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RESEARCH ARTICLE

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Scale of human mobility in northwestern Patagonia: An approach based on regional geology and strontium isotopes in human remains

M. Victoria Fernández[1] | Florencia Gordón[2] | Petrus J. le Roux[3] | Diego Winocur[4] | Gustavo Lucero[5] | Anahí Benítez[4] | Diego Rindel[6] | Claudia Della Negra[7] | Valeria Bernal[2] | Ramiro Barberena[8,9]

[1]CONICET, IIdyPCa, Universidad Nacional de Río Negro, San Carlos de Bariloche, Argentina

[2]CONICET, División Antropología, Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata, Argentina

[3]Department of Geological Sciences, University of Cape Town, Cape Town, South Africa

[4]Departamento de Ciencias Geológicas. IDEAN Instituto de Estudios Andinos (UBA-CONICET), Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Buenos Aires, Argentina

[5]Departamento de Antropología, Facultad de Ciencias Sociales y Humanidades, Universidad Católica de Temuco, Temuco, Chile

[6]CONICET, Instituto Nacional de Antropología y Pensamiento Latinoamericano, Buenos Aires, Argentina

[7]Dirección de Patrimonio Material, Subsecretaría de Cultura, Gobierno de la Provincia de Neuquén, Neuquén, Argentina

[8]Laboratorio de Paleoecología Humana, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Instituto Interdisciplinario de Ciencias Básicas (ICB), Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Cuyo, Mendoza, Argentina

[9]Facultad de Filosofía y Letras, Universidad Nacional de Cuyo, Mendoza, Argentina

Correspondence
Ramiro Barberena, Laboratorio de Paleoecología Humana, CONICET, Instituto de Ciencias Básicas, Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Cuyo, Padre Jorge Contreras 1300 (5500), Mendoza, Argentina.
Email: ramidus28@gmail.com

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Abstract

Strontium isotopes facilitate the study of human paleogeography and have widened the scope of archaeological enquiries on mobility. We present an approach based on strontium isotopes ($^{87}Sr/^{86}Sr$) to study the mobility of hunter–gatherer societies from northwestern Patagonia (Neuquén, Argentina). The analysis is developed on the basis of a macro-regional geological framework that guides the sampling and interpretation of results. We also present results for fauna to begin building a landscape of bioavailable strontium to be utilized in the interpretation of results from human samples. These first results conform to general expectations and show the most radiogenic $^{87}Sr/^{86}Sr$ values for the oldest geological provinces, while low values are recorded for recent substrates. Additionally, we provide results for human samples from archaeological sites spanning the last 4000 years, a period during which a number of important socio-demographic changes occurred. The results in human samples indicate overall isotopic fidelity to the values recorded in the local geology, suggesting a relatively restricted spatial scale of mobility during the late Holocene. This discussion is situated in a biogeographic research framework assessing topographic variation and landscape seasonality, and contributes toward understanding the movements of people, flow of material objects, and circulation of information in the Patagonian Andes.

KEYWORDS
Andean geology, bioarchaeology, bioavailable strontium, human paleomobility, Patagonia

1 | INTRODUCTION

Strontium isotopes ($^{87}Sr/^{86}Sr$) provide a powerful tool to track animal and human geographic ranges in the present as in the past (Bentley, 2006). As such, this proxy has been widely utilized across disciplines including paleoecology, forensics, and archaeology (Crowley et al., 2017; Koch et al., 1995; Snoeck et al., 2018). Strontium is a trace element found in igneous, metamorphic, and sedimentary rocks and in soils, water, plants, and animals. Spatial resolution is largely determined by the amount and scale of geological heterogeneity compared to the scale of mobility of the organisms under study. Biologically available strontium as recorded in plants and animals with restricted mobility from a given geological region provides a straightforward frame of reference for the interpretation of values in human remains (Price et al., 2002; Scaffidi & Knudson, 2020; Sillen et al., 1998).

While systematically applied in many regions of the world for decades, its use in South America is largely limited to productive economies and complex societies from the south-central Andes of Peru, western Bolivia, northern Chile, and northwestern Argentina (e.g., Dantas & Knudson, 2016; Knudson et al., 2014; Mader et al., 2018), to the so-called southern agricultural frontier in central Argentina and Chile (Barberena, Durán, et al., 2017; Barberena, Tessone, et al., 2021; Barberena et al., 2020), and a first approach to northern Patagonia (Serna et al., 2020). In this study, we present a preliminary application of strontium isotopes to study the spatial scale of human mobility in the context of hunter–gatherer societies from northwestern Patagonia (Neuquén Province, Argentina). While the scope of this study is to initiate a strontium program, we present the geological framework that is key to guiding the construction of a frame of reference of bioavailable strontium in the southern Andes of Argentina (central-northern Neuquén) and Chile (Maule, Ñuble, and

