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Leading the Flock: Tracing Herding strategies and Resource Exploitation in the Valais Alps from Prehistory to the Middle Ages through Isotopic Analysis

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ABSTRACT

This study presents a comprehensive investigation of herd mobility strategies and resource exploitation in the Valais region, based on archaeological assemblages spanning from the Early Neolithic to the Early Middle Ages and encompassing sites from the Upper to the Lower Valais. Through stable isotope analyses (δ^{18}O and δ^{13}C) of sequential enamel samples from caprine molars, this research aims to explore pastoral exploitation of altitudinal zones, the use of associated ecological resources, and the role of seasonal vertical mobility in shaping subsistence strategies across millennia.

The dataset includes individuals recovered from high-altitude contexts, such as the Giétroz Devant chasm, which is likely linked to seasonal alpine pasturing. The observed isotopic patterns provide the first empirical validation of a model for vertical transhumance in the Western Alps. Similar signatures identified at La Planta suggest that this mobility practice was already in place during the 6th millennium BCE and continued throughout later periods. Results reveal a recurrent pattern of vertical mobility, combined with a flexible use of diverse environments, including forested areas—particularly in winter or transitional seasons. The variability in husbandry practices reflects both the adaptability and resilience of Alpine pastoral systems over time. This study not only offers a new framework for interpreting past mobility in mountainous regions but also establishes a reference dataset for future isotopic and geospatial investigations of complex pastoral networks in the Alps.

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Introduction and research objectives

This study investigates the mobility patterns and dietary management of caprines—pioneer species in the establishment of human communities in the Valais region—whose exploitation was favoured from the Neolithic through to the end of the Late Iron Age. The investigation is based on incremental stable isotope analysis of oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) in dental enamel. The Valais region (Switzerland), corresponding to the Upper Rhône valley, is a land of contrasts, characterised by a steep altitudinal gradient and a corresponding gradation in grassland resources (OZENDA 1985; GUISAN *et al.* 1998, 65-74). Today, the valley floor of Upper and Middle Valais is particularly arid, while the alpine and subalpine zones receive regular precipitation and snow cover (Swisstopo). To cope with this aridity, present-day agriculture and livestock farming, concentraded on the valeey floor in the continental region of Valais, have required the development of irrigation systems known as *bisses*. These systems were established as early as the 14th century CE, in parallel with the expansion of cattle husbandry and the export of cheese during this period (DUBUIS 1995, 39-47). Although this remains an isolated case, the earliest evidence of such irrigation systems probably date back to the Roman period (PACCOLAT 2011, 170-198).

The practice of seasonal mobility, referred to as the *remuage* in both present-day and sub-contemporary pastoral societies in Central Valais, is implemented annually from spring to autumn by local livestock herders (MAY 1985). This system involves regular movements between a permanent settlement situated at intermediate altitudes (within the collinean or montane ecological zones) and the subalpine and alpine zones (CROTTI *et al.* 1983, 55-80; GALLAY 1983 a.; CURDY 2007, 99-108; HAFNER 2015). This adaptive strategy enabled human communities to sustainably utilise pasture lands ranging from the valley floor to high mountain meadows (CURDY, CHAIX 2009, 93-116). The exploitation of herbaceous and forest resources across these distinct altitudinal zones likely emerged with the earliest Neolithic settlements in the region (MARTIN *et al.* 2019). However, the long-term use of vertical herd mobility, supply strategies, animal food management and the temporal dynamics of such practices remain poorly understood in the region.

The recent discovery of sheep that were trapped in the Giétroz Devant chasm during the Late Iron Age, located at over 2,000 meters asl, along with several Alpine ibex trapped during the Atlantic climatic period, is exceptional for two reasons:

(1) it provides compelling evidence for the presence of livestock in high alpine pastures during Late Iron Age (REYNAUD SAVIOZ *et al.* 2019, 21 30; REYNAUD SAVIOZ, BLANT 2022, 7-22);
(2) it offers an unprecedented opportunity to investigate patterns of vertical caprine mobility in the Valais through the sequential analysis of stable oxygen and carbon isotopes.

