

Revealing micro-environmental subsistence diversity in the SouthernAndes through organic residue analysis in pottery (Tucumán, Argentina, 200-800 CE).

Agustina Vázquez Fiorani, Mark Schurr, Valeria Franco Salvi y Eleanora Reber.

Cita:

Agustina Vázquez Fiorani, Mark Schurr, Valeria Franco Salvi y Eleanora Reber (2026). *Revealing micro-environmental subsistence diversity in the SouthernAndes through organic residue analysis in pottery (Tucumán, Argentina, 200-800 CE)*. *Archaeological and Anthropological Sciences*, 18 (96), 1-18.

Dirección estable: <https://www.aacademica.org/eascc/153>

ARK: <https://n2t.net/ark:/13683/pzay/3uv>



Esta obra está bajo una licencia de Creative Commons.
Para ver una copia de esta licencia, visite
<https://creativecommons.org/licenses/by-nc-sa/4.0/deed.es>.

Acta Académica es un proyecto académico sin fines de lucro enmarcado en la iniciativa de acceso abierto. Acta Académica fue creado para facilitar a investigadores de todo el mundo el compartir su producción académica. Para crear un perfil gratuitamente o acceder a otros trabajos visite:
<https://www.aacademica.org>.



Revealing micro-environmental subsistence diversity in the Southern Andes through organic residue analysis in pottery (Tucumán, Argentina, 200–800 CE)

Agustina Vázquez Fiorani¹ · Mark Schurr¹ · Valeria Franco Salvi² · Eleanora A. Reber³

Received: 20 October 2025 / Accepted: 25 March 2026 / Published online: 15 April 2026
© The Author(s) 2026

Abstract

The spread of agropastoralism in the South-Central Andes involved diverse local adaptations that are often difficult to detect due to poor preservation of organic remains. To address this challenge, we conducted a large-scale organic residue study of 172 Formative Period (200–800 CE) pots from three contemporaneous villages in the Tafi Valley, northwestern Argentina. Using gas chromatography–mass spectrometry (GC-MS), compound-specific isotope analysis (GC-C-IRMS), and bulk isotope analysis of charred food crusts (EA-IRMS), we reconstructed subsistence practices and local foodways across distinct micro-environments. Biomolecular and carbon-stable isotopes on lipids and charred food crusts ($\delta^{13}\text{C}$) showed the exploitation of C_3 plants and ruminant animals and a clear regional patterning of broad subsistence strategies. These findings provide the first direct chemical evidence of subsistence micro-diversity within the Southern Andes, demonstrating that neighboring communities pursued distinct combinations of farming and herding despite similar cultural traditions. Methodologically, the study highlights both the potential and limitations of lipid residues for detecting plant use in South American contexts, and underscores the need for expanded regional reference datasets.

Keywords Organic residue analysis · Stable isotopes · Foodways · Environmental diversity · Andes

Introduction

Two thousands years ago, people living in the South Central Andes started to increase their reliance upon a wide range of domesticated plants and animals, began living in progressively more clustered villages, and developed new technologies to support an agropastoral life (González and Nuñez Regueiro 1960; Bermann and Castillo 1995; Albeck 2000; Olivera 2001; Stanish 2003; Nuñez et al. 2006; Hastorf 2008; Capriles 2014; Scattolin 2015; Marsh 2015; Langlie and Capriles 2021). Nonetheless,

the types of crops, agricultural technology, labor organization, and social differentiation evolved regionally and formed ever-changing conditions across many different environments, reflecting people's different strategies to cope with the challenges of agropastoral lifestyles (Dillehay 2011).

The Southern Calchaquí valleys in Northwestern Argentina [NWA] are a series of adjacent valleys (El Cajón, Tafi, Yocavil) and high-altitude ravines (El Infiernillo) with evidence of early agropastoral communities from the beginning of the first millennium of the Christian Era (Aschero and Ribotta 2007; Berberian 1988; Cortés 2023; Cremonte 2003; Franco Salvi et al. 2023; Gero 2015; Moyano et al. 2023; Oliszewski et al. 2017; Palamarczuk et al. 2007; Salazar et al. 2022, 2024; Salazar and Kuijt 2016; Scattolin 2019; Scattolin et al. 2009). In the Southern Calchaquí valleys, mobility reduction and the emergence of year-round settlements seem to have been linked to the progressive consolidation of intensive, productive economies based on the exploitation of domesticated and wild plants and animals, many

✉ Agustina Vázquez Fiorani
mvazque3@nd.edu

¹ Department of Anthropology, University of Notre Dame, 296 Corbett Family Hall, South Bend, Indiana, USA

² Instituto de Humanidades, CONICET, Haya de la Torre s/n, Córdoba, Argentina

³ Department of Anthropology, University of North Carolina Wilmington, 601 S. College Rd., Wilmington, NC, USA

of which were already being exploited by hunter gatherers, such as quinoa (Albeck 2000; Calo 2014; Korstanje et al. 2015; Oliszewski and Arreguez 2015; Franco Salvi et al. 2025).

Extensive archaeological research has been conducted in the Tafi Valley (Tucumán, Argentina), showing strong social and material ties between autonomous agropastoral communities that intensively populated the area during 200–800 CE. Moreover, the Tafi Valley provides a great laboratory to explore the variable and flexible ways by which early farmers and herders built their subsistence basis: topography, altitude, and temperature variations across this narrow basin generate several micro-niches with different potentials for human exploitation. Nonetheless, this enterprise is severely hampered by the poor preservation of organic remains, such as macrobotanical and faunal specimens, mostly due to soil humidity and acidity. Such conditions limit our ability to fully reconstruct subsistence strategies and food systems through traditional archaeological methods and underscores the need for analytical techniques that can recover biomolecular evidence resistant to such taphonomic processes.

Lipid residue analysis offers a powerful tool to address these issues. Lipids are highly resistant to decay due to their hydrophobic nature and can be preserved over long timescales within a ceramic matrix, providing an integrated record of vessel use (Evershed 2008a; Roffet-Salque et al. 2017; Craig et al. 2019; Reber 2022). The application of high-resolution chromatographic and isotopic techniques (GC-MS, GC-C-IRMS) allows for the discrimination of different food groups, including C_3/C_4 plants and animal fats, even when macroscopic remains are absent (Roffet-Salque et al. 2017). However, in South America such applications remain relatively novel (Lantos et al. 2025), with a growing but still limited number of large-scale regional investigations (Admiraal et al. 2023; Montalvo-Cabrera et al. 2024, 2025). The potential of this methodology to address questions of micro-scale economic diversity remains largely untapped.

This paper presents the first large-scale, cross-sectional application of biomolecular (GC-MS) and isotopic techniques (GC-C-IRMS, EA-IRMS) to investigate the interplay between subsistence strategies and ecological diversity in the Argentinian Andes. By analyzing a robust sample of 172 vessels from three villages situated in different micro-environments within the Tafi Valley, we aim to address how early Andean villagers diversified subsistence across distinct ecological conditions, testing the feasibility and effectiveness of organic residue analysis in a region known for poor organic preservation.

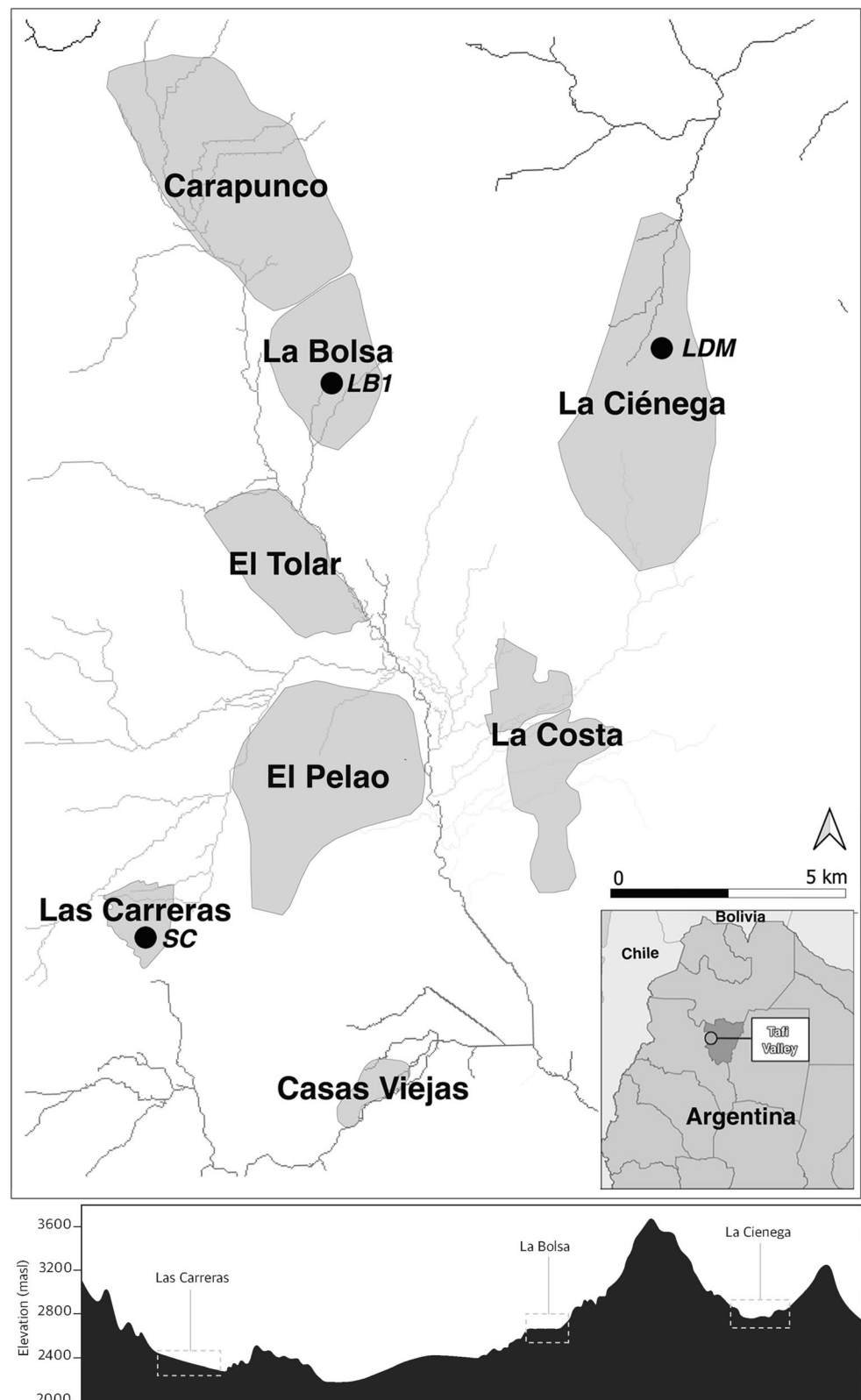
The Tafi Valley during the first millennium CE

From 200 BCE to approximately 800 CE, human groups settled permanently in the Tafi Valley (Tucumán, Argentina), densely populating it with dozens of villages and hamlets scattered across the landscape and occupied year-round (González and Nuñez Regueiro 1960; Bernasconi de García and Baraza de Fonts 1982; Berberían 1988; García Azcárate 1996; Cremonte 2003; Sampietro and Vattuone 2005; Dlugosz et al. 2009; Salazar and Kuijt 2016; Oliszewski et al. 2017; Manasse 2023; Franco Salvi et al. 2025). From 200 to 800 CE, the basic unit of socio-political and economic organization was the household, which exhibited a high degree of autonomy at the residential and ceremonial scale with the decentralized control of productive lands surrounding the houses (González and Nuñez Regueiro 1960; Berberian and Nielsen 1988; Cremonte 2003; Sampietro and Vattuone 2005; Salazar and Kuijt 2016; Oliszewski et al. 2017; Molar 2022; Franco Salvi et al. 2025). Participation and/or access to regional exchange networks is also seen in the presence of fruits, obsidian, and other nonlocal raw materials, but no evidence for differential access to resources suggestive of marked social differences at the household or village level is observed (Franco Salvi et al. 2017; Moyano et al. 2023; Salazar and Kuijt 2016 a). Instead, Tafi peoples seems to have managed to craft sustainable and enduring lifestyles that persisted successfully for several centuries without developing marked socio-economic inequalities.