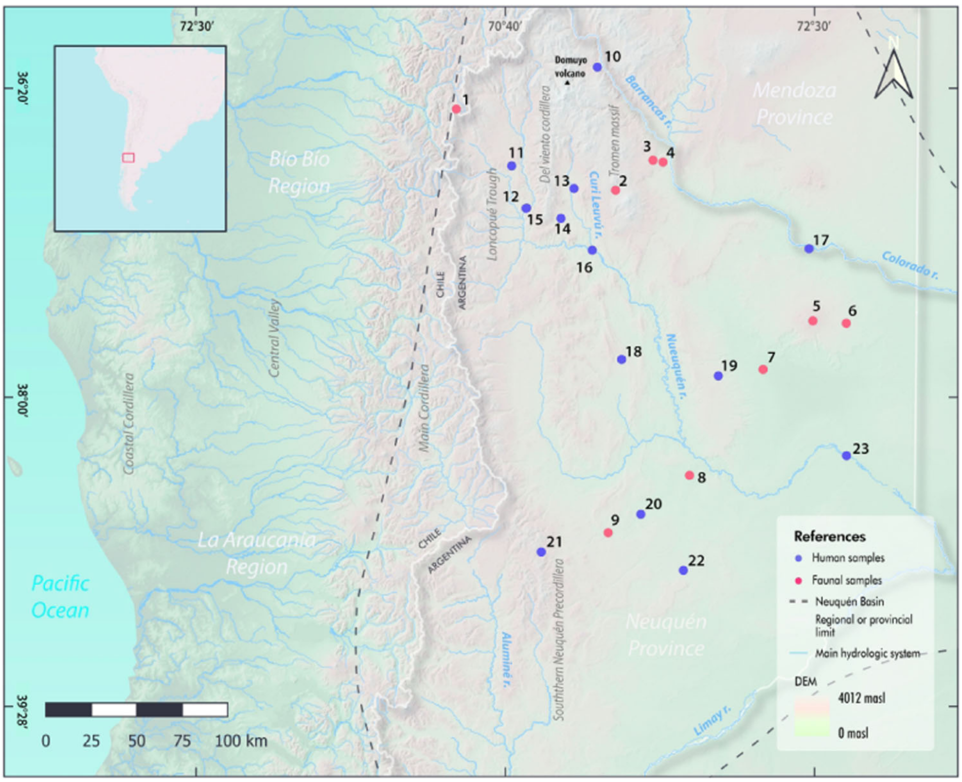

FIGURE 1 Study area and location of the faunal and human samples. References: *Faunal samples*: (1) Epu Lauquen-Lumabia-El 25; (2) Laguna del Tromen; (3) Cueva Yagui; (4) Cueva Huenul 1; (5) Techos Verdes; (6) Loma Amarilla; (7) El Orejano; (8) Fortín Covun-Có; (9) Alero Portada Covunco. *Human samples*: (10) Cochico-Márquez; (11) El Panteón; (12) Andacollo; (13) Aquihuecó; (14) Hermanos Lazcano; (15) Gubevi; (16) Chacra Alvarez; (17) Rincón de los Sauces; (18) Chorriaca; (19) Chihuidos; (20) Piera; (21) Michacheo; (22) Retamal I; and (23) Añelo [Color figure can be viewed at wileyonlinelibrary.com]

Bio Bio regions) (Figure 1). We also present a set of results for rodent and wild camelid samples from these main geological provinces. This database is then applied in a preliminary and exploratory manner to strontium values for a set of human remains from archaeological sites spanning the last 4000 cal years. The use of this biogeochemical proxy will complement ongoing efforts to study human paleomobility by means of oxygen isotopes in human remains (Bernal et al., 2020; Gil, Neme, et al., 2014; Serna et al., 2019). The application of strontium isotopes will contribute to central issues in the archaeology of northern Patagonia and the southern Andes, including the scale of mobility, the existence of transhumant mobility connecting different altitudinal levels, and the intensity of trans-Andean human mobility (Barberena, Romero Villanueva, et al., 2017; Campbell et al., 2017; Gordón et al., 2018; Hajduk et al., 2011). In addition, by characterizing multiple tissues from the same individuals, it will also be possible in the future to assess the incidence of migration in the conformation of these mobile groups (Barberena et al., 2020; Berón et al., 2013; Price et al., 2000).

2 | GEOLOGIC, GEOGRAPHIC, AND ARCHAEOLOGICAL BACKGROUND

2.1 | Geological history and main landscape features

Northwestern Patagonia largely corresponds to the so-called Neuquén Basin (Figure 1) that originated in the margin between convergent geologic plates: an oceanic plate, which formed the Proto-Pacific Ocean, and a continental plate constituting the southwestern limit of Gondwana (Arregui et al., 2011). This old basin contains a unique sedimentary sequence of over 6000 m that includes marine and continental rocks deposited between the Upper Triassic and the Paleocene (Arregui et al., 2011; Casadío & Montagna, 2015).

From west (Chile) to east (Argentina), the first large-scale geological feature is the Coastal Cordillera range (Figure 1), a Paleozoic metamorphic complex intruded by the coastal batholith and by diverse Mesozoic complexes (Vásquez et al., 2011). Eastward from this range, there is a set of intra-arch volcanic, clastic, and volcaniclastic sequences of the Jurassic age. The current Central Valley in Chile (Figure 1) corresponds to a depression filled by clastic, volcanic, and volcaniclastic Plio–Pleistocene sediments (Fuenzalida, 1965). This valley is then followed by the Cordillera Principal unit (Figure 1), which, at this latitude, lies almost completely in current Chilean territory and includes the highest mountains between 2750 and 3500 masl. It is composed of sedimentary deposits of Jurassic and Cretaceous age interspersed with volcanic rocks produced in association with the magmatic arch. Continuing eastward, the Cordillera Principal range is delimited by the "Fosa de Loncopué" (Figure 1), a Plio–Quaternary depression filled by Quaternary volcanic deposits, currently channeling the Neuquén River basin in Argentinean territory. On the eastern side of this basin lies the "Precordillera Neuquina" unit, which can be divided into two latitudinal segments. The northern Precordillera is a structural unit encompassing the Cordillera del Viento range (Figure 1), with altitudes between 2800 and 2950 masl, and the Domuyo volcano that reaches 4707 masl and is the highest peak in all of Patagonia (Ramos et al., 2011). Eastward from this high range, there is the Tromen volcanic field (Figure 1) with the Tromen Quaternary basaltic strato-volcano (4114 masl) developed over Pliocene rocks as its most conspicuous feature (Kay et al., 2006). The area located eastward from this volcanic zone corresponds to extra-Andean Patagonia and is characterized by a gentler landscape composed of Mesozoic and Tertiary folded sequences (Ramos et al., 2011), where the Pleistocene Auca Mahuida volcanic field stands out as the most remarkable geological feature (Bernardi et al., 2019).

2.2 | Landscape, seasonality, and implications for human biogeography

Northwestern Patagonia is characterized by steep topographic and ecological contrasts largely produced by the presence of the Andes mountain range near the current international border between Argentina and Chile, the Cordillera del Viento range running parallel to the Andes ca. 40 km eastward, and then the Tromen volcanic field (Figure 1). This rugged topography, coupled with a cold winter regime, produces tight ecological successions and a highly seasonal landscape.

The areas roughly above 1500–1700 masl are usually covered by snow during the winter, as shown in Figure 2, and would have been available for systematic human use only during 4 or 5 months per year during the summer season. A geographic information system (GIS) analysis based on mean snow cover as shown by the Normalized Difference of Snow Index (NDSI) in satellite images from the sources MODIS and Landsat (Shea et al., 2013) shows that the winter-scape in northwestern Patagonia can be characterized as a fragmented landscape with low connectivity across the main Andean range and the Cordillera del Viento (Figure 2, D'Abramo et al., 2021). In this context, these highlands would act as temporary barriers (Veth, 1993) and the Neuquén, Curi Leuvú, and part of the Grande–Barrancas–Colorado basins would constitute temporary dead-ends or *cul de sacs* (Figure 2) (Barberena, Romero Villanueva, et al., 2017; Romero Villanueva et al., 2020).

Previously, we have argued that the fluvial basins located ≤1500 masl such as the ñuble and Bio Bio in Chile and the upper Neuquén and Curi Leuvú in Argentina would have been nodal areas from which seasonally available—or internodal—spaces were utilized (Barberena, Romero Villanueva, et al., 2017). However, some of the highland areas would have been key for human mobility networks in terms of social connectivity, summer pastures, and access to primary outcrops of obsidian (Barberena, Romero Villanueva, et al., 2017; Fernández et al., 2017). The potential to connect this biogeographic approach to northern Patagonian archaeology with different bioavailable strontium signatures across the Patagonian Andes is beginning to be explored systematically (Bernal et al., 2020; Gil, Neme, et al., 2014; Serna et al., 2019, 2020).