This study aims, first, to investigate pastoral exploitation of distinct altitudinal zones and their associated ecological resources over the long term in the Valais region; and second, to empirically assess the impact of vertical mobility on sequential oxygen and carbon isotope signatures recorded in caprine dental enamel in the Western Alps. The paper is based on a set of archaeological caprine from sites located in the Upper to Lower Valais, covering an extensive chronological range from the Early Neolithic to the Early Middle Ages.

Investigating the Study of Mobility and Food Management through Stable Isotope Analysis ($\delta^{18}O/\delta^{13}C$): Principles, Current Knowledge, and a Novel Methodological Approach

The combined analysis of carbon ($\delta^{13}C$_bioapatite) and oxygen ($\delta^{18}O$_bioapatite) isotopes from incrementally sampled enamel from hypsodont ruminant molars (notably domestic caprine) is a valuable tool for investigating dietary patterns and, biomes frequented by livestock at a seasonal scale. Enamel forms directionally from the apex to the cervix of the tooth crown and is not remodelled once fully mineralised. In the second and third molars, this process occurs during the first and second years of the animal's life (MILHAUD, NEZIT 1991, 121 127). Intra-tooth $\delta^{13}C$ values recorded in caprine molar enamel reflect diet, while $\delta^{18}O$ values are primarily derived from ingested water and are related to the oxygen isotope composition of local precipitation ($\delta^{18}O_p$) (LAND *et al.* 1980, 143-151; D'ANGELA, LONGINELLI 1990, 75-82).

General principles of $\delta^{18}O$ analysis

At mid and high latitudes, the $\delta^{18}O_p$ values vary seasonally, with ambient temperatures leading to the highest $\delta^{18}O_p$ values during the warmest season (summer) and the lowest during the coldest season (winter) (ROZANSKI *et al.* 1993, 1-36). The current seasonal variations of $\delta^{18}O_p$ values at Sion (Central Valais) are consistent with this model *(Fig. 1)*. Thus, the $\delta^{18}O$ values recorded in enamel preserve the seasonal oxygen isotope signal—typically exhibiting a sinusoidal pattern (BALASSE *et al.* 2012, 349-368).