The Tafi Valley's setting between the eastern Andean rainforests (*yungas*) and the high-altitude plateau (*puna*) combines gentle alluvial slopes with rugged hills, and encompasses different altitudinal zones up to 3000 m.a.s.l (Fig. 1). This geographical setting belongs to the *keshua* ethno-category; the Quechua name for “protected and cultivated valleys”. It has an average temperature of 13.5 °C, a semi-arid steppe climate with seasonal rains and a dry winter, with approximately 400 mm of annual precipitation, mainly concentrated in the summer months (87%) (Sesma 1987). Nonetheless, altitude and topographic variation influence vegetation distributions and temperature fluctuations, generating several micro-climate niches (García Salemi 1988).

Berberían (1995) suggests that differences in agricultural systems and productivity levels exist between the southern (Las Carreras) and northern (Carapunco) parts (or subregions) of the Tafi Valley. Based on experimental work with native crops and traditional farming techniques, he observed that unfertilized tubers and quinoa yields were higher in Carapunco than in Las Carreras, which were productive for maize and potato harvests (Berberían 1995). Conversely, maize did not yield any harvests in the northern sector.

Fig. 1 Map of the Tafi Valley with its different parts or subregions including location of archaeological sites analyzed in this article



Thus, it is possible that different areas of the Tafi Valley afforded particular ecological constraints and possibilities in terms of access to natural resources and economic practices,

shaping local farming lifestyles in the past. Yet most of research in the Tafi Valley is limited by soil humidity and acidity that impacts the preservation of human, fauna, and

plant remains and thus, restrict our reconstruction of past foodways and subsistence strategies.

To date, scholars have investigated agropastoral practices by studying plant microfossils in sediments and ceramics, soil chemistry (mapping higher phosphorous levels in houses, fields, and corrals), topography, and architectural features (i.e., terraces, crop plots, corrals) (Franco and Berberian 2012; Franco Salvi et al. 2014, 2023, 2025; Molar 2022; Chiavassa-Arias and Franco Salvi 2024). Because intra-site reconstructions of food choices and culinary practices are often difficult with fragmentary datasets, archaeologists agree on the existence of a mixed agropastoral economy shared by different autonomous communities

during 200–800 CE (Salazar and Kuijt 2016; Molar 2022; Franco Salvi et al. 2025), with eventual participation in complementarity networks with the eastern rainforests for non-staple goods (i.e. wood, fruits, salt) (Cremonte 2003). In some cases, it was inferred that the northern parts of the Tafi valley could have a stronger herding component in their economy (Berberian and Nielsen 1988; Cremonte 2003), although this interpretation was nuanced by the analysis of agricultural landscapes at La Bolsa and Carapunco (Franco Salvi 2012).

In this paper, we focus on three agropastoral settlements: La Bolsa 1, Santa Cruz, and Lomita del Medio. Each archaeological site is located at different altitudinal zones in the southern (Las Carreras: Santa Cruz) and northern (La Ciénega: Lomita del Medio and La Bolsa: La Bolsa 1) subregions of the Tafi Valley (Figs. 2 and 3). The sites are separated by a distance of 10 km approximately.

Previous studies demonstrated that these settlements were inhabited during the period from 250 to 800 CE. All of them exhibit strong similarities in terms of the built environment and material culture, including shared ways of making pottery and flint-knapping (Berberian and Nielsen 1988; Franco Salvi et al. 2017; Montegu and Franco 2020; Vázquez Fiorani et al. 2026), domestic architecture (Berberian and Nielsen 1988; Franco Salvi et al. 2023; Moyano et al. 2023; Salazar et al. 2024), and burial practices (Franco Salvi 2018; Salazar and Kuijt 2016). Figure 4 presents the floorplan of the excavated residential units presented in this article, showing the similar architectural pattern. Based on that evidence, the three settlements can be interpreted as part of a same social and cultural universe, yet it is possible that each one might have enacted different relationships to their local environment, creating diversified subsistence strategies and foodways.

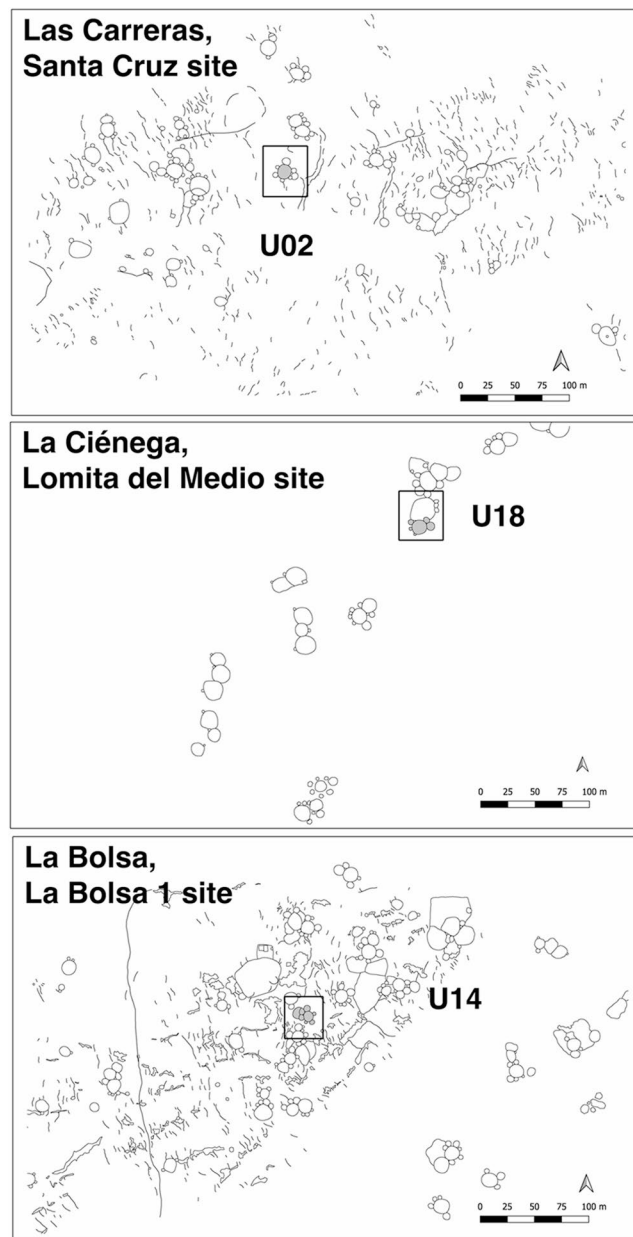


Fig. 2 Map of each archaeological site analyzed in this article

La Ciénega, Lomita del Medio site Located in a high-altitude ravine in the northeastern portion of the Tafi Valley, La Ciénega has a maximum altitude of 2800 m.a.s.l, with a semi-arid climate and is located in the foggy glasslands, a transition area between the montane forest and puna [high-altitude plateau] (Cabrera 1976). Local vegetation in La Ciénega is well suited to cold and wet weather, and is resistant to the cloud covers, mists and rains that affect the valley, especially during the winter. It has been interpreted that people living in this ecotone focused on camelid herding due to its abundant pastures (Cremonte 1997), yet there are areas with good agricultural potential including fertile soil and gentle slopes (Franco Salvi et al. 2025). At La Ciénega, we excavated one residential unit (U18) in the Lomita del Medio (LDM) archaeological site (Fig. 4a).

La Bolsa, La Bolsa 1 site Located in the narrow and higher tip of the Tafi Valley, La Bolsa is characterized by a semi-arid climate

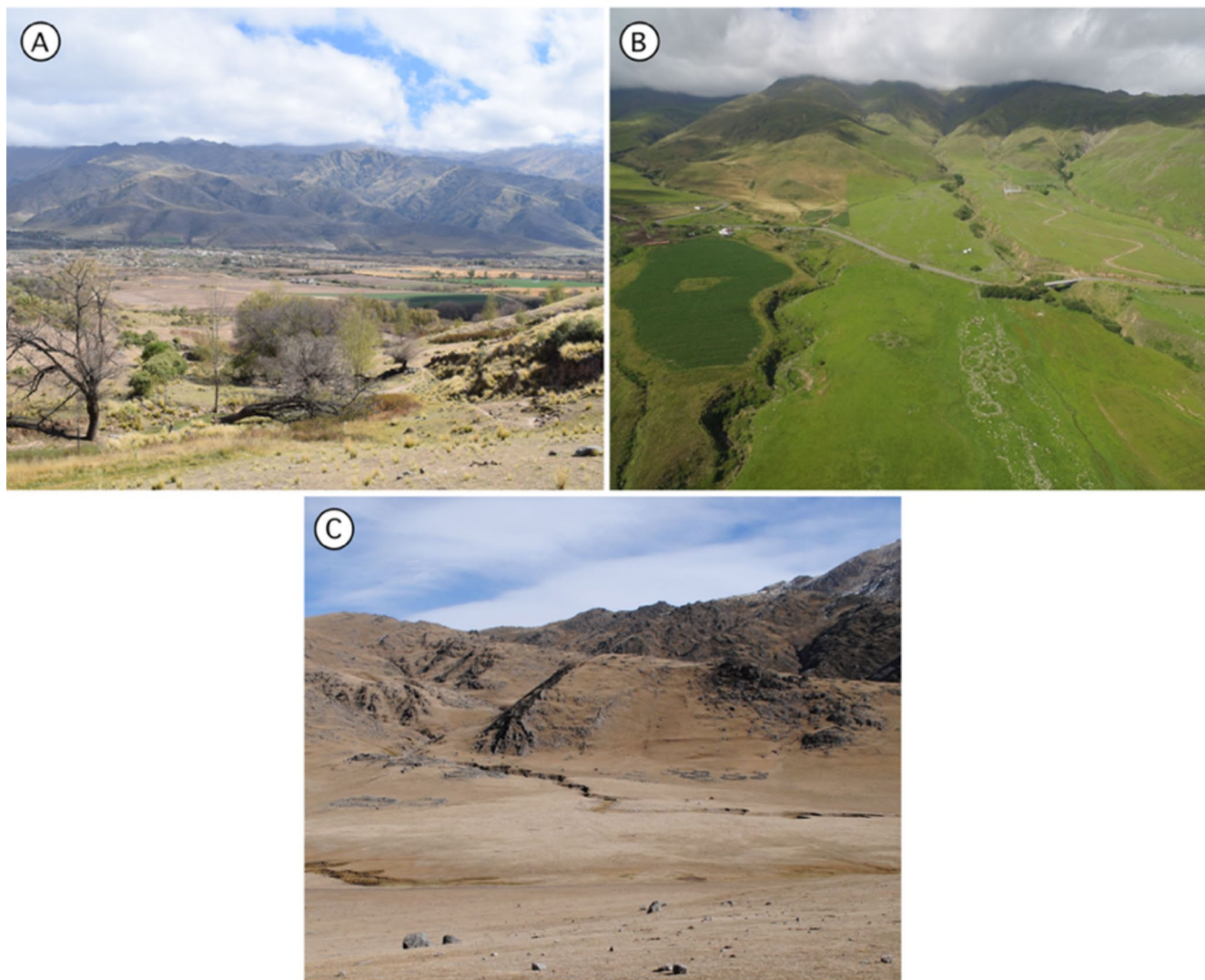


Fig. 3 Aerial and lateral views of the southern and northern parts of the Tafi Valley, **a**) Las Carreras (winter), **b**) La Bolsa (summer), **c**) La Ciénega (winter)

with vegetation adapted to the colder temperatures, dryer conditions, and higher altitude at 2500 m.a.s.l. Local flora is composed of short shrubs. Gentle slopes ($>8\%$) and good soil humidity retention make the area well-suited for agriculture without specialized infrastructure (Berberían 1995). Nevertheless, archaeological features identified in the site include terraces, irrigation channels, and corrals (Franco Salvi et al. 2014; Molar 2015). Salazar (2010) excavated a residential unit (U14) in La Bolsa 1 (LB1) archaeological site (Fig. 4b).