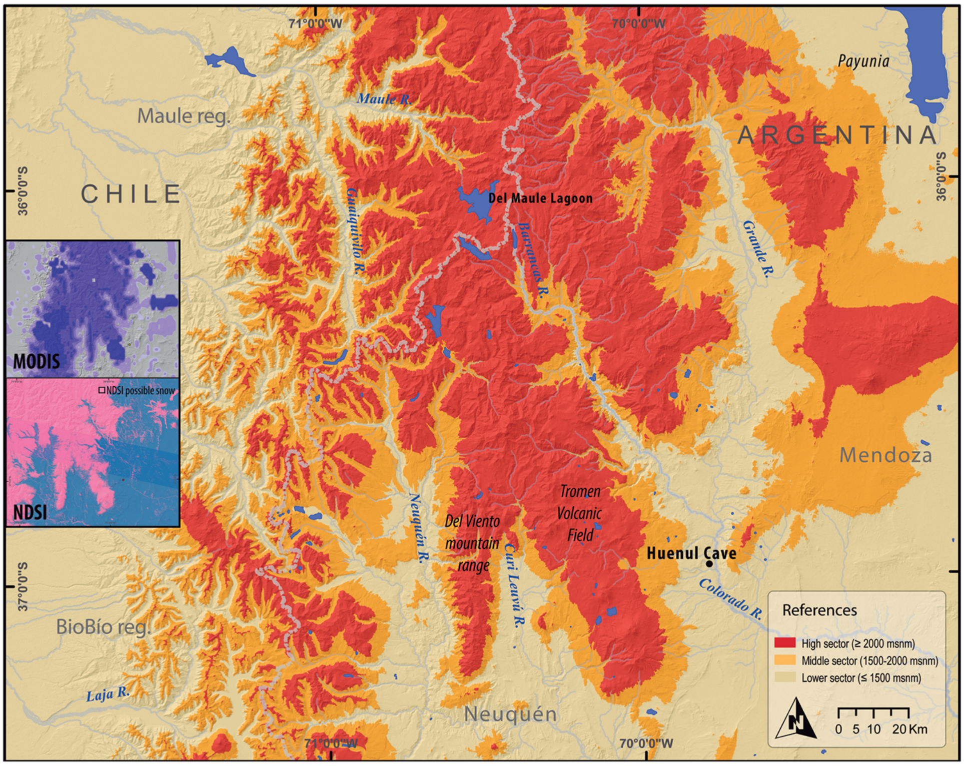

FIGURE 2 Geographic information system (GIS) reconstruction of seasonality and probable nodal and internodal areas in northwestern Patagonia (Barberena, Romero Villanueva, et al., 2017) [Color figure can be viewed at wileyonlinelibrary.com]

2.3 | Archaeological background: From the early human peopling to the historic period

Northwestern Patagonia east of the Andes shows a first conclusive signal of human presence after ~12,000 cal years BP, as shown by the cases of Cueva Traful I, Cueva Huenul 1, and Cuyín Manzano, among others (Barberena, 2015; Crivelli Montero et al., 1993; Gordón, Beguelin, Rindel, et al., 2019). These cases show a delayed human arrival compared to the areas where the clusters of the earliest sites are found, including Monte Verde II and Chinchihuapi (Dillehay et al., 2015; Prates et al., 2020). Indeed, unlike the earliest records where temporal overlap with megafauna is recorded, many of these eastern sites present a gap between the last presence of megafauna and the first human occupations (Barberena, 2015; Borrero, 2009). The mid-Holocene period has been the focus of debate regarding the existence of macro-regional occupational discontinuities across arid South American areas (Barberena, Méndez, et al., 2017; Gordón, Beguelin, Rindel, et al., 2019; Neme & Gil, 2009). A recent analysis of radiocarbon dates for the South American Arid Diagonal, where northern Neuquén is situated, shows that the period between 10,821 and 7055 cal years BP is characterized by a demographic change of −0.05% per 25-year generation, suggesting populations that were failing to grow (Timpson et al., 2021). Archaeological and molecular proxies coincide in suggesting a regional increase in human occupational intensity that may be indicative of marked demographic growth after 4000 cal years (Barberena et al., 2015; Gordón, Beguelin, Rindel, et al., 2019; Perez et al., 2016). While still coarsely placed in time, the last ca. 1800 years are associated with the incorporation of new technologies such as bow and arrow and ceramics (Marsh, 2017), and the presence of domesticated plant species including maize and squash, which were likely exchanged and not locally produced (Gil, Giardina, et al., 2014; Lema et al., 2012; Llano et al., 2019). The period of most significant cultural and demographic change is represented by the Hispanic conquest, which triggered a sustained period of conflict, demographic re-localization, and economic change that included the adoption of the horse by the indigenous societies. Relevant for this project, these changes would have been associated with significant migration and changes in the scale and patterns of human ranges of mobility (Boccara, 1999; Goñi, 1986; Mitchell, 2015). The bioarchaeological record from northwestern Patagonia is characterized by its temporal depth, by the early formation of formal burial areas, as exemplified by the Aquihuecó site dated between ca. 4300 and 3650 years BP (Della Negra & Novellino, 2005; Gordón, Béguelin, Novellino, et al., 2019), and by an increasing rate of deposition of human remains during the last ca. 2000 years (Bernal et al., 2017).

3 | MATERIALS AND METHODS

3.1 | Materials

We present results for a small first set of faunal specimens distributed among the main geological areas. We include rodent samples

($n = 9$) and, in cases where these samples were not available or well preserved, we processed guanaco (*Lama guanicoe*) samples ($n = 3$). While rodents would be a better proxy of locally bioavailable strontium due to their restricted home ranges, guanacos are territorial and have relatively small ranges (Ortega & Franklin, 1995; Puig et al., 2011), making them a possible alternative when rodents are not present. Previous comparisons of rodents and camelids from Mendoza Province did not show important differences (Barberena, Tessone, et al., 2021). Modern plants have also been widely used as a proxy for bioavailable strontium (Copeland et al., 2016; Montgomery et al., 2007; Serna et al., 2020; Snoeck et al., 2018). However, a recent approach in central Argentina produced inconsistent results compared with those from rodents (Barberena et al., 2021), probably due to the incorporation of dust particles in plant tissue associated with mining activities. We plan to explore their potential in the next stages of research.

The rodent samples come from the following sites: Cueva Huenul 1, Cueva Yagui, and Laguna Tromen, all located near the Tromen volcanic field, Lagunas Epu Lauquen in the Cordillera Principal near the international border, Auca Mahuida volcanic field in the eastern lowlands, Aquihuecó in the Curi Leuvú basin, and Mariano Moreno—near the Alero Portada Covunco site—(Figure 1). Three guanaco samples from the sites Techos Verdes, El Orejano, and Loma Amarilla in the Auca Mahuida Protected Natural Area were also included to build the preliminary bioavailable strontium framework.