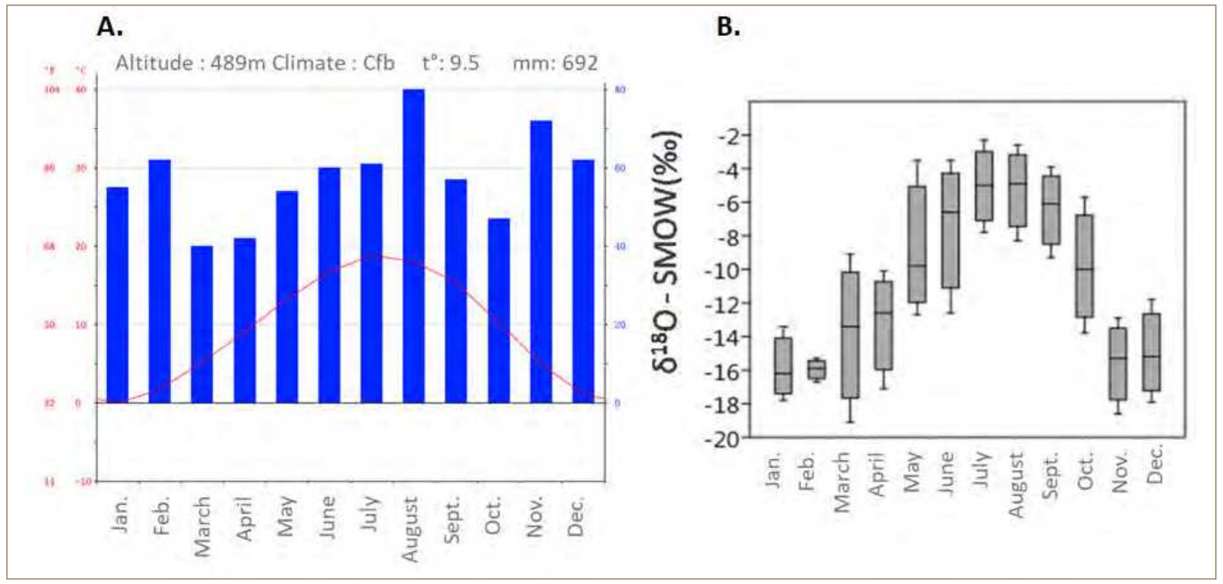

Fig. 1 - A. Monthly precipitation (in blue) and temperature (in red) in Sion, based on data collected from 1998 to 2021 (Source: climate-data.org). B. Monthly $\delta^{18}O$ values of precipitation based on data collected from 1994 to 2016 for the city of Sion (GNIP database, Physikalisches Institut, Universität Bern).

Furthermore, $\delta^{18}O_p$ values are modified by geospatially defined parameters, including continental positioning as well as altitude (GAT 1980, 21-47; LONGINELLI, SELMO 2003, 75-88). Within the hydrological cycle, due to the faster evaporation of the light ^{16}O, water evaporated from water bodies (e.g. seas or oceans) is depleted in ^{18}O. The gradual decrease in the $\delta^{18}O$ values of water stored in clouds leads to lower values the further the water masses precipitate from the original source, and consequently, $\delta^{18}O_p$ values are lower in continental areas (GAT 1980, 483-480; ROZANSKI *et al.* 1993, 1-36). In addition, decreasing temperatures lead to a negative correlation between $\delta^{18}O$ values and altitude. Due to this mechanism, a decrease from 0.1 to 0.4‰/100m of the $\delta^{18}O_p$ values occurs in the Alps according to local conditions (Swiss Alps: SIEGENTHALER, OESCHGER 1980, 314-317; KERN *et al.* 2014, 1987-1907; Italian Alps: LONGINELLI, SELMO 2003, 75-88).

Certain factors, such as the amount of precipitation, the source of evaporated water, and seasonal shifts in air mass trajectories from their origins, can affect the seasonal variability of $\delta^{18}O$ in meteoric water (GAT 1980, 483-480). Additionally, seasonal mobility causes animals to drink from a variety of water sources that may exhibit distinct $\delta^{18}O$ values (ZHAN *et al.* 2025, 820). Furthermore, the input of snow and ice melt—representing water accumulated from winter precipitation with lower $\delta^{18}O$ values—into spring and summer drinking water may influence the seasonal variation of $\delta^{18}O$ sequences typically recorded in tooth enamel. However, studies conducted on modern transhumant sheep in the Pyrenees (KNOCKAERT *et al.* 2017, 60-74; TORNERO *et al.* 2018, 94-106) suggest that the contribution of snowmelt may not significantly affect the seasonal $\delta^{18}O$ signal recorded in dental enamel, thereby tempering the assumed impact of this factor.

Accordingly, MAKAREWICZ (2017, 16-29), based on sequential $\delta^{18}O$ measurements in obligate and non-obligate drinkers from southern Jordan, argues that relying solely on the amplitude of $\delta^{18}O$ variation to assess vertical mobility produces inconclusive results. Nevertheless, $\delta^{18}O$ values preserved in tooth enamel remain a valuable tool for distinguishing animal exploitation of ecologically distinct environments, both across broad altitudinal gradients and in relation to distance from the sea (i.e., the continental effect). This is illustrated in figure 2 showing mean $\delta^{18}O$ values from teeth enamel of modern sheep raised respectively in Central Valais (characterised by an intra-valley vertical movement system with approximately 1,000 m elevation difference; KNOCKAERT *et al.* in prep.) and sedentary sheep raised in the Pre-Alps (Le Chaffaut-Saint-Jurson, Alpes-de-Haute-Provence; BLAISE, BALASSE 2011, 3085-3093) *(Fig. 2)*. Although this approach, based on modern reference data, is subject to several parameter-related biases — such as the influence of climate on atmospheric $\delta^{18}O$, the complexity of topography in moutainous regions or the contribution of variable water sources — it still provides, through extrapolation, a broad framework for identifying distinct ecological zones relevant to archaeological interpretation.