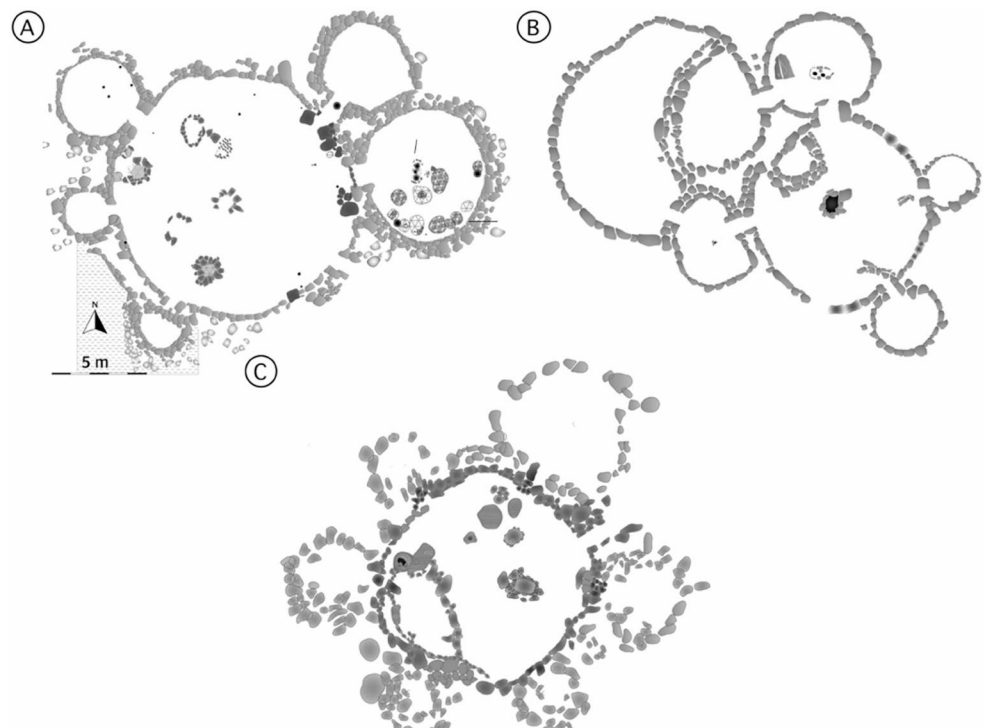
Las Carreras, Santa Cruz site Located in an alluvial cone in the southern portion of the Tafi Valley, Las Carreras has a maximum altitude of 2100 m.a.s.l, with a semi-arid climate. Local vegetation is composed of several types of grasslands with few local tree species. Soils have low

humidity retention, requiring intense labor for farming, and likely artificial fertilization (Berberían 1995). Intensive food production practices are revealed by the presence of terraces, irrigation channels, and corrals (Franco Salvi et al. 2023). Here, we excavated a residential unit (U02) in the Santa Cruz (SC) site (Fig. 4c).

Complementary data from published research in the Tafi Valley

As we mentioned earlier, the poor preservation of organic materials in the Tafi Valley deeply impacts the reconstruction of subsistence strategies and foodways. In the following, we summarize the available archaeological evidence for plant and animal resources exploited in the area.

Fig. 4 Floor plans from the three analyzed houses in the Tafi Valley, **a)** La Ciénega, Lomita del Medio, U18, **b)** La Bolsa, La Bolsa 1, U14, and **c)** Las Carreras, Santa Cruz, U02



Scholars have identified the presence of phytoliths associated with *Zea mays*, *Phaseolus* sp., and *Cucurbita* sp. in grinding stones and ceramics from La Bolsa 1 site (Franco Salvi et al. 2014; Molar 2022). Such findings were corroborated by phytolith and starch analyses on sediments taken from terraces and crop plots from the same site, suggesting that these plants were being grown in the area (Franco Salvi et al. 2014). Additionally, a small room inside the U14 house at La Bolsa 1 showed the presence of maize phytoliths, indicative of storage practices (Franco Salvi 2012; Molar 2022). The presence of charred fruits of *chañar* (*Geoffroea decorticans*) and likely, *algarroba* (*Prosopis* sp.) suggested the gathering of wild plants. Previous excavations at La Ciénega (El Pedregal site) reported the finding of charred remains of *Phaseolus* sp. (Cremonte 1997). Similarly, phytolith evidence from Lomita del Medio's pots indicated the presence of morphologies compatible with wild grasses (*Bromus* sp.). At Lomita del Medio, we also identified a few fragmented *chañar* fruits ($n=3$), again pointing to some degree of involvement in foraging practices. The ubiquity of grinding stones scattered across the settlement and inside the houses is strong evidence of plant processing and use at those sites, especially at Lomita del Medio and Santa Cruz (Vázquez Fiorani et al. 2026).

As we mentioned above, information on animal husbandry in Tafi is fragmentary, deriving from different datasets such as architecture (Chiavassa-Arias and Franco Salvi 2024), figurines depicting female and male llamas (Salazar 2010), and to a lesser extent, fauna remains (Molar 2022;

Chiavassa-Arias and Franco Salvi 2024). At El Tolar site, Sampietro (2002) mentions the recovery of wild faunal remains in a domestic structure, such as cervids (*Hippocamelus antisensis*, *Mazama* sp), camelids (*Lama guanicoe*) and rodents (*Ctenomys knighti*). Conversely, an offering of a male adult llama was found in one of La Bolsa 1's agricultural terraces (Franco Salvi and Salazar 2014). There, La Bolsa 1's inhabitants placed skeleton elements with low meat yields, such as skulls and limbs, suggesting that the meat-rich parts of the llama were eaten elsewhere and that the low food utility elements deposited in the ritual space symbolically representing the whole animal (Franco Salvi and Salazar 2014). A similar association between camelids and ritual practices is recorded in Lomita del Medio, where pits produced a few camelid and cervid remains associated with decorated broken sherds, likely part of propitiatory ceremonies (Franco Salvi and Justiniano 2021). At Santa Cruz, cervids and camelid fauna remains were identified in the occupation floor.

Nevertheless, some caution is needed to extrapolate the contextual association of such remains to broader socioeconomic practices. Site-formation processes and soil conditions within the Tafi Valley are highly variable and in many cases, they impact the overall preservation of organic remains, biasing the assemblages (that is, fauna could be better preserved in the closed environment of filled pits than in the house floors). Due to this, obtaining direct chemical evidence of the types of resources exploited in each settlement is fundamental to our understanding of past socio-economic dynamics in the Tafi Valley.

Materials and methods

Organic lipid analysis was conducted on 172 archaeological ceramics from three agropastoral settlements. In the case of Lomita del Medio, 15 additional samples were previously analyzed and published elsewhere (Vázquez Fiorani et al. 2025). Each sample represented one vessel, including cooking pots, jars, and bowls used for daily cooking and eating ($n=168$) but also used as grave goods ($n=4$). Functional characterization of the crockery can be found in Table 1. All samples were selected from patios and side-rooms with evidence of cooking (i.e., hearths). When possible, rims and upper body sections were preferred for sampling, as they were more likely to produce higher lipid yields (Evershed 2008b).

All samples were mechanically cleaned with a Dremel tool and then ground in a solvent-washed porcelain mortar to produce 2 g of fine powder that was subsequently stored at room temperature. In the case of 4 decorated bowls from La Ciénega, sherds were sampled by drilling to collect 2–3 mm of the inner surface (previously cleaned with distilled water after the surface sediment was mechanically removed). In this case, control samples from the outer sediment were analyzed in tandem. Then, lipids were extracted using a 2% sulfuric acid in methanol (Correa-Ascencio and Evershed 2014) to ensure a high lipid recovery, especially for plant-based residues (Reber 2021; Dunne 2022). Total acidic hydrolysis fractions were derivatized before GC-MS and GC-C-IRMS analyses using N, O-bis (trimethylsilyl) trifluoroacetamide with 1% trimethylchlorosilane (BSTFA+TMCS, 99:1) (Correa-Ascencio and Evershed 2014). Lipid extracts were analyzed with a Thermo Scientific Triple Quad GC-MS in the Material Characterization Facility (University of Notre Dame). Compound identification was done using the Thermo Chromeleon 7 software, comparing retention times with commercial standards (Supelco C4-C24 F.A.M.E. mix) and mass fragmentation patterns using NIST and Wiley mass spectra libraries and other online databases (Christie 2025). Semi-quantification of the extracts was conducted using the equation reported by Reber (2021).

A subset of samples with lipid yields higher than $5 \mu\text{g g}^{-1}$ ($n=60$) were subsequently analyzed by GC-C-IRMS to measure the $\delta^{13}\text{C}$ composition of the main alkanolic acids $\text{C}_{16:0}$ and $\text{C}_{18:0}$. The analyses were conducted at the University of

North Carolina Wilmington stable isotope facility using a Thermo Scientific GC coupled to a Iso Link II device. After the redilution of the sample aliquots for GC-C-IRMS injections, only 41 samples yielded results amenable for interpretation. Samples were run in duplicate and a calibration standard (IUB5) was run every four injections. The contribution of the extra carbon during methylation was calculated using a mass balance equation (Polissar and D'Andrea 2014). The $\delta^{13}\text{C}$ values of the archaeological lipid extracts were compared to modern and archaeological references for C_4 (maize, amaranth) and C_3 plants (quinoa, beans, *chañar*, *algarroba*), and ruminant carcass fat obtained during this study and from published data (Supplementary information 2). The threshold for South American camelids's $\Delta^{13}\text{C}$ ($\text{C}_{18:0}\text{-C}_{16:0}$) proxy values was set at -2.4 as suggested previously (Admiraal et al. 2023; Montalvo-Cabrera et al. 2025). Results were plotted using the R suite.

For the analysis of food crusts, sherds with visible adhered charred residues were sampled using a clean scalpel and stored in clean glassware until EA-IRMS analysis ($n=13$). A Finnegan Delta Plus mass spectrometer equipped with a Carlo-Erba elemental analyzer and a Conflo II interface was used at the Center for Environmental and Science and Technology (CEST), University of Notre Dame. Carbon and nitrogen isotopes were measured simultaneously. Results were standardized to USGS 43, USGS 40, sucrose, and protein standard OAS (Elemental Microanalysis). Method conditions are provided in Supplementary Materials 2.

Results

Absorbed residues

The lipid recovery yield was low overall, with only 36% of samples above the accepted threshold for interpretation ($>5 \mu\text{g g}^{-1}$, [Evershed 2008a]). This is likely due to the soil pH and moisture retention that deeply impacts the preservation of organic remains in the Tafi Valley. Cooking pots showed higher lipid preservation (up to 75% at Santa Cruz and Lomita del Medio, 60% at La Bolsa 1: the percentages were obtained from the subset of samples with interpretable results) than bowls and jars, perhaps due to the very porous fabrics of cooking pots compared with the fine and smoothed walls of service vessels which might prevent residues from being easily absorbed. Additionally, the heating of pots during cooking (rather than just containing or storing foods) might also contribute to the differences in yields we observe across groups.

Overall, the lipid extracts showed a mixture of saturated fatty acids ($\text{C}_{8:0}\text{-C}_{32:0}$), branched fatty acids ($\text{C}_{14}\text{-br-C}_{18}\text{-br}$),

Table 1 Functional characterization of selected samples by each settlement

	Cooking pots	Bowls and jars	Total
La Bolsa, La Bolsa 1	41	17	58
La Ciénega, Lomita del Medio	41	15	56
Las Carreras, Santa Cruz	42	16	58

and monounsaturated fatty acids ($C_{16:1}$, $C_{18:1}$). No polyunsaturated fatty acids were identified in any sample. Neutral compounds such as fatty alcohols (C_{18} – C_{30}) and sterols (with their degradation products) were occasionally identified in some samples. Control samples ran in tandem with archaeological specimens did not show traces of contaminant compounds. Supplementary Material 3 provides a summary of the main compounds identified in this study.