We also present isotopic results for the cortical tissue of ribs from human remains ($n = 15$) from sites located in the northern half of Neuquén province. These samples were selected on the basis of their good preservation as informed by a study of regional human taphonomy that included chemical and physical analyses on the sedimentary contexts, a macroscopic study of weathering, root marks, deposition of carbonates and manganese, among other variables (Vazquez, 2019), and microscopic studies conducted on bone thin sections (Vázquez, 2020). In addition, key samples from these sites were subjected to electron microscope analysis. While the deposition of $CaCO_3$ and of silica grains in external surfaces was observed, the analysis did not show any evidence of replacement in the chemical composition of the bones (Vázquez, 2020). In synthesis, while the influence of diagenesis in the isotopic values cannot be completely ruled out, we have contextual taphonomic and ecological information that suggests that the individuals analyzed here have a good preservation of the external cortical surface and the internal microscopic structure.

For this first sampling stage, we opted for a wide spatial and temporal coverage at the expense of localised sampling intensity. This limits the depth of observations for any given archaeological context, but maximizes the possibility of structuring a large-scale framework with an available small first set of samples. Accordingly, we selected samples from sites that—taken together—span the late Holocene, beginning at the mid–late Holocene transition (4300 years BP) and reaching the period of Hispanic contact in Patagonia (XVII Century). These are mortuary contexts corresponding to mobile hunter–gatherers with contextual elements that show the Hispanic–indigenous contact in two sites from the historical period. The contextual information available is heterogeneous, since the strategy of excavation and or/collection was diverse (i.e., systematic excavations, rescue archaeology, and fortuitous finds).

Aquihuecó and Hermanos Lazcano sites are the earliest burial sites considered here (Figure 3). Chronologically, these sites are located during the mid–late Holocene transition (~4300–3700 years BP). Both are located in high areas of the landscape and have an unusually elevated number of buried individuals (minimum number of individuals [MNI] = 64; MNI = 12, respectively). Likewise, they share cultural characteristics such as the artificial cranial deformation type (i.e., circular) and the presence of grinding stones, shell beads, projectile points, cutting sharp instruments, and lithic spheres (Della Negra et al., 2014; Gordón, Béguelin, Novellino, et al., 2019). The Cochico-Márquez site is dated to ~2500 years BP and was rescued as a product of the use of backhoe loaders. In addition to human remains, bone fragments of *Ctenomys* and *L. guanicoe*, lithic flakes, grinding stones, and charcoal were found (Gordón, Beguelin, Rindel, et al., 2019; Vázquez, 2020).

The Gubevi and Michacheo sites share a similar chronology, around 1800 years BP, representing the earliest records of ceramic technology in the area. Micro-remains of *Prosopis* sp. and *Zea mays* were recovered from the pottery sherds from Michacheo site (Della Negra, 2008; Lema et al., 2012). The individual from Chorriaca site was also rescued as a result of a Police Force denouncement. A radiocarbon date of ~1150 years BP was obtained. In addition to human remains, a lip-plug or *tembetá* and faunal remains were found (Gordón, Béguelin, Novellino, et al., 2019; Vázquez, 2020). Loma de La Lata site, from which the Añelo C1.4 individual comes, is located chronologically between 600 and 740 years BP. An MNI = 19 was estimated for this site. In addition to the human remains, different types of projectile points, lip-plugs, and shell beads were found (Cúneo et al., 2016; Perez et al., 2009).

Sites dated after 330 years BP were considered post-contact. These sites are Retamal 1, Andacollo, El Panteón, Mariano Moreno (Piera), Rincón de los Sauces, Chacra Álvarez, and Los Zorrillos. In some of them, remains of horse (*Equus ferus*), metal elements, and glassy beads (*chakiras*) were found, which indicate contact with colonial society. In addition, indigenous elements were found, such as ceramic vessels and lithic instruments. In one of the sites, Chacra Álvarez, a characteristic precontact burial type for Pampa and northern Patagonia was described, involving the use of red pigment and leather wraps (Bernal et al., 2017; Gordón, Béguelin, Novellino, et al., 2019; Navarro, 2016; Vázquez, 2020).

3.2 | Analytical methods

The $^{87}Sr/^{86}Sr$ analyses were performed at the Department of Geological Sciences, University of Cape Town, South Africa, following established procedures (Copeland et al., 2010). Powdered samples were processed following routine chemical and multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS) (Pin et al., 1994). $^{87}Sr/^{86}Sr$ data are referenced to a value of 0.7102 for the

FIGURE 3 Main archaeological contexts studied: (a) Aquihuecó archaeological site; (b) a detail of the Hermanos Lezcano archaeological context; (c) Gubevi archaeological site; and (d) Piera archaeological context [Color figure can be viewed at wileyonlinelibrary.com]

international standard SRM987. Repeat analyses of an in-house carbonate reference material NM95 processed as unknown along with samples from this study yielded an $^{87}Sr/^{86}Sr$ average (0.7089 ± 0.000037 2σ; n = 17) in agreement with long-term data from this facility (0.7089 ± 0.000040 2σ; n = 414 over >8 years).

The separation chemistry was performed in the clean-chemistry laboratory of the MC-ICP-MS facility in the Department of Geological Sciences, University of Cape Town (UCT), using ultra-pure two-bottle-distilled HNO_3. Powdered samples were weighed into 7 ml Savillex Teflon beakers, 2–3 ml of 65% HNO_3 was added, and the closed beakers were placed at 140°C for an hour. Following complete sample dissolution, the beakers were opened and the samples were dried. The samples were taken up in 1.5 ml of 2 M HNO_3 in preparation for elemental separation chemistry. The Sr fraction was isolated following the methods detailed in (Pin et al., 1994) using TrisKem International Sr Spec resin, dried down, and re-dissolved in 0.2% HNO_3. $^{87}Sr/^{86}Sr$ isotope analyses were performed using a Nu Instruments NuPlasma HR in the MC-ICP-MS facility housed in the Department of Geological Sciences on 200 ppb Sr solutions. $^{87}Sr/^{86}Sr$ data presented are referenced to bracketing analyses of the international strontium isotope standard SRM987, using an $^{87}Sr/^{86}Sr$ value for this standard of 0.7102. Isobaric interference of ^{87}Rb on ^{87}Sr was corrected using the measured signal for ^{85}Rb and the natural $^{85}Rb/^{87}Rb$ ratio, while the effect of instrumental mass fractionation was corrected using the exponential law and an $^{86}Sr/^{88}Sr$ value of 0.1194. Repeat analyses of an in-house carbonate reference material NM95 as unknown during the processing of samples for this study yielded an $^{87}Sr/^{86}Sr$ result (0.7089 ± 0.000037; n = 17), in agreement with long-term data for this material (0.7089 ± 0.000040 2σ; n = 414; over >8 years). Total procedural strontium blanks were typically better than ~250 pg and therefore negligible.