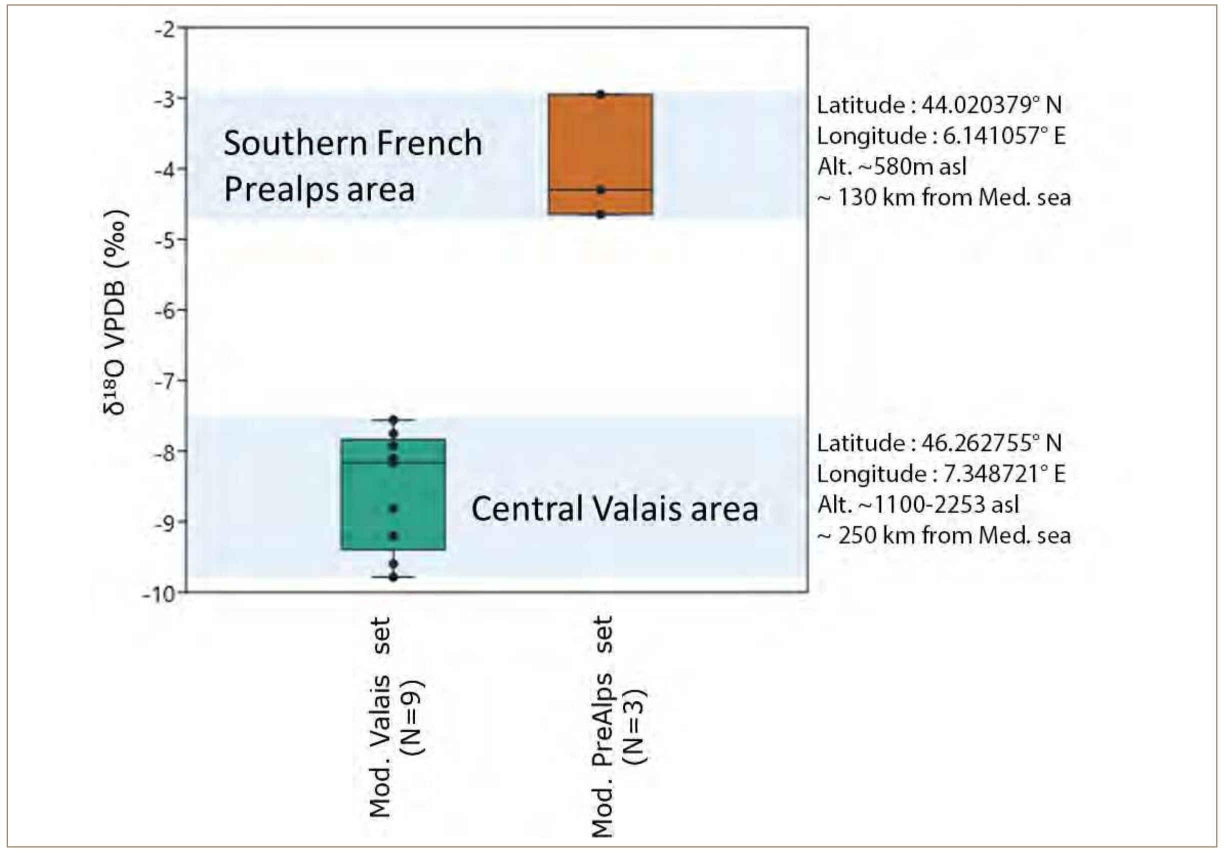

Fig. 2 - Box plot of mean $\delta^{18}O$ values derived from incremental tooth enamel analyses of second (M_2) and third molars (M_3) of modern sheep raised respectively in Central Valais (Savièse; KNOCKAERT et al. in prep.) and in the Southern French Prealps (Carmejane, Le Chaffaut-Saint-Jurson, BLAISE, BALASSE 2011, 3085–3093). Sample sizes are shown in parentheses. The observed difference reflects the combined effect of continentality and altitude.