Lipid profiles suggest differences in the types of food resources processed and/or consumed between the northern (Lomita del Medio and La Bolsa 1) and southern (Santa Cruz) settlements. In the former case, recovered compounds are associated with the presence of degraded ruminant fats, while the latter exhibit evidence of plant oils and waxes (Fig. 5).

Odd-chain fatty acids such as $C_{15:0}$ and $C_{17:0}$ (but up to $C_{29:0}$ in a few samples) are widely distributed in the samples, although their presence together with $C_{19:0}$ is sparse. This combination is higher at La Bolsa 1 (43%) and Lomita del Medio (35%) than at Santa Cruz (25%), indicating a more widespread presence of degraded animal fats in the first two cases. Up to 90% of samples from Lomita del Medio and La Bolsa 1 exhibit branched fatty acids (i.e., C_{14} -br, C_{15} -br, C_{16} -br). These fatty acid compounds are often associated with the bacterial action in the rumen and used as evidence of carcass ruminant fats processing in pots (Lantos et al. 2015). Nevertheless, their presence in soil bacteria makes them unsuitable for determining food origins alone (Dudd et al. 1998). Thus, although we acknowledge their presence in our samples we do not use them as specific biomarkers.

Long-chain saturated fatty acids (LCFA, longer than 20 carbon atoms and very long-chain fatty acids >26 carbon atoms) and a predominance of even- over odd-chain fatty acids suggests the processing of epicuticular waxes of plants. Because they can also occur in ruminant products, incorporated *via* routing from the animal's plant diet, they can only be used as indicators of plant resources if found together with long-chain *n*-alkanols and *n*-alkanes (Dunne 2022; Dunne et al. 2022). Finally, fatty acids in the range C_{20} – C_{24} are also distinctive of fish resources, although they tend to be highly unsaturated, and the latter has not been found in our study.

Very long-chain fatty acids presence were confirmed in 70% of the samples (SC=70%, LB1=76%, LDM=75%). Long-chain *n*-alkanes (up to C_{35}) with a clear predominance of odd over even-numbered are widely distributed (SC=90%, LB1=85%, LDM=80%) (Dove and Mayes 2006; Whelton et al. 2021; Dunne et al. 2022). Nonetheless, the presence of long-chain *n*-alkanols (up to OL 26) is more sparse in our dataset (LB1=47%, LDM=35%) and are absent at Santa Cruz. For interpretative purposes, we consider them as a group rather than individually.

At La Bolsa 1, LCFA co-occur in samples displaying odd-chain fatty acids (38%). These might indicate the presence of degraded ruminant fats. Samples with LCFA and even-numbered *n*-alkanols along with odd-chain fatty acids suggest mixing of plant and animal products in the same containers at La Bolsa 1 (47%). A sub-set of Lomita del Medio's pots might have been used for processing plants due to the combination of even-numbered *n*-alkanols, LCFA, and odd-numbered *n*-alkanes (35%).

The maize biomarker *n*-dotriacontanol (Reber and Evershed 2004; Reber et al. 2004, 2020) is absent in all of our samples. Previously, Vázquez Fiorani and colleagues (2025) identified this compound in one sample from a pot from Lomita del Medio. This is perhaps due to the overall low lipid recovery rates or the preferential leaching and/or oxidation of such compounds.

Phytosterols were identified in a few samples (less than 5%), mainly stigmasterol and β -sitosterol in trace amounts, which are known constituents of Andean species such as maize and beans (Lantos et al. 2015, 2018). Cholesterol degradation products were mostly absent in the analyzed samples, except in a few samples from Lomita del Medio and La Bolsa 1. No indication of handling contamination, such as squalane (Whelton et al. 2021; Reber 2022), was observed in any sample.

The ratio of palmitic/stearic acid (P/S ratio) can theoretically provide insights into differences between terrestrial and plant commodities (Dunne et al. 2016). The P/S at Lomita del Medio and La Bolsa 1 exhibit values that are mainly around 1–2, suggestive of degraded animal fats, while Santa Cruz had higher ratios up to 5 consistent with plant oils. Nevertheless, the P/S patterning is not proven to remain stable over archaeological timescales, as $C_{16:0}$ is more soluble than $C_{18:0}$ and therefore, prone to leaching during burial, thus producing misleading ratios (Whelton et al. 2021). This might explain why some samples from Santa Cruz (SC-33, SC-08, SC-50) have P/S ratios assignable to degraded animal fats but isotopic values consistent with C_3 plants (see below). Additionally, there were several samples from La Bolsa 1 with high P/S ratios and biomolecular evidence indicative of plant processing.

In order to tackle the origin of residues in the analyzed pots, we conducted compound specific isotopic analysis on 60 samples. We only considered peaks with an area threshold exceeding 1000 Vs (volt-seconds) to ensure an adequate signal-to-noise ratio and to maintain analytical precision and accuracy. Due to this, we only report the $\delta^{13}C$ values of the main alkanolic acids ($C_{16:0}$ and $C_{18:0}$) in 41 samples. Table 2 presents the main biomarkers of interest, P/S ratio and the isotopic attribution of residue origin.

Overall, both palmitic and stearic acids are depleted in $\delta^{13}C$ (as low as -33‰) at the three sites (Table 2), suggesting

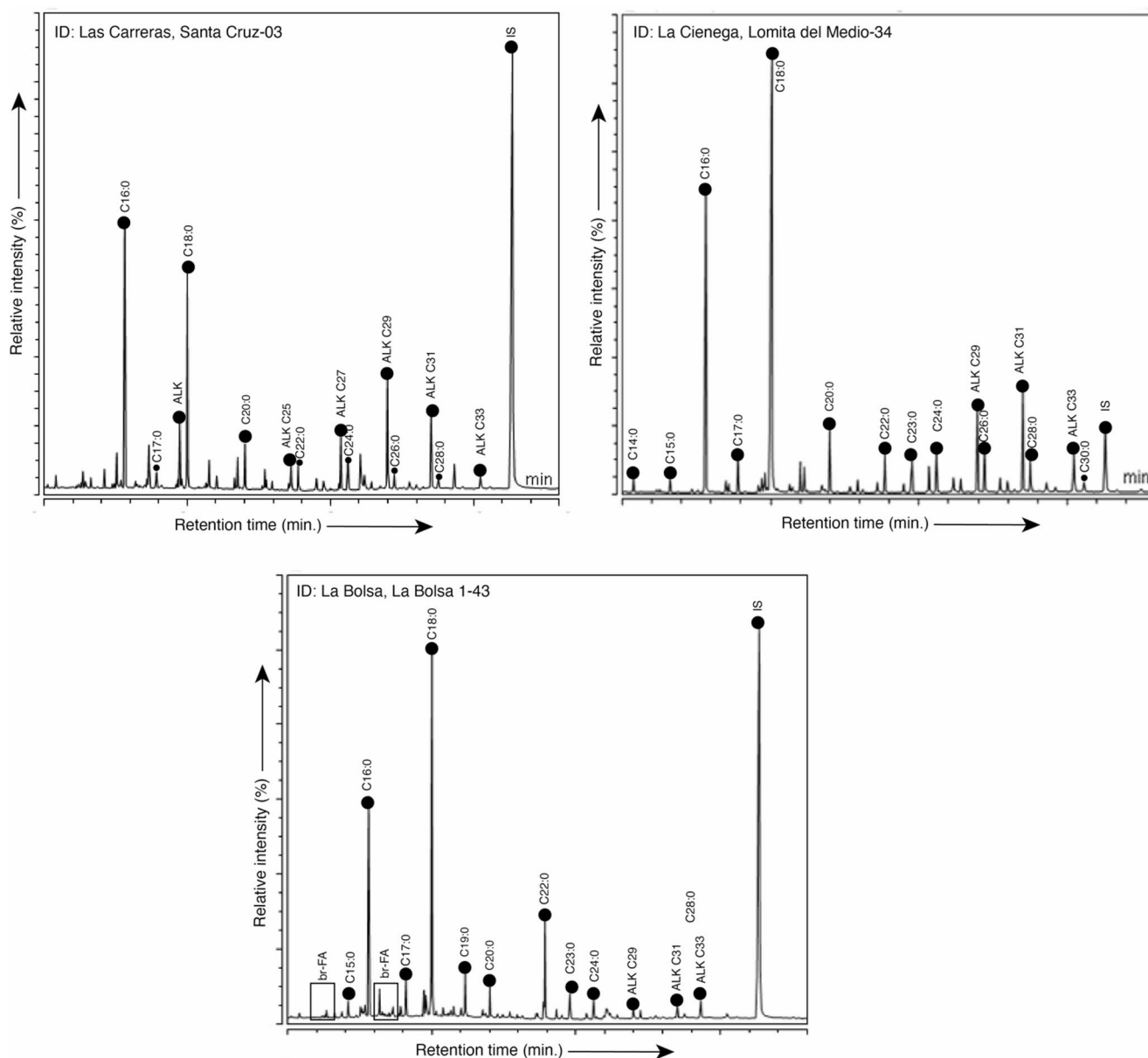


Fig. 5 Total ion chromatograms (TIC) of selected samples from the three analyzed sites. The methyl ester (ME) derivatives of relevant compounds are expressed as Cx: n (x carbon atoms, n representing

single or double carbon bonds). ALK=alkane with x carbon atoms, br-FA=branched fatty acids, IS= internal standard (C³⁴, n-tetatriacontane)

a high contribution of C₃ plants and ruminant adipose fats. It is worth noting that $\delta^{13}\text{C}$ values align clearly within the mentioned ranges, without any evidence of outlier samples in the marine or nonruminant ranges. While there is partial overlapping of freshwater and C₃ plant values in reference databases (Supplementary Info 2), there is no indication of exploitation of freshwater resources in the analyzed sites, nor biomarkers associated with such foods (Reber 2022) and thus, we confidently ruled out these.

When compared between sites, there are differences in the isotopic composition of the main alkanoic acids between Santa Cruz and La Bolsa 1/Lomita del Medio (Fig. 6a).

Slightly more positive $\delta^{13}\text{C}$ values from some pots from Santa Cruz and La Bolsa 1 could suggest the mixing of C₃ plants with C₄ plants (Fig. 6b and d). Additionally, the more widely dispersed values (or more variable) in Santa Cruz could indicate variable mixing of C₄/C₃ plants or recipe switching over time. Conversely, at Lomita del Medio and La Bolsa 1, we observe a higher contribution of residues deriving from ruminant adipose fats (LDM=61%, LB1=87%, SC=25%) and C₃ plants (LDM=39%, LB1=13%, SC=75%) compared to Santa Cruz.