4 | RESULTS

4.1 | Geological framework for bioavailable strontium studies

We have simplified the highly complex geological structure of the Andean landscape at this latitude, emphasizing those aspects most relevant for strontium isotopic analyses, particularly rock age and composition (Bentley, 2006). Thus, we propose a medium-resolution scheme organized into five main geological provinces corresponding to the main periods of formation of the landscape (Figure 4). These geological units range from the Pacific coast in Chile to the eastern lowlands in Argentina and are described from the oldest to the most recent.

1. *Pre-Jurassic units*: These formations include diverse metamorphic rocks that outcrop in the Coastal Cordillera from Chile. In addition, these rocks outcrop very restrictedly in Carboniferous sedimentites and Triassic volcanic rocks making up part of the Cordillera del Viento in Argentina (Giacosa et al., 2014). From the archaeological perspective of mobile human societies, the highly circumscribed nature of these units in the Argentinean side could make them almost negligible.
2. *Jurassic and Cretaceous sedimentary rocks*: During the Lower Jurassic, a subduction system was developed in the western margin of Gondwana, thus producing the first Mesozoic magmatic arch

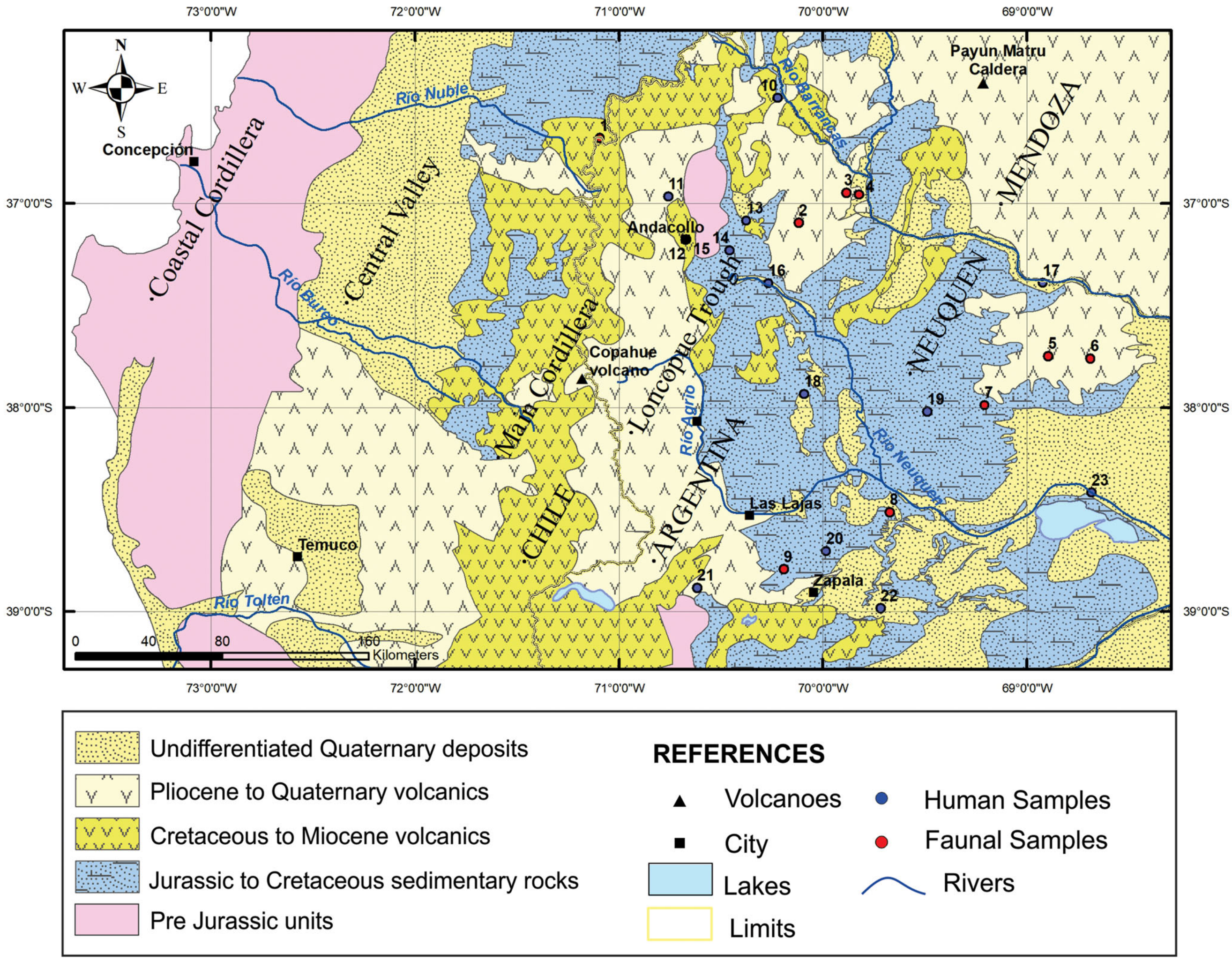

FIGURE 4 Main geological provinces in northwestern Patagonia and location of the faunal and human samples. References: *Faunal samples*: (1) Epu Lauquen-Lumabia-El 25; (2) Laguna del Tromen; (3) Cueva Yagui; (4) Cueva Huenul 1; (5) Techos Verdes; (6) Loma Amarilla; (7) El Orejano; (8) Fortín Covun-Có; (9) Alero Portada Covunco. *Human samples*: (10) Cochico-Márquez; (11) El Panteón; (12) Andacollo; (13) Aquihuecó; (14) Hermanos Lazcano; (15) Gubevi; (16) Chacra Alvarez; (17) Rincón de los Sauces; (18) Chorriaca; (19) Chihuidos; (20) Piera; (21) Michacheo; (22) Retamal I; and (23) Añelo [Color figure can be viewed at wileyonlinelibrary.com]

and the formation of the first marine basins (Casadío & Montagna, 2015). From the mid-Jurassic to the lower Cretaceous, the Neuquén basin was situated in a back-arch position and toward the end of the Lower Cretaceous, it began to act as a foreland basin due to the incipient Andean orogenesis (Casadío & Montagna, 2015). Geographically, these units are associated to the Chañarcillo basin in Chile and the Neuquén Basin in Argentina (Figure 4).

3. *Cretaceous to Miocene Volcanic rocks*: The process of Andean orogenesis produced the final retreat of the Pacific seas, allowing the first marine transgression from the Atlantic during the Upper Cretaceous. These groups of units encompass the intrusive and extrusive rocks formed during the expansion of the Andean magmatic arch that began after the Cretaceous (Kay et al., 2006). The reactivation of the fold–thrust belt during the Miocene marks the culmination of the structuration of the basin (Ramos & Folguera, 2009). This unit is largely located in the Andean highlands along the current international border. Most of this area would be available for systematic human use only during the summer.
4. *Pliocene to Quaternary volcanic rocks*: All the recent volcanic emissions have been grouped under this unit. They encompass a sequence with a thickness of over 2200 m and were produced by volcanoes emplaced in the Andean magmatic arch and, more recently, in the back-arch (Vergara & Muñoz, 1982). The Tromen, Auca Mahuida, and Payunia volcanic fields are included in this unit. However, the volcanism associated with this period is compositionally diverse, ranging from basic features in the Tromen and Payunia to acid Pliocene ignimbrites such as the Tilhué Formation that covers part of the area of the Cueva Huenul 1 and Cueva Yagui sites studied here. It is likely that this unit will have to be subdivided in light of wider results. From a strontium perspective, it is expected that the basic and recent units have poorly radiogenic values in opposition to more alkaline rocks and sediments.

