreland and eastern Precordillera (Hoke et al., 2013). This precipitation has an average of $-5.4‰$, making it isotopically distinct from precipitation in the Andes (Jobbágy, Nosetto, Villagra, & Jackson, 2011).

c. Small streams and springs that may be alternatively fed by mountain water infiltration or local rainfall deep drainage. Information available for northern Mendoza indicates that the phreatic groundwater feeding these water sources is largely of Andean origin, and has depleted values compared to local rains (Jobbágy et al., 2011).

We can compare these values to our human sample by estimating the isotope values of drinking water (Table 2). Humans sampled drank water with an average $\delta^{18}O$ value of $-11.3 \pm 2.7‰$ with values in different regions clustering between $-11.7‰$ and $-10.7‰$ (calculated according to Knudson, 2009). Alternatively, if we utilize the equation 6 in Chenery et al. (2012), we obtain a mean value of $-12.3 \pm 3.4‰$ (Table 2), with the average in each region varying between $-12.8‰$ and $-11.6‰$. Overall, the mean difference between the reconstructions of drinking water using the two equations is $1 \pm 0.7‰$. While an assessment of these alternative procedures is beyond our goals, both equations indicate a wide overlap in the values reconstructed for $\delta^{18}O_{dw}$ in the different regions of the Andes.

There are two main likely causes of such similar $\delta^{18}O$ values throughout the region. First, that even when working with temporally restricted precipitation samples, there is large inter-annual variation due to climatic fluctuations (Hoke et al., 2013). In the southern Andes, it is highly problematic to model the incidence of this annual variation in the average signals recovered from human remains (Knudson, 2009; Pellegrini et al., 2016). Second, much of the water available to humans in different areas is ultimately derived from the same source: depleted Andean precipitation, which includes highlands precipitation, rivers draining the Andes and traversing the eastern lowlands, and a large part of groundwater feeding reservoirs in the eastern lowlands. This is consistent with the view of "these arid and semiarid sedimentary landscapes as systems of negligible local recharge" (Jobbágy et al., 2011, 689). While isotopic fractionation introduces variation in these processes, inter-regional values for different water sources overlap widely (Hoke et al., 2013; Ugan et al., 2012; Vogel et al., 1975). Interestingly, the only cases that present distinctly higher $\delta^{18}O$ values come from very dry areas that do not receive significant input of Andean-derived waters, such as the lowlands in southern Mendoza Province (Ugan et al., 2012) and the adjacent dry Pampas (Berón et al., 2013). In these cases, local water recharge predominates, producing a distinct isotopic signal.

5.2 | Fidelity to local isotopic signals and life histories

Human $^{87}Sr/^{86}Sr$ values are very similar to the local baselines, with the exception of the samples from Laguna del Diamante site 13 (see below). The small samples size currently available prevents us from defining a local range for each region, though the remarkable similitude between the values for fauna and humans would indicate human residence within isotopically homogeneous and distinct geological regions. This is particularly evident when comparing the samples from the eastern intermountain valley (Barrio Ramos) and the full set for the eastern lowlands. On the other hand, there is some overlap between the lowland sites Barrancas B6 and Capiz Alto. Considering that the lowland sites are situated in the same Quaternary sedimentary basin, this is expected. Large numbers of soil, plant, and faunal samples will be required to improve the resolution of the method in the eastern foreland, because the mixing of sediments from different sources decreases isotopic resolution.

The four human samples from Laguna del Diamante site 13 have values that are considerably depleted in comparison to the local rodent (Fig. 5). This seems to be an average of the signal from the highlands and the western intermountain valleys in Chile, which would be evidence that these individuals resided for most of their juvenile and adult lives in the western Andean slope, making recurrent stays in the highlands, likely on a seasonal basis. This is supported by the spatial distribution of the two obsidian types from Laguna del Diamante, which is heavily skewed towards the western slope (Cortegoso et al., 2016; Durán et al., 2017). From the full set of archeological human samples analyzed here, these are the only individuals that would have spent considerable amounts of time in the western Andean watershed, since all the other cases present high $^{87}Sr/^{86}Sr$ values that do not suggest their systematic occupation.