Another approach to distinguish the origin of animal fats is the $\Delta^{13}\text{C}$ proxy, which allows to discriminate between

Table 2 Main biomarkers identified in our samples, P/S ratio, and attribution of residue's origin based on isotopic signatures. Samples with * indicate that we were not able to obtain $\delta^{13}\text{C}$ values to assign isotopic origin

SAMPLE ID	Biomarkers of interest	P/S ratio	Attribution ($\delta^{13}\text{C}$)
SC-13	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd chain <i>n</i> -alkanes	1.6	(*)
SC-14	Long-chain FAs, monounsaturated FA ($\text{C}_{18:1}$), odd chain <i>n</i> -alkanes (C27, C29, C31)	1.5	(*)
SC-15	Long-chain FAs, monounsaturated FA ($\text{C}_{18:1}$), odd chain <i>n</i> -alkanes (C27, C29, C31)	3.8	C3 plant
SC-16	Long-chain FAs, monounsaturated FA ($\text{C}_{18:1}$), odd chain <i>n</i> -alkanes (C27, C29, C31)	4.6	C3 plant
SC-17	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd chain <i>n</i> -alkanes (C27, C29, C31), sitosterol	1	Ruminant adipose fat
SC-03	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), odd-chain FAs, odd chain <i>n</i> -alkanes (C27, C29, C31), sitosterol	1.2	Ruminant adipose fat
SC-04	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd chain <i>n</i> -alkanes (C27, C29, C31), sitosterol	6.8	(*)
SC-07	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), odd-chain FAs, odd chain <i>n</i> -alkanes (C27, C29, C31)	1.7	C3 plant
SC-44	Long-chain FAs, monounsaturated FA ($\text{C}_{18:1}$), odd chain <i>n</i> -alkanes (C29)	1.9	(*)
SC-50	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), odd-chain FAs, odd chain <i>n</i> -alkanes (C27, C31)	1	C3 plant
SC-52	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd-chain FAs, odd chain <i>n</i> -alkanes (C27, C31)	1	(*)
SC-55	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), odd-chain FAs, odd chain <i>n</i> -alkanes (C27, C29, C31)	1.9	(*)
SC-41	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), odd-chain FAs, odd chain <i>n</i> -alkanes (C27, C31, C33)	4.2	C3 plant
SC-33	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd-chain FAs, odd chain <i>n</i> -alkanes (C27, C29, C31)	1.1	C3 plant
SC-27	Long-chain fatty acids ($\text{C}_{24:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd chain <i>n</i> -alkanes (C27, C31)	1.7	C3 plant
SC-51	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd chain <i>n</i> -alkanes (C27, C29, C31)	1	(*)
SC-08	No diagnostic biomarkers.	1.1	C3 plant + ruminant fats
SC-02	Long-chain fatty acids ($\text{C}_{24:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd chain <i>n</i> -alkanes (C27, C29, C31)	5.8	C3 plant
SC-26	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd chain <i>n</i> -alkanes (C27, C29, C31)	4	C3 plant
SC-28	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$)	1.1	(*)
LB1-43	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), odd-chain FAs, long-chain <i>n</i> -alkanols (C_{24} OH) odd chain <i>n</i> -alkanes (C27, C31)	1	Ruminant adipose fat
LB1-06	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), long-chain <i>n</i> -alkanes (C27, C29, C30)	1.1	Ruminant adipose fat
LB1-23	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), odd-chain FAs, odd chain long-chain <i>n</i> -alkanes (C27, C29, C30)	1	Ruminant adipose fat
LB1-57	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), odd-chain FAs, long-chain <i>n</i> -alkanols (C_{24} OH), <i>n</i> -alkanes (C27, C29, C30)	1.4	(*)
LB1-10	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), odd chain <i>n</i> -alkanes (C27, C31)	1	(*)
LB1-38	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), odd-chain FAs, <i>n</i> -alkanes (C27, C29, C31)	2.5	Ruminant adipose fat
LB1-36	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), <i>n</i> -alkanes (C27, C29, C31)	1	Ruminant adipose fat
LB1-05	Long-chain FAs ($\text{C}_{24:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), <i>n</i> -alkanes (C27, C29, C30)	2.4	Ruminant adipose fat
LB1-16	Long-chain FAs ($\text{C}_{24:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanes (C27, C29, C31)	1.4	Ruminant adipose fat
LB1-48	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd-chain FAs, <i>n</i> -alkanes (C27, C29, C31)	1	(*)
LB1-58	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd-chain FAs, <i>n</i> -alkanols (C_{24} OH) <i>n</i> -alkanes (C27, C29, C31)	1	Ruminant adipose fat
LB1-41	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd-chain FAs, <i>n</i> -alkanols (C_{24} OH) <i>n</i> -alkanes (C27, C29, C31)	1.6	Ruminant adipose fat
LB1-27	Even-numbered LCFA, <i>n</i> -alkanes (C29, C31)	1.2	Ruminant adipose fat

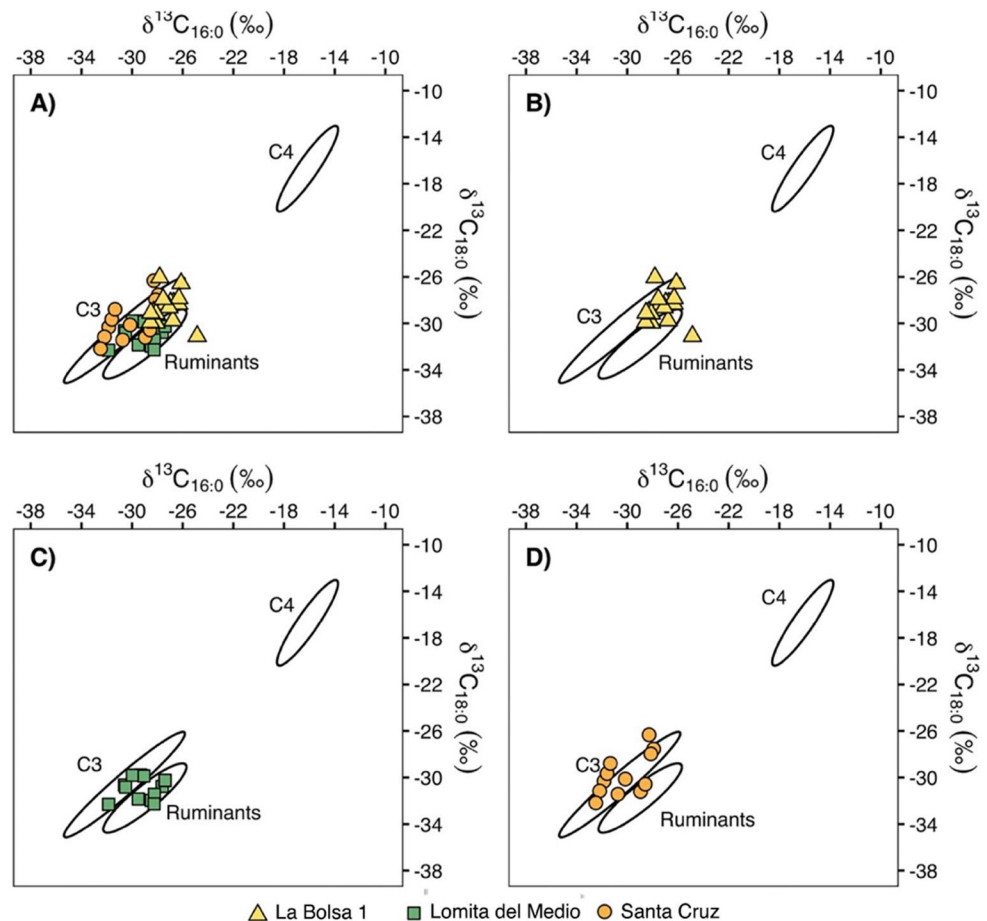
Table 2 (continued)

SAMPLE ID	Biomarkers of interest	P/S ratio	Attribution ($\delta^{13}\text{C}$)
LB1-59	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{18:1}$), odd-chain FAs, <i>n</i> -alkanols (C_{24} OH) <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1.2	Ruminant adipose fat
LB1-01	Long-chain FAs ($\text{C}_{24:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanols (C_{24} OH) <i>n</i> -alkanes (C_{29})	1	(*)
LB1-40	Long-chain FAs ($\text{C}_{24:0}$), monounsaturated FA ($\text{C}_{18:1}$, $\text{C}_{16:1}$), <i>n</i> -alkanols (C_{24} OH) <i>n</i> -alkanes (C_{29} , C_{31})	1	(*)
LB1-35	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1	C3 plant+ruminant adipose fat
LB1-42	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanes (C_{29} , C_{31})	2.4	Ruminant adipose fat
LB1-39	Odd-chain FAs, monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanols (C_{24} OH), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	2.4	Ruminant adipose fat
LB1-60	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanes (C_{29} , C_{31})	2.3	(*)
LB1-51	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), <i>n</i> -alkanols (C_{24} OH), <i>n</i> -alkanes (C_{29} , C_{31})	1.3	Ruminant adipose fat
LB1-15	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanols (C_{24} OH), <i>n</i> -alkanes (C_{29} , C_{31})	1.5	Ruminant adipose fat
LDM-61	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanols (C_{24} OH), <i>n</i> -alkanes (C_{29} , C_{31})	2	(*)
LDM-27	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1	(*)
LDM-12	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$, $\text{C}_{32:0}$), odd-chain FAs, monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanols (C_{24} OH, C_{26} OH), <i>n</i> -alkanes (C_{29} , C_{31})	1	Ruminant adipose fat
LDM-08	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$), odd-chain FAs, monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanols (C_{24} OH, C_{26} OH), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1	Ruminant adipose fat
LDM-53	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), odd-chain FAs, monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1	Ruminant adipose fat
LDM-R91-02	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), <i>n</i> -alkanols (C_{24} OH), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1.2	C3 plant
LDM-R91-01	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{16:1}$, $\text{C}_{18:1}$), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1	C3 plant
LDM-R91-03	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$, $\text{C}_{32:0}$), odd-chain FAs, monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanols (C_{24} OH, C_{26} OH), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31}), cholesterol	1	C3 plant
LDM-R91-04	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanols (C_{24} OH), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31}), cholesterol	1.2	C3 plant
LDM-01	No diagnostic biomarkers	1	(*)
LDM-17	No diagnostic biomarkers	1	(*)
LDM-41	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$), odd-chain FAs, monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	5.7	C3 plant+ruminant adipose fat
LDM-33	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$, $\text{C}_{32:0}$), odd-chain FAs, monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanols (C_{24} OH, C_{26} OH), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31}),	1	Ruminant adipose fat
LDM-20	Even-numbered FAs, <i>n</i> -alkanes (C_{29})	1.2	C3 plant
LDM-42	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1	(*)
LDM-34	Very long-chain FAs ($\text{C}_{26:0}$, $\text{C}_{28:0}$, $\text{C}_{30:0}$), odd-chain FAs, monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1	Ruminant adipose fat
LDM-36	Even-numbered FAs, <i>n</i> -alkanols (C_{24} OH), <i>n</i> -alkanes (C_{29})	1	(*)
LDM-52	Long-chain FAs ($\text{C}_{24:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1	(*)
LDM-35	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1	C3 plant
LDM-51	Very long-chain FAs ($\text{C}_{26:0}$), monounsaturated FA ($\text{C}_{18:1}$), <i>n</i> -alkanes (C_{27} , C_{29} , C_{31})	1	C3 plant

non-ruminant, ruminant adipose, and ruminant dairy fats (Roffet-Solque et al. 2014; Chakraborty et al. 2020). This was conducted by subtracting the corrected $\delta^{13}\text{C}$ values of $\text{C}_{18:0}$ from that of $\text{C}_{16:0}$ and plotting it to $\delta^{13}\text{C}_{16:0}$ values, only in samples that exhibit biomolecular evidence

of animal fats (Roffet-Solque et al. 2014). For La Bolsa 1, $\Delta^{13}\text{C}$ values (Fig. 7) align well with the reference values for South American ruminant adipose fats, although contribution from plants cannot be ruled out (as suggested by the presence of long-chain fatty acids and *n*-alkanols).

Fig. 6 Carbon stable isotopes ($\delta^{13}\text{C}$) of the main alkanolic acids from residues extracted from (a) Lomita del Medio, La Bolsa 1, and Santa Cruz showing the inter-site patterning, (b) La Bolsa 1, (c) Lomita del Medio, (d) Santa Cruz. Confidence ellipses ($p=68\%$) were built using modern references compiled from the literature (Supplementary material 2)



For Lomita del Medio, we observed very negative $\Delta^{13}\text{C}$ values, which in many cases fall into the ruminant dairy category (that is, below -2.6). As dairying was not a recorded practice with camelids during pre-Hispanic times in South America, we can confidently rule out that explanation. Recently, Admiraal and colleagues (2023) and Chakraborty et al. (2020) suggested that more negative and widely dispersed $\Delta^{13}\text{C}$ values could be explained by processing C_4 plant oils and C_3 -fed animal fats together in the same pot, but only if there is a higher $\text{C}_{18:0}$ fatty acid contribution of C_4 products (maize having very low concentrations of $\text{C}_{18:0}$). Such explanations are consistent with the hypothetical simulations obtained by Hendy and collaborators that suggest that mixing C_3 -fed ruminant fats with C_4 plant oils will overlap with ruminant dairy $\Delta^{13}\text{C}$ values (Hendy et al. 2018). Importantly, in this model it was impossible to generate dairy values mixing C_3 plants and ruminant adipose fats (Hendy et al. 2018).