5. *Quaternary sedimentary deposits*: This is the most recent unit and contains genetically diverse landforms, such as alluvial, glacial, and colluvial deposits. This unit can be recognized in the Andean and extra-Andean fluvial valleys and in the Central Valley and Pacific coast in Chile. Ultimately, the isotopic signature of these deposits will be determined by their catchment area.

4.2 | $^{87}Sr/^{86}Sr$ values for faunal and human remains

We present a first sampling of 12 faunal specimens from the different geological units in Neuquén Province (Table 1). Seven of these samples correspond to rodents (Rodentia, *Ctenomys* sp., and *Zaedyus pichiy*) and three to guanacos (*L. guanicoe*). Four rodent samples from Cueva Huenul 1 and Cueva Yagui sites come from archaeological contexts, while the rest are modern. The spatial distribution of the faunal samples is as follows: four come from the Jurassic/Cretaceous units (4), one from Cretaceous/Miocene units (3), and seven from Pliocene to Quaternary volcanic units (4), which, as mentioned, vary considerably in compositional terms (basic basalts to alkaline ignimbrites).

Overall, the faunal values vary between 0.7040 and 0.7070, with a global average of 0.7061. The least radiogenic samples come from the recent basaltic lavas of Laguna Tromen and from the Lumabia creek near the Epu Lauquén lagoons (Figure 4). While the geologic context of the Epu Lauquen sample is more complex (Utgé et al., 2009), the sample from Tromen adjusts to expectations based on rock age and composition (Bentley, 2006). The most radiogenic faunal samples, on the contrary, come from the Jurassic/Cretaceous units and from Pliocene/Quaternary contexts. Interestingly, this range is very similar to that reported by (Serna et al., 2020) for Río Negro Province ($^{87}Sr/^{86}Sr$ = 0.7046–0.7082), southward from our study area. The most radiogenic values in Río Negro (>0.7070), which are higher than those recorded so far for Neuquén, are spatially associated with the Jurassic silicic province of the northern Patagonian Massif, between the Somuncura plateau and the Atlantic coast.

In Table 2, we present the $^{87}Sr/^{86}Sr$ for the human samples (n = 15) from 14 well-dated archaeological sites that span the last 4300 years. The values for human samples range between 0.7043 and 0.7077, with an average of 0.7064. Overall, this range and the mean value coincide with those from the faunal samples from Neuquén.

In Figure 5, we present the faunal and human samples organized on the basis of the geology of the place of recovery. There is an almost complete overlap between the rodent and human samples from the Jurassic/Cretaceous units. The unit (2) Jurassic to Cretaceous Sedimentary rocks is the most represented, accounting for nine of the samples and including the earliest remains from the neighboring sites Aquihuecó and Hermanos Lezcano, dated at ca. 4000 years BP (Della Negra et al., 2014; Gordón, Béguelin, Novellino, et al., 2019). These two sites represent formal burial areas containing a minimum number of individuals of 64 (Aquihuecó) and 12 (Hermanos Lazcano), respectively. Interestingly, the three early human samples present very similar values (0.7070), which are also nearly indistinguishable from a rodent sample from Aquihuecó.

TABLE 1 $^{87}Sr/^{86}Sr$ values for faunal remains from Neuquén Province

Code	Site	Geological unit	Taxón	Latitude	Longitude	Context	$^{87}Sr/^{86}Sr$	±2 s internal
#202	Fortín Covun-co	(2) Jurassic/Cretaceous sedimentary	*Zaedyus pichiy*	−38.5126	−69.6732	Modern	0.7066	0.000013
#203	Alero Portada Covunco	(2) Jurassic/Cretaceous sedimentary	Rodentia	−38.7928	−70.1914	Modern	0.7062	0.000012
#206	Aquihuecó	(2) Jurassic/Cretaceous sedimentary	Rodentia	−37.0843	−70.3752	Modern	0.7070	0.000014
#208	El Orejano	(2) Jurassic/Cretaceous sedimentary	*Lama guanicoe*	−37.9892	−69.2079	Modern	0.7069	0.000009
#204	Epu Lauquen, Lumabia-El 25	(3) Cretaceous to Miocene volcanics	Rodentia	−36.6801	−71.0921	Modern	0.7040	0.000012
#205	Laguna Tromen	(4) Pliocene to Quaternary volcanics (basaltic)	*Ctenomys* sp.	−37.0955	−70.118	Modern	0.7045	0.000013
#207	Techos Verdes	(4) Pliocene to Quaternary volcanics	*L. guanicoe*	−37.7485	−68.8964	Modern	0.7066	0.000013
#209	Loma Amarilla	(4) Pliocene to Quaternary volcanics	*L. guanicoe*	−37.76	−68.6876	Modern	0.7066	0.000009
#49	Cueva Huenul 1	(4) Pliocene to Quaternary volcanics (ignimbrite)	Rodentia	−36.957	−69.822	Archaeological	0.7068	0.000016
#50	Cueva Huenul 1	(4) Pliocene to Quaternary volcanics (ignimbrite)	Rodentia	−36.957	−69.822	Archaeological	0.7062	0.000013
#34	Cueva Yagui	(4) Pliocene to Quaternary volcanics	Rodentia	−36.948	−69.884	Archaeological	0.7059	0.000011
#35	Cueva Yagui	(4) Pliocene to Quaternary volcanics	Rodentia	−36.948	−69.884	Archaeological	0.7065	0.000013