General principles of $\delta^{13}C$ analysis

The $\delta^{13}C$ values recorded in the enamel of herbivores reflect the $\delta^{13}C$ composition of the vegetation they consume. $\delta^{13}C$ plants are mainly determined by their photosynthetic pathway (C_3 or C_4, CAM) (LEE-THORP 2008, 925-950) but also by environmental parameters such as biome type (altitude, vegetation cover, precipitation, and temperature). A predominance of C_3 plants is expected in Western Europe throughout the Holocene, consistent with the global pattern observed in present-day (KOHN 2010, 19691-19695; PYANKOV *et al.* 2010, 283-304). Indeed, wild C_4 plants are only marginally present in temperate environments (PYANKOV *et al.* 2010, 283-304), thus presence of C_4 plant consumption by the caprine in the studied chronotopic context will suggests that animals ingested cultivated C_4 crops, such as broomcorn millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*), whose introduction occurred during the Bronze Age in the Valais and the Italian Alps (TAFURI *et al.* 2009, 146-153). From modern plants, the average $\delta^{13}C$ value expected for C3 plants is -28.5‰, ranging from -20‰ to -37‰. To estimate the expected $\delta^{13}C$ values in plants from pre-industrial times, it is necessary to apply a correction of +1.5‰ to compensate for the fossil fuel effect (FRIEDLI *et al.* 1986, 237-238; MARINO, MC ELROY 1991, 127-131). Furthermore, an enrichment factor of 14.5‰ between Δbioap-diet (CERLING *et al.* 2021) must be taken into account to estimate the values of the plants consumed based on the $\delta^{13}C$ of enamel ($\delta^{13}C$bioap.). In closed forest environments, the 'canopy effect' results in lower $\delta^{13}C$ values in plants due to several parameters of the carbon biogeochemical cycle, including low light intensity and the recycling of carbon from the decomposition of ^{13}C-depleted organic matter (VAN DER MERWE, MEDINA 1991, 249-259; BONAFINI *et al.* 2013, 3926 3935). The $\delta^{13}C$ threshold value below which a significant dietary contribution of forest resources can be inferred from carbon values recorded in enamel is −13.2‰ (based on −27.7‰ d^{13}C$_{plants}$ adjusted for Δbioap-diet by −14.5‰). The estimation of this threshold is supported by a dataset of $\delta^{13}C$ values obtained from contemporaneous deer bone collagen (GILLIS *et al.* 2025, 87-98).

Combining Oxygen and Carbon Isotopes to Reconstruct Vertical Mobility: Current State of Knowledge

The combined analysis of sequential $\delta^{13}C$ and $\delta^{18}O$ values has been used for several decades to infer vertical mobility in animal husbandry. Depending on environmental contexts, the factors influencing isotopic data can be highly variable, and the methodological approaches adopted may therefore differ accordingly (BALASSE, AMBROSE 2005, 147-166; MAKAREWICZ 2017, 16-29; KNOCKAERT *et al.* 2017, 60-74; TORNERO *et al.* 2018, 94-106 ; JANZEN *et al.* 2020; TEJEDOR-RODRÍGUEZ *et al.* 2021; MESSANA *et al.* 2025).

In Western Europe, where vegetation is dominated by C_3 plants, $\delta^{13}C$ values in C_3 vegetation vary seasonally—rising during summer and decreasing in winter (SMEDLEY *et al.* 1991, 314 320). Consequently, when caprines graze continuously over a single pasture throughout the year, $\delta^{13}C$ and $\delta^{18}O$ sequences in tooth enamel tend to vary in phase *(Fig. 3)*. Conversely, seasonal vertical movements can be inferred when $\delta^{13}C$ and $\delta^{18}O$ sequences are not in phase—i.e., when their respective maxima and minima do not align along the tooth crown. Deviations from this expected pattern may also indicate seasonal dietary shifts due to foddering, or movement between environments with differing vegetation growth dynamics (BALASSE *et al.* 2012, 29-44; KNOCKAERT *et al.* 2017, 60-74).