Because four of the outlier samples exhibit $\delta^{13}\text{C}_{18:0}$ and $\delta^{13}\text{C}_{16:0}$ values that fall into the ruminant fat range (LDM-33, LDM-08, LDM-53, LDM-12, Fig. 6) there are two possible scenarios. In the first case, the $\Delta^{13}\text{C}$ offsets

might derive from the mixing of animal fats and C_4 plants (masked by the lipid-rich animal fats), as suggested by Admiraal and colleagues. Secondly, $\Delta^{13}\text{C}$ values might be explained by the processing of wild ruminant adipose fats from an unknown species, as it has been observed in the case of European red deer carcass meat (Craig et al. 2012). More experimental work and an enhanced reference library for South American wild species is needed to reach a conclusive interpretation.

Charred food crusts

Bulk carbon and nitrogen stable-isotope analyses in food crusts are particularly difficult to interpret, as it is hard to untangle the contribution of different types of biomolecules to each residue's isotopic value. Additionally, amorphous crusts do not necessarily derive from the meals prepared in the pots but could be derived from the fuel used during cooking. Still, chars can provide some insights about the types of foods cooked in pots and overall culinary practices (Yoneda et al. 2019). Here, we do not use them independently of the absorbed and microbotanical remains nor

Fig. 7 Biplot of $\delta^{13}\text{C}_{16:0}$ fatty acid versus $\Delta^{13}\text{C}_{(\text{C}_{18:0}-\text{C}_{16:0})}$ values from La Bolsa 1, Santa Cruz, and Lomita del Medio. Dashed lines indicate the threshold for ruminant carcass fats of -2.4‰ for South-American camelid adipose fats (Montalvo-Cabrera et al. 2025)

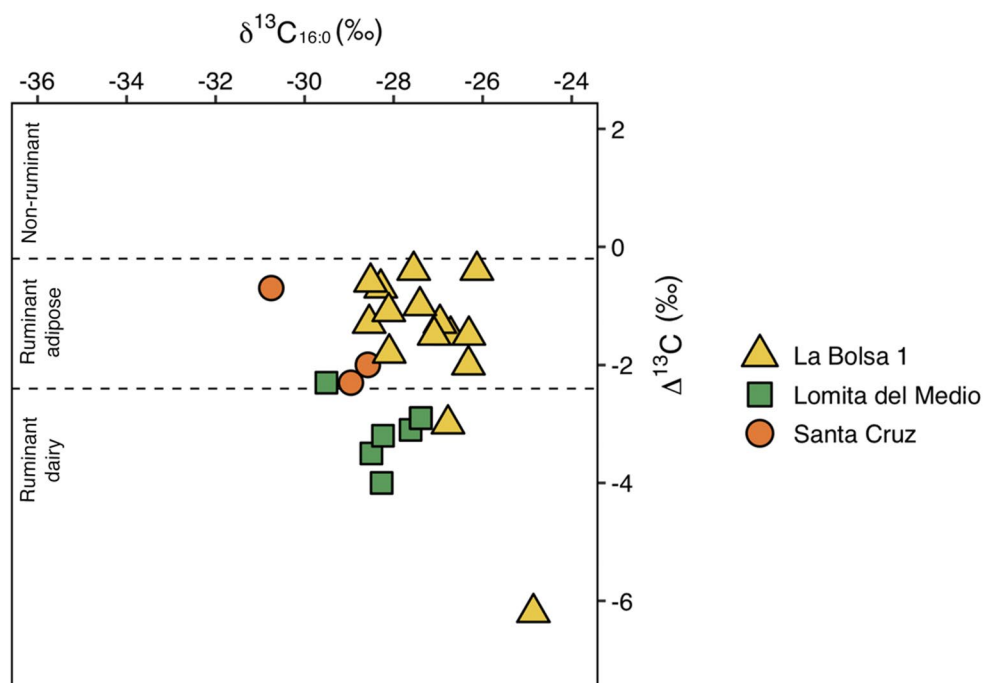


Table 3 Bulk $\delta^{13}\text{C}$ values of charred food crusts recovered from La Bolsa 1 and Lomita del Medio

Sample ID	Site	Cal $\delta^{13}\text{C}$
M01	LB1	-22.4
M02	LB1	-20.7
M03	LB1	-24.8
M04	LDM	-26.1
M05	LDM	-25.9
M06	LDM	-23.4
M07	LB1	-20.1
M08	LB1	-20.7
M09	LB1	-20.2
M10	LB1	-21.3
M11	LB1	-13.8
M12	LB1	-20.3
M13	LB1	-24.3

as diagnostic of the processing or consumption of specific foodstuffs. Rather, we take it as a complementary proxy to lipid residues (Kooiman et al. 2022).

Samples from Lomita del Medio and La Bolsa 1 showed the presence of C_3 -related commodities (Table 3). Nitrogen voltage signals were low precluding a confident determination of the $\delta^{15}\text{N}$ values in many samples and thus are not presented here. Values for $\delta^{13}\text{C}$ around -20‰ in La Bolsa 1 could indicate the mixing of C_3 and C_4 plants, as was already suggested in isotopic values of lipid residues, whereas the more depleted values from Lomita del Medio point towards higher C_3 input. Only one sample displayed a clear C_4 value (-13.8‰), that was probably derived from maize.

Discussion

The results of this study provide clear chemical evidence of regional subsistence diversification and local foodways that is not readily apparent from the archaeological record alone. The significant inter-site patterning in the $\delta^{13}\text{C}$ values of the major fatty acids ($\text{C}_{16:0}$ and $\text{C}_{18:0}$), combined with the biomolecular identification of compounds, demonstrates the efficacy of lipid residue analysis for uncovering economic micro-diversity in terms of the types of resources exploited, processed, and/or consumed, despite the overall challenge of poor residue preservation in the Tafi Valley, including macrobotanical and faunal remains.

At its broadest, the picture obtained by molecular and isotopic analyses indicate that while the southern parts of the Tafi Valley (Las Carreras-Santa Cruz) could have had a more established farming economy focused on the exploitation of C_3 plants (tubers, quinoa, beans), people inhabiting the northern areas (La Ciénega-Lomita del Medio, La Bolsa-La Bolsa 1) focused on animal husbandry with different degrees of agricultural exploitation. Maize did not play a significant role in overall subsistence practices and foodways in the Tafi Valley, but it was likely used on restricted social occasions. Figure 8 present a boxplot of $\Delta^{13}\text{C}$ values across sites, showing the generally lower values for La Bolsa 1/Lomita del Medio compared to Santa Cruz.

The emphasis on C_3 crops and ruminant animals in the Tafi Valley matches what is observed in other nearby valleys and ravines, such as El Cajón and El Infiernillo. There, scholars applying stable isotopes on human remains have

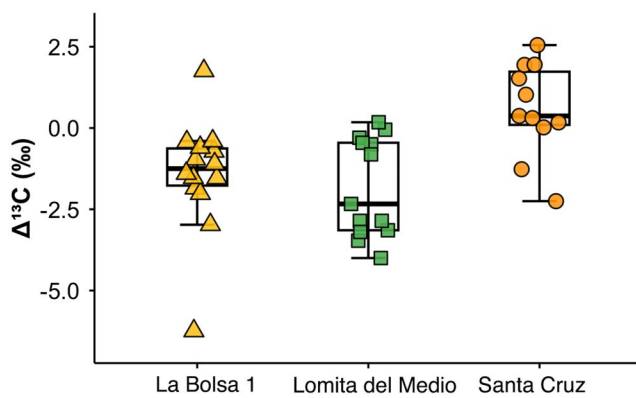


Fig. 8 Boxplot displaying the $\Delta^{13}\text{C}$ values across the three analyzed settlements

recognized how people established complex agricultural and herding economies, combining the exploitation of animal resources and altitude-resistant crops, with minor contributions of maize to the overall diet until the decay of villager lifestyles by the end of the first millennium CE (Calo et al. 2009; Galván et al. 2021; Neveu Collado et al. 2024; Oliszewski et al. 2020).

The isotopic profiles in our study indicate a strong reliance on C_3 plants at Santa Cruz, which correlates with the molecular evidence of plant waxes and oils (e.g., even numbered long-chain fatty acids, odd-numbered n -alkanes). At Santa Cruz, C_3 crops might have been more resistant to the ecological conditions than maize, constituting a reliable strategy in a region where low temperatures and seasonal freezing could damage more temperate cultigens. Additionally, the early presence of domesticated C_3 plants, such as quinoa and beans in the Southern Calchaquí Valleys (Oliszewski and Arreguez 2015; Oliszewski et al. 2017; Arreguez et al. 2021) could indicate an entrenched preference for such foods, and a slow and patchy incorporation of maize into the diet. More work is required to identify what types of species were being cultivated in Santa Cruz, and also, if farming activities required some degree of artificial fertilization to enhance the productivity due to the low humidity retention of the soils (Berberían 1995).

The more enriched $\delta^{13}\text{C}$ values from La Bolsa 1 and Lomita del Medio, alongside $\Delta^{13}\text{C}$ values from La Bolsa 1 that fall within the range for ruminant adipose fats, point to different economic foci involving animal products. In both cases, the presence of high-altitude and cold-resistant grasses and shrubs could provide excellent fodder for sustaining camelid herds (Cremonte 2003). Moreover, it is possible that different degrees of agricultural exploitation and/or reliance on plant foods occurred at each site.

At La Bolsa 1, biomolecular data suggest that some plant resources were processed in the pots (based on LCFA, n -alkanes, n -alkanols, and P/S ratios) but mixed with the

ruminant adipose fats that dominate the isotopic values. This interpretation is also supported by the archaeobotanical evidence of maize, squashes, and beans cultivated using the area's agricultural infrastructure. That lead us to think that it is possible that people living at La Bolsa 1 combined a high reliance on herding and the frequent consumption of camelid meat with some degree of agricultural exploitation.

Similarly, herding is revealed as an important component of overall subsistence at Lomita del Medio. Samples from this site exhibited mixed results, with to one group of residues reflecting C_3 plants and ruminant carcass fats, and the other group reflecting only C_3 plants. Particularly, the notably negative $\Delta^{13}\text{C}$ values observed in several samples from Lomita del Medio present a compelling interpretive challenge. While in European contexts such values might suggest dairy fats, this is an unlikely explanation for pre-Hispanic South American camelids. Alternative explanations must be considered, for instance the mixing of C_4 plants and ruminant adipose fats resources in specific culinary practices (Hendy et al. 2018; Chakraborty et al. 2020; Admiraal et al. 2023), and also the presence of unknown wild ruminant species that can be very $\text{C}_{18:0}$ depleted (Craig et al. 2012). Importantly, results in this study highlight the critical need for expanded modern reference lipid libraries and experimentation for South American species.

Indeed, the molecular evidence obtained in this study must be evaluated alongside other proxies. The phytolith evidence for maize and squash at La Bolsa 1 (Molar 2022; Franco Salvi et al. 2014) seems at odds with the lack of a clear C_4 signal in the lipids from the same site. This discrepancy can be explaining by considering the culinary and taphonomic factors at play: maize may have been consumed as a fermented beverage (*chicha*) or in low-lipid preparations that are less visible in the residue record (i.e. roasting, popcorn). Its signal may also be masked by the presence of lipid-rich animal fats (Reber and Evershed 2004). For instance, the mixing of C_4 plants and ruminant adipose fats might explain the very negative $\Delta^{13}\text{C}$ values obtained in a sub-set of Lomita del Medio, yet we cannot rule out that these values derive from unknown wild ruminant sources.

Overall, our results suggest that it is possible that even when maize was cultivated, its use was restricted, for instance, to social gatherings and ceremonies that are unlikely to be represented in averaged lipid signals. The evidence of *Zea mays* phytoliths on a funerary bowl (Molar 2022) with clear $\delta^{13}\text{C}$ evidence for ruminant fats (sample LB1-58) could point in this direction. The socially restricted role of maize, especially in ritual or ceremonial contexts, has been noted by several authors in the recent years (Pazzarelli 2013; Lantos et al. 2015; Admiraal et al. 2023; Montalvo-Cabrera et al. 2024).