TABLE 2 $^{87}Sr/^{86}Sr$ values for human remains from Neuquén Province

Code	Site	Individual	Radiocarbon dates	Sample	Geologic unit	$^{87}Sr/^{86}Sr$	±2 s internal
#187	Hermanos Lazcano	C2I3	3780 ± 50 (Hajduk et al., 2007)	Rib (cortical tissue)	(2) Jurassic/Cretaceous sedimentary	0.7070	0.000010
#188	Aquihuecó	43	4199 ± 35 (Gordón, Beguelin, Rindel, et al., 2019)	Rib (cortical tissue)	(2) Jurassic/Cretaceous sedimentary	0.7070	0.000013
#201	Aquihuecó	38	~4000	Rib (cortical tissue)	(2) Jurassic/Cretaceous sedimentary	0.7070	0.000014
#189	Añelo	C1.4	~600	Rib (cortical tissue)	(2) Jurassic/Cretaceous sedimentary	0.7070	0.000009
#190	Chorriaca		1152 ± 33 (Gordón, Beguelin, Rindel, et al., 2019)	Rib (cortical tissue)	(2) Jurassic/Cretaceous sedimentary	0.7077	0.000011
#192	Rincón de los Sauces rescue		Unknown	Rib (cortical tissue)	(2) Jurassic/Cretaceous sedimentary	0.7067	0.000012
#193	Zorrillos/Chihuidos		Unknown	Rib (cortical tissue)	(2) Jurassic/Cretaceous sedimentary	0.7064	0.000013
#194	Chacra Álvarez		330 ± 32 (Gordón, Beguelin, Rindel, et al., 2019)	Rib (cortical tissue)	(2) Jurassic/Cretaceous sedimentary	0.7072	0.000010
#199	M. Moreno (Piera)		229 ± 32 (Gordón, Beguelin, Rindel, et al., 2019)	Rib (cortical tissue)	(2) Jurassic/Cretaceous sedimentary	0.7072	0.000012
#191	Gubevi	I2	1878 ± 43 (Della Negra, 2008)	Rib (cortical tissue)	(3) Cretaceous to Miocene volcanics	0.7048	0.000012
#196	Andacollo		Post-contact	Rib (cortical tissue)	(3) Cretaceous to Miocene volcanics	0.7047	0.000011
#197	Cochico Márquez		2449 ± 34 (Gordón, Beguelin, Rindel, et al., 2019)	Rib (cortical tissue)	(4) Pliocene to Quaternary volcanics	0.7058	0.000013
#198	El Panteón		Post-contact	Rib (cortical tissue)	(4) Pliocene to Quaternary volcanics	0.7043	0.000013
#200	Michacheo		1860 ± 40 (Lema et al., 2012)	Rib (cortical tissue)	(4) Pliocene to Quaternary volcanics	0.7058	0.000010
#195	Retamal I		Post-contact (190 BP)	Rib (cortical tissue)	(5) Quaternary undifferentiated	0.7072	0.000019

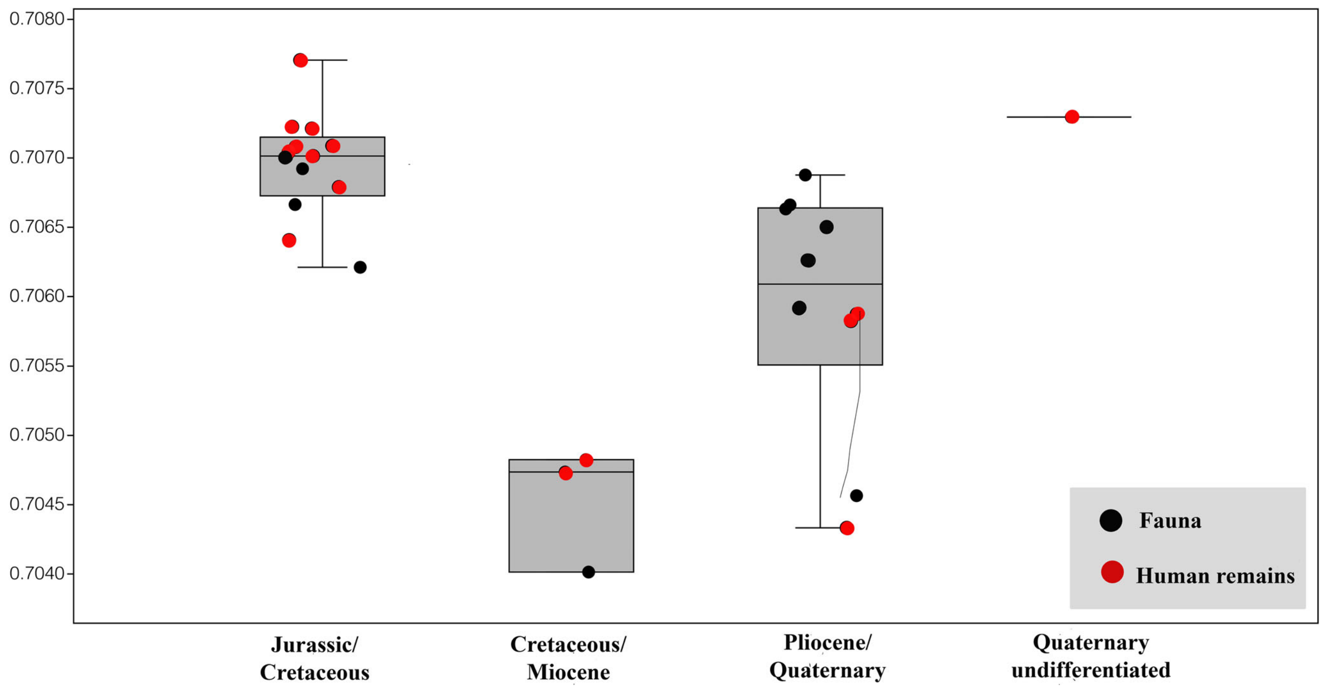

FIGURE 5 $^{87}Sr/^{86}Sr$ values for faunal and human remains from Neuquén Province analyzed by geological provenience [Color figure can be viewed at wileyonlinelibrary.com]

However, other human samples located in a similar geological context but distantly located, such as Chihuidos and Piera-Mariano Moreno, display very similar $^{87}Sr/^{86}Sr$ values (~0.7070). This suggests that there is a potential situation of equifinality where geological contexts of a similar age but located far from each other produce a similar strontium signature. The human sample from Retamal site, pertaining to the Post-contact period (190 years BP) and located in the geological unit (5) Undifferentiated Quaternary deposits, produces a very similar value (0.7072) that could be due to the contiguity between this site and the unit (2) Jurassic to Cretaceous Sedimentary rocks, from where the sediments may be ultimately derived.

The two human samples from the geological unit (3) Cretaceous to Miocene volcanics present the least radiogenic $^{87}Sr/^{86}Sr$ values, averaging 0.7047. The sample from Andacollo corresponds to a Post-contact context, while the sample from Gubevi has been dated to 1800 years BP and is associated with the earliest ceramics in the region (Della Negra, 2008). Finally, we present results for three human samples from the unit (4) Pliocene to Quaternary volcanic, ranging between 0.7043 and 0.7058 (Table 2). The sample with the lower value comes from the historic site El Panteón, which is associated with horse remains (Navarro, 2016), while the other two come from contexts dated between 2500 and 1800 cal years BP.

5 | DISCUSSION AND CONCLUSIONS

In this study, we have presented the first set of results of strontium isotopes in faunal and human samples from Neuquén province, northwestern Patagonia, in combination with a macro-regional geological framework that guides current and future sampling. The discussion is preliminary since the study area is large and the sample size is small. However, a number of tendencies relevant in methodological and archaeological terms can be discussed. Overall, the results conform to general expectations derived from rock age and composition (Bentley, 2006; Faure & Powell, 2012), since the oldest geological province in the study area (Jurassic–Cretaceous sedimentary rocks) presents the most radiogenic $^{87}Sr/^{86}Sr$ values (0.7066 ± 0.0003). Conversely, the lowest values (~0.704) are recorded for samples from recent basaltic geological substrates, such as the Laguna del Tromen area (Folguera et al., 2008) and Epu Lauquen-Lumabia.