A large $^{87}Sr/^{86}Sr$ database has been recently published for archeological sites in the El Mauro Valley in the semi arid north of Chile (Fig. 1; Gómez & Pacheco, 2016). The chronology of these sites ranges between 8,300 and 1,000 cal years BP, though most of the samples fall between 3,000 and 1,000 cal years BP (Gómez & Pacheco, 2016, Table 2). The authors suggest a local strontium baseline of $^{87}Sr/^{86}Sr = 0.70410 \pm 0.00023$, within our estimates for a section of the western valleys located further south (Fig. 5). With the exception of one individual, with a value of $^{87}Sr/^{86}Sr = 0.70556$, the other 29 samples produce values well within the local range, suggesting low systematic mobility, whether to the Pacific coast or the Andean highlands (Gómez & Pacheco, 2016).

6 | ASSESSING SCALE OF HUMAN MOBILITY IN THE SOUTHERN ANDES

The small sample size currently available does not allow assessing historical changes in scale of mobility. Considering this limitation, we have presented a temporally averaged analysis covering the last 2,300 years (i.e., analytical time-averaging, *sensu* Behrensmeyer, Bobe, & Alemseged, 2007). It is remarkable that, despite the large socio-economic changes recorded for this period, $^{87}Sr/^{86}Sr$ values indicate a persisting scenario of low systematic mobility between the different geological regions here defined. This has direct implications on the scale of human mobility in the past. Synthesizing recent research and the analysis presented here, there are two main alternative hypotheses to account for the scale of mobility and connectivity between different parts of the macro-regional landscape. On the one hand, based on the homogeneous record of $\delta^{18}O$ values in human remains, Ugan et al. (2012) have suggested a high degree of residential mobility throughout much of the region, including the upland and lowland areas. This can be termed as the "High mobility hypothesis." Building on this, the authors argue that this contradicts the historic ethnographic record of the Huarpe people depicting more residentially stable societies (Michieli, 1983).

On the other hand, our $^{87}Sr/^{86}Sr$ results suggest a smaller spatial scale of human mobility during the last 2,300 years. The distinctiveness in the $^{87}Sr/^{86}Sr$ values for samples from the highlands, Precordillera, and eastern foreland does not suggest human home ranges that connected the different geological regions systematically. The information available for the western valleys in El Mauro in Chile agrees with the patterns that we have presented (Gómez & Pacheco, 2016; see also Sanhueza & Falabella, 2010). These macro-regional patterns do not necessarily imply low residential mobility, but they do imply that the scale of mobility in a west-east axis is smaller than that of the geological units characterized here.

The isotopic assessment of the spatial scale of systematic human mobility provides a promising framework for assessing spatial patterns in other fields of archeological data, such as bioarcheology, obsidian artifacts, ceramics, and settlement patterns. In addition, the reliable determination of the geographic origin of humans occupying the highlands holds the potential to redefine debates on the human use of the Andes (Durán et al., 2017). The strontium values from enamel and bone samples from nine individuals have allowed a first exploration of life histories, suggesting residential stability within the geological regions occupied throughout life.

In this article, we have presented a new geology-based framework for the use of strontium isotopes in the southern Andes of Argentina and Chile. Our first results for rodent and human samples made it possible to explore the spatial scale and patterns of mobility between geologic regions of the Andes over the last 2,300 years. These results suggest that, in this region, strontium isotopes have higher spatial resolution than oxygen isotopes. Based on an initial comparison of the two isotope systems, we have argued against the "high mobility hypothesis" (Ugan et al., 2012). The main challenge for future research lies in building a robust map of bioavailable strontium (Copeland et al., 2016; Grimstead et al., 2017) throughout a region that extends from the Pacific coast in Chile, across the Andes, and down to the eastern lowlands in Argentina. We are currently advancing in producing results for soil, plant, and faunal samples from the main regions analyzed. Against a more robust landscape of bioavailable strontium, we will analyze a large number of human samples from different periods in order to better track temporal trends in mobility and correlate them with other shifts in human societies of the southern Andes.

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