Overall, it seems clear that each settlement's combination of soil humidity, temperature, and slopes might have compelled villagers to rely more heavily on certain economic activities than on others. Yet, the contemporaneity and similarities in the built-environment and material culture between settlements raises the question of the nature of their socio-political organization and inter-site interactions. The diversification between northern and southern communities could reflect food preferences locally attuned to household and village-level culinary traditions. If so, people living in the Tafi Valley during 200–800 CE could have expressed their autonomy at the socio-economic level by crafting distinct interactions with their surroundings and nonhumans plants and animals, while reinforcing membership in a regional community through shared architecture and potting practices. While certain aspects of their social identity were displayed in a more open fashion, such as the built-environment, household identity was expressed in the discrete arena of daily food consumption practices, often conducted privately inside houses.

Our results in the Tafi Valley cast light on the building of early farming subsistence practices and foodways. They show that even with small distances between settlements, villager groups pursued their sustenance differently, foregrounding the role of human-environment interactions in the creation of socio-economic systems in Andes, with potential applications in other early village societies worldwide.

Conclusions

This study successfully demonstrates the value of systematic organic residue analysis for investigating subsistence practices in archaeologically challenging preservation environments. Our study shows that even with low overall lipid yields, biomolecular and compound-specific isotope analysis of absorbed residues can yield interpretable and significant results that reveal previously invisible economic behaviors.

The chemical evidence provides direct proof of subsistence micro-diversity among early agropastoral villages in the Southern Andes. The distinct isotopic profiles between Santa Cruz (C_3 plant-focused) and the northern villages like Lomita del Medio and La Bolsa 1 (mixed ruminant and C_3/C_4 plant) indicate that communities enacted localized economic strategies tailored to their immediate micro-environments, despite sharing common socio-material practices such as pottery making and architecture. This finding challenges homogeneous models of regional economies and emphasizes the flexibility

of Andean agropastoralism, calling attention for more localized and fine-grained research with a comparative lens.

Future work should focus on expanding modern reference databases for South American plant and animal lipids, especially of wild ruminant adipose fats, to refine our interpretations of $\Delta^{13}C$ values. Furthermore, integrating residue analysis with other microscopic techniques (e.g., phytolith, starch analysis) on the same vessels will provide a more holistic understanding of past social practices.

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1007/s12520-026-02462-0>.

Acknowledgements Dr. Chad Lane and Taylor Conklin from the University of North Carolina: Wilmington assisted in the instrumentation for CSIA analysis, providing invaluable guidance to conduct this research. Dr. I. Lightcap and A. Matzner from the Material Characterization Facility (U. of Notre Dame) provided training and assistance during GC-MS analyses. Bulk isotopes analysis conducted at the CEST laboratory were assisted by Dr. Biasatti. Several people collaborated in fieldwork seasons, J. Salazar, J. Montegú, R. Molar, L. Justiniano, J. Lopez Lillo, and G. Moyano. C. Sanguinetti and J. Salazar assisted in the classification of the ceramic assemblage from Santa Cruz and Lomita del Medio and A. Arbello collaborated in the cleaning of samples. The indigenous community of Tafi del Valle, the ones who own the land ancestrally allowed us to work in the valley. Especially to Hilda Santo Mamani and her partner, Rogelio Armando Ayala, Bartolina and Marilina Casimiro, Mónica Méndez and Fabián Lara.

Author contribution A. Conceptualization, data acquisition and interpretation, funding acquisition, methodology, visualization, tables and figures, writing (original draft, review, editing).

B. Editing, supervision, and funding acquisition.

C. Funding acquisition, project management, microfossil analysis/review.

D. Editing and supervision.

Data availability Not applicable.

Ethical approval

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Admiraal M, Colonese AC, Milheira RG et al (2023) Chemical analysis of pottery reveals the transition from a maritime to a plant-based economy in pre-colonial coastal Brazil. *Sci Rep* 13:16771. <https://doi.org/10.1038/s41598-023-42662-5>
- Albeck ME (2000) La vida agraria en los Andes del Sur. *Nueva Historia Argentina* 1:187–228
- Arreguez GA, Oliszewski N, Martínez Burzaco GJ (2021) *Chenopodium quinoa* Willd. en la Quebrada de Los Corrales (Tucumán, Argentina): una Tradición de tres mil años (ca. 3.800–630 ap) Boletín de la Sociedad Chilena de Antropología Número Especial 275–298
- Aschero C, Ribotta E (2007) Usos del espacio, tiempo y funebria en RI Remate (Los Zazos, Amaicha del Valle, Tucumán). In Arenas, P., Manasse, B. & Noli, E. (Ed.), Paisajes y procesos sociales en Tafi del Valle 79–94, Imprenta UNT
- Berberián E (1988) Sistemas de asentamiento prehispánicos en el Valle de Tafi. Editorial Comechingonia, Cordoba
- Berberián EE (1995) Sistemas agrícolas prehispánicos y tecnología apropiada: un experimento arqueológico en el Valle de Tafi (Pcia. de Tucumán, Rep. Argentina). *Comechingonia: Revista de Arqueología* 8(1):79–95
- Berberián E, Nielsen A (1988) Sistemas de asentamiento prehispánicos en el valle de Tafi. *Brujas*
- Bermann M, Castillo JE (1995) Domestic artifact assemblages and ritual activities in the Bolivian Formative. *J Field Archaeol* 22:389–398. <https://doi.org/10.1179/009346995791974116>
- Bernasconi de García MT, Baraza de Fonts AN (1982) Estudios arqueológicos del Valle de la Ciénaga (departamento Tafi, provincia de Tucumán). *Anales de Arqueología y Etnología* 117–138
- Cabrera A (1976) Fitogeografía de la República Argentina. *Boletín de la Sociedad Argentina de Botánica* 14(1–2):1–42
- Calo CM (2014) Archaeobotanical remains found in a house at the archaeological site of Cardonal, Valle del Cajón, Argentina: a view of food practices 1,800 years ago. *Veget Hist Archaeobot* 23:577–590. <https://doi.org/10.1007/s00334-013-0406-2>
- Calo CM, Leticia I, Cortés (2009) A contribution to the study of diet of formative societies in Northwestern Argentina: isotopic and archaeological evidence. *Int J Osteoarchaeology* 19(2):192–203
- Capriles JM (2014) Mobile communities and pastoralist landscapes during the Formative Period in the Central Altiplano of Bolivia. *Latin Am antiq* 25:3–26. <https://doi.org/10.7183/1045-6635.25.1.3>
- Chakraborty KS, Slater GF, Miller HM-L et al (2020) Compound specific isotope analysis of lipid residues provides the earliest direct evidence of dairy product processing in South Asia. *Sci Rep* 10:16095
- Chiavassa-Arias S, Franco Salvi V (2024) El pastoreo en un paisaje aldeano del valle de Tafi (Tucumán, Argentina). *Arqueología* 30:1–24
- Christie WW (2025) The lipid web
- Correa-Ascencio M, Evershed RP (2014) High throughput screening of organic residues in archaeological potsherds using direct acidified methanol extraction. *Anal Methods* 6:1330. <https://doi.org/10.1039/c3ay41678j>
- Cortés LI (2023) Nuevas investigaciones en el sur del Valle del Cajón extienden el área de ocupaciones Formativas (1000 a.C.–1000 d.C., Catamarca). *Relaciones* 48:087. <https://doi.org/10.24215/18521479e087>
- Craig OE, Allen RB, Thompson A et al (2012) Distinguishing wild ruminant lipids by gas chromatography/combustion/isotope ratio mass spectrometry. *Rapid Comm Mass Spectrom* 26:2359–2364. <https://doi.org/10.1002/rcm.6349>
- Craig OE, Saul H, Spiteri C (2019) Residue analysis. In: Richards M, Britton K (eds) *Archaeological Science*, 1st edn. Cambridge University Press, pp 70–98
- Cremonte MB (1997) Investigaciones arqueológicas en la Quebrada de la Ciénaga (Dpto. Tafi, Tucumán). Universidad Nacional de La Plata
- Cremonte MB (2003) Producción cerámica de la tradición Tafi. Estudios tecnológicos de la alfarería arqueológica de La Ciénaga (Tucumán, noroeste de Argentina). *Rev Mus Arqueol Etnol* 57. <https://doi.org/10.11606/issn.2448-1750.revmae.2003.109465>
- Dillehay TD (2011) From foraging to farming in the Andes: new perspectives on food production and social organization. Cambridge University Press
- Dlugosz JC, Manasse B, Castellanos M, Ibáñez SS (2009) Sociedades aldeanas tempranas en el valle de Tafi: algunas aproximaciones desde la alfarería. *Andes* 20(2):1–26
- Dove H, Mayes RW (2006) Protocol for the analysis of n-alkanes and other plant-wax compounds and for their use as markers for quantifying the nutrient supply of large mammalian herbivores. *Nat Protoc* 1:1680–1697. <https://doi.org/10.1038/nprot.2006.225>
- Dudd SN, Regert M, Evershed RP (1998) Assessing microbial lipid contributions during laboratory degradations of fats and oils and pure triacylglycerols absorbed in ceramic potsherds. *Org Geochem* 29:1345–1354. [https://doi.org/10.1016/S0146-6380\(98\)00093-X](https://doi.org/10.1016/S0146-6380(98)00093-X)
- Dunne J (2022) Gone to seed? Early pottery and plant processing in Holocene North Africa. *Quatern Int* 608–609:178–193. <https://doi.org/10.1016/j.quaint.2021.02.004>
- Dunne J, Höhn A, Neumann K et al (2022) Making the invisible visible: tracing the origins of plants in West African cuisine through archaeobotanical and organic residue analysis. *Archaeol Anthropol Sci* 14:30. <https://doi.org/10.1007/s12520-021-0147-0>
- Dunne J, Mercuri AM, Evershed RP et al (2016) Earliest direct evidence of plant processing in prehistoric Saharan pottery. *Nat Plants* 3:16194. <https://doi.org/10.1038/nplants.2016.194>
- Evershed RP (2008a) Organic residue analysis in archaeology: the archaeological biomarker revolution*. *Archaeometry* 50:895–924. <https://doi.org/10.1111/j.1475-4754.2008.00446.x>
- Evershed RP (2008b) Experimental approaches to the interpretation of absorbed organic residues in archaeological ceramics. *World Archaeol* 40:26–47. <https://doi.org/10.1080/00438240801889373>
- Franco Salvi V (2012) Estructuración social y producción agrícola prehispánica durante el primer milenio dC en el Valle de Tafi (Tucumán, Argentina). Universidad Nacional de Córdoba
- Franco Salvi V (2018) Autonomía doméstica en un mundo complejo (Valle de Tafi, Argentina). *BOLARQ* 55–76. <https://doi.org/10.18800/boletindearqueologiapucp.201801.003>
- Franco Salvi VL, Justiniano L (2021) La práctica de realizar pozos en la vida cotidiana. Valle de La Ciénaga, Argentina. *Come* 26:133–150. <https://doi.org/10.37603/2250.7728.v26.n2.34315>
- Franco Salvi V, López Lillo JA, Salazar J (2025) Archaeology of agriculture in the Cumbres Calchaquies (Tucumán, Argentina): new insights into La Ciénaga and Tafi Valleys during the first millennium CE. *Front Environ Archaeol* 4:1453746. <https://doi.org/10.3389/fearc.2025.1453746>
- Franco Salvi V, López ML, Molar RM (2014) microrrestos vegetales en campos de cultivo del primer milenio de la era en el Valle de Tafi (Prov. De Tucumán. República Argentina. <https://doi.org/10.5281/ZENODO.1311765>
- Franco Salvi VL, Salazar J (2014) Llama offerings in an early village landscape: new data from northwestern Argentina (200 b.c.–a.d. 800). *Nawpa Pacha* 34:223–232. <https://doi.org/10.1179/0077629714Z.00000000022>