Our results identify both advantages and limitations for strontium research in Neuquén. On the one hand, this is a geologically diverse landscape associated to variable isotopic values. The $^{87}Sr/^{86}Sr$ range is similar to that recorded by Serna et al. (2020) on the basis of a larger sampling for Río Negro Province. While our faunal sampling is small, apparently, there is a relation between rock age and type and isotopic value, where the Jurassic/Cretaceous rocks provide the most radiogenic endmember and the Pliocene to Quaternary basaltic volcanic features are associated with the least radiogenic ratios. This may suggest that the effect of isotopic homogenization across the landscape produced by volcanic activity and dust transport (Serna et al., 2020) is not prevailing in Neuquén. However, a larger sample size is needed in our study area. On the other hand, the bioavailable $^{87}Sr/^{86}Sr$ isotopic range reconstructed for both Neuquén and Río Negro Provinces is more restricted than was reconstructed for Mendoza Province and Central Chile, northward from Patagonia, where the presence of Paleozoic rocks outcropping in the Precordillera region produces highly radiogenic values up to 0.7110 (Barberena et al., 2020), not recorded yet in northwestern Patagonia.

While preliminary, our results show a situation of equifinality that configures a limitation in terms of spatial resolution that needs to be acknowledged. For instance, the Jurassic/Cretaceous units (2) outcrop in multiple areas of northwestern Patagonia, ranging from the seasonal highlands near the international Argentina–Chile border to the Auca Mahuida volcanic field in the eastern lowlands, and something similar occurs with the Pliocene to Quaternary volcanics. The first results indicate a similar isotopic composition in different areas coinciding with the age and general composition of the rock substrates.

The results in human samples would indicate fidelity of the human samples to the values recorded in the local geology, in some cases in a clearer manner than in others. While preliminary, this may suggest a *restricted spatial scale of mobility* during the late Holocene, which would not have systematically connected distant altitudinal areas. However, this does not necessarily imply low mobility, since mobility could have been high within widespread geologically homogeneous areas. The bioarchaeological context of the earliest samples included here—Aquihuecó and Hermanos Lezcano—dated to ca. 4000 years BP provides additional and independent insights into a possible situation of reduced mobility. The values obtained for two individuals from Aquihuecó and one from Hermanos Lazcano are almost identical to one rodent sample from Aquihuecó, hence suggesting reduced human mobility already established for the transition between the mid–late Holocene. Recently reported $\delta^{18}O$ values for Aquihuecó, Hermanos Lazcano, and Cape Malal sites in the Curi Leuvú basin display a similar range of variation, indicating a similar pattern of mobility throughout the mid to late Holocene and suggesting that the highlands were part of a regional system of mobility that included the Curi Leuvú basin as a residential area (Bernal et al., 2020). In addition, these sites can be characterized as formal burial areas redundantly used through time, including an association with grinding artifacts for processing plant foods (Della Negra & Novellino, 2005; Della Negra et al., 2014; Gordón, Béguelin, Novellino, et al., 2019). In this case, then, strontium isotopes would independently corroborate inferences made on the basis of $\delta^{18}O$ values, demographic, and contextual information.

Three human samples produce particularly low isotopic values of around 0.7046. Two of these samples come from historical contexts in Andacollo and El Panteón sites, while the third comes from Gubevi site, which presents some of the earliest associations with ceramic technology in the region at 1800 years BP (Della Negra, 2008; Hajduk et al., 2011). On the one hand, these samples may reflect high fidelity to those areas with very low radiogenic signals in Neuquén. While possible, this is not likely, given the highly circumscribed spatial configuration of these units. Another possibility is that these are nonlocal individuals that migrated from other regions. The main option could be the Chilean Central Valley, which has not been characterized yet at this latitude, but that shows a very low and homogeneous signature northward (Barberena, Tessone, et al., 2021). Importantly, in the context of macro-regional interaction networks, the western Andean shed was the source of people, information, and technological innovations during the early ceramic period and in historical times (Berón et al., 2013; Boccara, 1999; Hajduk et al., 2011; Pérez et al., 2013; Romero Villanueva et al., 2020).

5.1 | Perspectives

The study of strontium isotopes as a proxy for spatial scales of human paleomobility is articulated with multiple lines of evidence in a biogeographic research framework that seeks to understand the movements of people, flow of material objects, and circulation of information across and along the rugged landscape of the Patagonian Andes. An ongoing macro-regional program of geoarchaeological and geochemical characterization of Andean and extra-Andean obsidian sources allows tracking lithic provisioning, use, and discard (Barberena, Fernández, et al., 2019; Fernández et al., 2017, 2019; Rindel et al., 2020). We are also conducting a large-scale survey and morphological characterization of rock art in northern Neuquén Province, which suggests the existence of a sphere of exchange of information that ties distant areas (Barberena, Romero Villanueva, et al., 2017; Romero Villanueva, 2019; Romero Villanueva et al., 2020; see also Campbell et al., 2020; Martínez et al., 2017). Finally, at a much smaller regional scale, we have recently presented a systematic survey across a representative topographical profile that informs not on scale, but on modes of mobility (Rughini et al., 2020). In synthesis, and far from providing redundant information, each line of archaeological evidence yields insights on different levels of the spatial and social organization of mobile societies in Patagonia.

While the strontium results presented here are certainly preliminary, they go a long way in helping us define the steps forward. The main task ahead lies in a thorough characterization of isotopic variability across this complex geological landscape, not only in northwestern Patagonia but also in southern Mendoza, La Pampa, and Río Negro Provinces, and the western Andean shed. For instance, a comparison of the results on bioavailable strontium presented here for Neuquén with those from the neighboring Payunia volcanic field in southern Mendoza, largely dominated by recently deposited basic volcanic rocks (Españon, 2010), holds great potential for discriminating human groups inhabiting on both sheds of the Colorado River. In doing this, we will be able to bridge the systematic information that is being produced northward for an Andean transect in northern Mendoza and Central Chile (Barberena et al., 2020) and southward in Río Negro Province (Serna et al., 2020). In addition, we will conduct a wider study of human remains from the sites initially characterized here, incorporating the analysis of different tissues, thus providing access to the study of human life histories (Torres-Rouff & Knudson, 2017). The combination of radiogenic and stable isotopes such as oxygen will provide the most robust approach by combining the respective strengths of these paleogeographic markers. Building on this, we look forward to improving our understanding of the historical evolution of the Patagonian societies in this fascinating Andean landscape.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

ORCID

Ramiro Barberena http://orcid.org/0000-0002-4323-1197

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