To date, this model has been empirically tested on only two modern sheep managed in contrasting ecological settings in Western Europe (Between northern Spain and the Pyrenees, characterised by significant altitudinal variation and pronounced arid conditions in the plains; TORNERO *et al.* 2018, 94-106). While this dual-isotope approach has established a conceptual framework applicable to archaeological specimens (*e.g.* MESSANA *et al.* 2025), reference datasets remain scarce. Moreover, potential methodological biases must be acknowledged, particularly those arising from modern zootechnical practices—such as dietary supplementation or the use of non-local water sources. In this paper, we therefore propose to empirically test this approach on archaeological domestic and wild individuals that became trapped at high altitudes and who most likely practised seasonal vertical mobility.

A New Empirical Threshold Approach for Detecting Heterogeneity in mobility trajectories in a zooarchaeological context

To assess internal variability in herd mobility patterns, the **MIGA-$\delta^{18}O$** (Maximum Intra-Group $\delta^{18}O$ Amplitude) was calculated within several modern sheep groups within which individuals are known to have followed homogeneous mobility trajectories and comparable herd management strategies (BLAISE, BALASSE 2011, 3085-3093; KNOCKAERT *et al.* 2017, 60-74; BALASSE *et al.* 2024, 75-92; KNOCKAERT *et al.* in prep). These modern reference datasets are derived from flocks managed under a range of husbandry systems, including sedentary practices, limited vertical mobility, and long-distance transhumance *(Tab. 1)*. Although the small dataset, which remains to be expanded in the future, must be taken into account, MIGA-$\delta^{18}O$ values are higher in the two sedentary groups than in those practicing short-distance mobility, highlighting that the range of $\delta^{18}O$ values can be relatively large even within a homogeneous sedentary system. The highest recorded MIGA-$\delta^{18}O$ value was observed in the Merle reference set (BALASSE *et al.* 2024, 75-92). The sheep in this set originate from the Domaine du Merle in southern France (Salon-de-Provence), where they undertake seasonal transhumance to the Southern Alps (Col des Champs, over 2,000 m elevation and more than 200 km away, KNOCKAERT *et al.* in prep). This MIGA-$\delta^{18}O$ value of 2.4‰ was considered an empirical threshold, above which potential heterogeneity related to mobility patterns and/or herding strategies could be identified within archaeological assemblages.

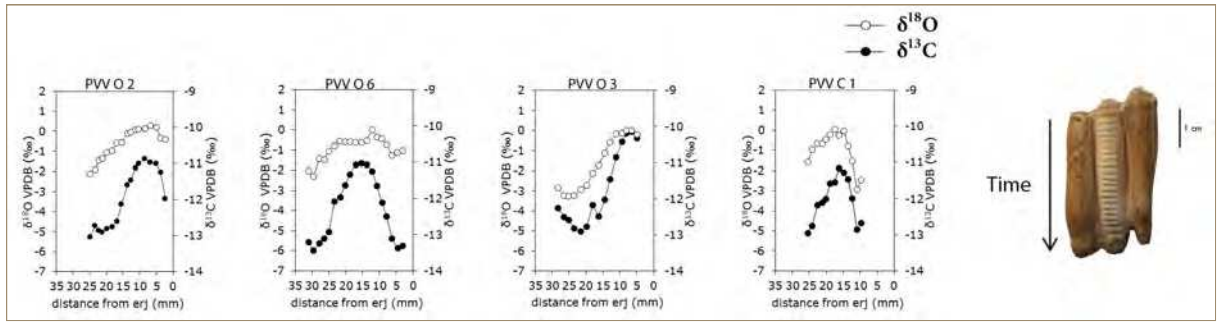

Fig. 3 - Example of positive correlation observed in the oxygen and carbon sequences of the dental enamel of caprine reared in lowland areas at mid-latitude in Europe (From KNOCKAERT et al. 2017, 60-74, Fig. 5).