- Franco Salvi VL, Salazar J, Montegu JM (2017) Prácticas cotidianas y vida aldeana. Un análisis desde la tecnología lítica en el Valle de Tafi (Tucumán, Argentina). Cuadernos del Instituto Nacional de Antropología y Pensamiento Latinoamericano 25(2):141–158
- Franco Salvi V, Salazar J, López Lillo JA et al (2023) Mundos aldeanos. El valle de La Ciénega en la larga duración (Tucumán, Argentina). Estudios atacameños 69:e5387. <https://doi.org/10.22199/issn.0718-1043-2023-0019>
- Harcourt V, Berberian E (2012) Prácticas agrícolas de sociedades campesinas en el Valle de Tafi (100 a.C.- 900 d.C.). Revista Chil de Antropología 24(2):119–145. <https://doi.org/10.5354/0719-1472.2011.18161>
- Galván KVA, Cortés LI, Rabuffetti N (2021) Composition of Prehispanic Diets from Stable Isotope Analysis in Human Remains of the Southern Calchaquies Valleys, Northwest Argentina (3600–1300 BP). Latin Am Antiq 32(2):350–367
- García Azcárate J (1996) Monolitos-huancas: un intento de explicación de las piedras de Tafi (Rep. Argentina). Chungara 159–174
- García Salemi MA (1988) Aspectos geomorfológicos e hidrológicos de la Cuenca de Tafi. (Departamento Tafi del Valle, Provincia de Tucumán). Breves contribuciones del I.E.G. N°5:5–22
- Gero JM (2015) Yutopian: archaeology, ambiguity, and the production of knowledge in Northwest Argentina. University of Texas
- González A, Nuñez Regueiro V (1960) Preliminary report on archaeological research in Tafi del Valle, NW Argentina. In: Akten 34. Viena, pp 18–25
- Hastorf CA (2008) The Formative Period in the Titicaca Basin. In: Silverman H, Isbell WH (eds) The Handbook of South American Archaeology. Springer New York, New York, NY, pp 545–561
- Hendy J, Colonese AC, Franz I et al (2018) Ancient proteins from ceramic vessels at Çatalhöyük West reveal the hidden cuisine of early farmers. Nat Commun 9:4064. <https://doi.org/10.1038/s41467-018-06335-6>
- Kooiman SM, Albert RK, Malainey ME (2022) Multiproxy analysis of adhered and absorbed food residues associated with pottery. J Archaeol Method Theory 29:795–830. <https://doi.org/10.1007/s10816-021-09537-3>
- Korstanje MA, Quesada MN, Franco Salvi VL et al (2015) Gente, tierra, agua y cultivos. los primeros paisajes agrarios del hoy Noroeste argentino. In: Kornstanje A, Lazzari M, Basile M, Bugliani F, Lema V, Pereyra-Domingorena L, Quesada M (eds) Crónicas materiales precolombinas. Arqueología de los primeros poblados del Noroeste Argentino. Sociedad Argentina de Antropología
- Langlie BS, Capriles JM (2021) Paleoethnobotanical evidence points to agricultural mutualism among early camelid pastoralists of the Andean central Altiplano. Archaeol Anthropol Sci 13:107. <https://doi.org/10.1007/s12520-021-01343-y>
- Lantos I, Chaile C, Careaga VP et al (2025) Organic residue analysis in Latin American archaeology: Past, present, and future perspectives. Archaeometry 67:503–519. <https://doi.org/10.1111/arc.12978>
- Lantos I, Palamarczuk V, Orgaz M et al (2018) Exploring the culinary uses of Santa María and Belén painted vessels from the Late Intermediate Period in Catamarca, Argentina. J Archaeol Science: Rep 18:660–667. <https://doi.org/10.1016/j.jasrep.2017.03.019>
- Lantos I, Spangenberg JE, Giovannetti MA et al (2015) Maize consumption in pre-Hispanic south-central Andes: chemical and microscopic evidence from organic residues in archaeological pottery from western Tinogasta (Catamarca, Argentina). J Archaeol Sci 55:83–99. <https://doi.org/10.1016/j.jas.2014.12.022>
- Manasse B (2023) Las piedras largas del Valle de Tafi, Tucumán: ancestralidad y territorialidades. Andes 34:255–292
- Marsh EJ (2015) The emergence of agropastoralism: accelerated eco-cultural change on the Andean altiplano, ~3540–3120 cal BP. Environ Archaeol 20:13–29. <https://doi.org/10.1179/1749631414Y.0000000036>
- Molar RM (2022) Alimentación y reproducción social en sociedades aldeanas tempranas: un estudio comparativo en valles y quebradas del noroeste de la Provincia de Tucumán (República Argentina). Universidad Nacional de Córdoba
- Montalvo-Cabrera JA, Campbell R, Colonese AC et al (2025) Evaluating the culinary significance of maize in the Araucanía, Southern Chile: Evidence from organic residue analysis of pre-colonial pottery. J Archaeol Sci 173:106118. <https://doi.org/10.1016/j.jas.2024.106118>
- Montalvo-Cabrera JA, Colonese AC, Campbell R et al (2024) unraveling island economies through organic residue analysis: the case of Mocha Island (Southern Chile). Latin Am antiq 35:1003–1017. <https://doi.org/10.1017/laq.2023.58>
- Montegu JM, Franco F (2020) ¿ Materiales pasivos en espacios vacíos? análisis lítico y cerámico de un sector extramuros del sitio La Bolsa 1 en el Valle de Tafi (Tucumán, Argentina) Cuadernos del INALP: Serie Especiales 8(1):210–223
- Moyano G, Franco F, López Lillo JA et al (2023) Espacialidad y temporalidad de paisajes aldeanos tempranos en el sur de las Cumbres Calchaquies. La Ciénega y Anfama Tucumán relaciones 48:e048. <https://doi.org/10.24215/18521479e048>
- Neveu Collado C, Killian Galván VA, Mondini M, Korstanje MA (2024) Human and camelid paleodiets in El Bolsón Valley (NW Argentina): A stable isotope approach. Int J Osteoarchaeology 34(3):e3248 <https://doi.org/10.1002/oa.3248>
- Nuñez AL, Cartajena FI, Carrasco GC et al (2006) Emergencia de comunidades pastoralistas formativas en el sureste de la Puna de Atacama. Estud atacam 32: 93–117 <https://doi.org/10.4067/S0718-10432006000200008>
- Oliszewski N, Arreguez G (2015) Manejo de recursos vegetales alimenticios en la Quebrada de los Corrales, El Infiernillo, Tucumán (2100–1550 años AP). Come 19:111–140. <https://doi.org/10.37603/2250.7728.v19.n2.18134>
- Oliszewski N, Galván VK, Srur G, Olivera DE, Martínez JG (2020) Human paleodiet studies between ca. 3300–1500 Years BP in Quebrada de Los Corrales (Tucumán, Argentina). J Archaeol Sci Rep 32:102429
- Olivera DE (2001) Sociedades agro-pastoriles tempranas: el Formativo Inferior del Noroeste Argentino. In: Berberian E (ed) Historia argentina prehispánica. Brujas, Cordoba, pp 83–126
- Pazzarelli FG (2013) Otros-maíces: trayectorias y transformaciones culinarias del maíz en Ambato. Catamarca, Noroeste Argentino Revista Española de Antropología Americana 42(2):329–351
- Polissar PJ, D'Andrea WJ (2014) Uncertainty in paleohydrologic reconstructions from molecular δD values. Geochim Cosmochim Acta 129:146–156
- Reber EA (2021) Comparison of neutral compound extraction from archaeological residues in pottery using two methodologies: a preliminary study. Separations 8:6. <https://doi.org/10.3390/separations8010006>
- Reber EA (2022) An archaeologist's guide to organic residues in pottery. University of Alabama, Tuscaloosa
- Reber EA, Dudd SN, Van Der Merwe NJ, Evershed RP (2004) Direct detection of maize in pottery residues via compound specific stable carbon isotope analysis. Antiquity 78:682–691. <https://doi.org/10.1017/S0003598X00113316>
- Reber EA, Evershed RP (2004) Identification of maize in absorbed organic residues: a cautionary tale. J Archaeol Sci 31:399–410. <https://doi.org/10.1016/j.jas.2003.09.008>
- Reber EA, Kelly JE, Boswell E, Lane CS (2020) Molecular evidence of changing foodways across the Mississippian transition at the George Reeves site (11S650). Southeast Archaeol 39:71–88. <https://doi.org/10.1080/0734578X.2020.1724020>

- Roffet-Salque M, Dunne J, Altoft DT et al (2017) From the inside out: upscaling organic residue analyses of archaeological ceramics. *J Archaeol Science: Rep* 16:627–640. <https://doi.org/10.1016/j.jasrep.2016.04.005>
- Roffet-Solque M, Dunne J, Ryan K et al (2014) Extending the carbon isotope proxy for animal fat identification in lipid residue preserved in archeological vessels to a wide range of ruminants and non-ruminant fats. In: Izeta A (ed) *Libro de Resúmenes ICAZ*, Mendoza, Argentina.
- Salazar J (2010) Reproducción social doméstica y asentamientos residenciales entre el 200 d.c. y 800 d.c. en el Valle de Tafi, Provincia de Tucumán. Universidad Nacional de Córdoba
- Salazar J, Franco Salvi VL, López Lillo JA (2024) Materia y tiempo en La Ciénega. Aportes al estudio de paisajes aldeanos del Noroeste Argentino (500 AC-900 DC). *Intersecciones* 26(1):73–94
- Salazar J, Kuijt I (2016) Dynamic places, durable structures: Early Formative agropastoral settlements of the southern Andes, Argentina. *Antiquity* 90:1576–1593. <https://doi.org/10.15184/aqy.2016.213>
- Salazar J, Montegú JM, Molar RM et al (2022) Ocupaciones dispersas, paisajes persistentes: la arqueología de Anfama, Tucumán (400 aC-1500 dC). *Latin Am antiq* 33:155–174. <https://doi.org/10.1017/laq.2021.36>
- Sampietro MM, Vattuone MA (2005) Reconstruction of activity areas at a Formative household in northwest Argentina. *Geoarchaeology* 20:337–354. <https://doi.org/10.1002/gea.20053>
- Scattolin C (2019) Yutopián, donde los objetos se sublevan. *RMLP* 4:69–102. <https://doi.org/10.24215/25456377e070>
- Scattolin MC (2015) Formativo: el nombre y la cosa. *Crónicas materiales precolombinas Arqueología de los primeros poblados del Noroeste Argentino*. In: Kornstanje A, Lazzari M, Basil, M, Bugliani F, Lema V, Pereyra-Domingorena L, Quesada M (eds)
- Crónicas materiales precolombinas. Arqueología de los primeros poblados del Noroeste argentino*. Sociedad Argentina de Antropología Publications, pp. 35–48
- Scattolin MC, Cortés LI, Bugliani MF et al (2009) Built landscapes of everyday life: a house in an early agricultural village of North-Western Argentina. *World Archaeol* 41:396–414. <https://doi.org/10.1080/00438240903112310>
- Sesma JP (1987) *Geología del Cuaternario y geomorfología aplicada en el Valle de Tafi*. Bachelor thesis, University of Tucumán
- Stanish C (2003) *Ancient Titicaca*, 1st edn. University of California Press
- Vázquez Fiorani A, Fundurulić A, Manhita A, Franco Salvi V, Barrocas Dias C (2025) Evidence of plant processing in early villages of Northwestern Argentina revealed by organic residue analysis in pottery (La Ciénega Valley, ca. AD 200–600). *Lat Am Antiq* 36(3):827–847. <https://doi.org/10.1017/laq.2024.41>
- Vazquez Fiorani A, Salazar J, Chesson M (2026) Crafting a shared history of learning: Pottery making and the building of agropastoral communities (Argentina, 200-850 CE). *J Anthropol Archaeol* 82:101752. <https://doi.org/10.1016/j.jaa.2026.101752>
- Whelton HL, Hammann S, Cramp LJE et al (2021) A call for caution in the analysis of lipids and other small biomolecules from archaeological contexts. *J Archaeol Sci* 132:105397. <https://doi.org/10.1016/j.jas.2021.105397>
- Yoneda M, Kisida K, Gakuhari T et al (2019) Interpretation of bulk nitrogen and carbon isotopes in archaeological foodcrusts on potsherds. *Rapid Comm Mass Spectrom* 33:1097–1106. <https://doi.org/10.1002/rcm.8446>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.