Modern reference sets	MIGA-δ^{18}O (Maximum Intra-Group δ^{18}O Amplitude)
Ossau Short-Mobility (N=5)[1]	0.56
Valais Short-Mobility (N=6)[2]	0.72
Valais Sedentary (N=3)[2]	0.84
Carmejane Sedentary (N=3)[3]	1.90
Merle Long-Mobility (N=9)[4]	2.41

Tab. 1 - Reference datasets used to estimate the MIGA-δ^{18}O value (Maximum Intra-Group δ^{18}O Amplitude) in this study. The original data come from four sources: (1) KNOCKAERT et al. 2017, 60-74 (2) KNOCKAERT et al. in prep. (3) BLAISE, BALASSE 2011, 3085-3093 and (4) BALASSE et al. 2024, 75-92.

Environmental and chronocultural context

The region is under a continental climate with Mediterranean influence characterised by a relatively dry climate, Foehn effect and a significant seasonal variation of temperatures, with warm summers and cold winters (From 1971 to 2000, the maximum amplitude of the temperature at Savièse, a locality near Sion, reaches 18.9°C between July and January). The continental part of the Valais, where Sion, Savièse and Gamsen are located, comprises strongly contrasting ecological zones, ranging from low, particularly dry valleys to wet, high alpine meadows, whereas Giétroz Devant is situated in the more humid “Atlantic” Valais. The annual rainfall in the lowland zones does not exceed 700mm/year, whereas it can reach 2,000mm/year in the surrounding highland areas (MeteoSuisse, data from 1961 to 2020).

The dataset comprises material from the archaeological sites of La Planta, La Soie, and Gamsen, located in the central and Upper Valais, and spanning a chronological range from the Early, Middle, and Late Neolithic to the Early and Late Iron Age, and the Early Middle Ages. In addition, a natural chasm in the Lower Valais yielded individuals naturally trapped in an alpine zone. All these contexts are distributed across distinct geological, climatic, and topographical zones, ranging from valley floor to alpine environments (512 m asl to 2,178 m asl) *(Fig. 4)*.

La Planta: An open-air settlement

La Planta is located in the Rhône Valley plain. The settlement excavated in 1980 in Sion (512 m asl) and dated between 5200 and 4800 BCE, is one of the earliest examples of agro-pastoral societies in Western Switzerland and the Alps (GALLAY *et al.* 1983 b., 43-73; CHAIX, 2008). Archaeozoological analysis shows dominance of domestic cattle and caprines, with recent reassessment indicating a higher proportion of caprines than initially thought (CHIQUET, REYNAUD SAVIOZ 2019, 175-188).

La Soie: An open-air spur-top settlement

Situated at 872 m asl, La Soie lies strategically between the Rhône plain and the Sanetsch Pass mountains, overlooking central Valais *(Fig. 4)*. Excavations revealed occupations from Middle Neolithic I (4700-4050 BCE), Middle Neolithic II (3550-3350 BCE), and Late Neolithic (3350-2950 BCE) (BAUDAIS 1995, 91-96). Sheep dominated in Middle Neolithic I, used for meat and milk. Over time, the number of goats increased, supporting greater milk production and resulting in a mixed sheep-goat husbandry system (1:1) during the Late Neolithic, along with an increasing importance of cattle (CHIQUET 2019). The predominance of caprine husbandry characterising these Neolithic sites is a distinctive feature of the Upper Rhône valley that persists into the Metal Ages (CHIQUET, REYNAUD SAVIOZ 2019, 175-188).

Gamsen: A settlement established on artificial terraces

The site of Gamsen (670 m asl), located on the left bank of the Rhône (north-facing slope), at the foot of the Glishorn *(Fig. 4)*, yielded a rich faunal assemblage reflecting a strong focus on sheep and goats from the Early Iron Age to the Early Middle Ages (REYNAUD SAVIOZ, 2018). Although deprived of winter sunlight, the villages were strategically located within a network of transalpine routes, at the convergence of several major passes leading southward (e.g., Albrun, Simplon). They also benefited from high-quality local resources that suported their economy. Throughout the sequence, caprines remained predominant; however, a marked decline is oberved between the Early and Late Iron Ages, coincinding with an increase in cattle proportions that continues into the Roman Period.

Giétroz Devant: A natural chasm

The Giétroz Devant chasm, situated in the Susanfe Valley at an altitude of 2,178 m in Lower Valais *(Fig. 4)*, preserves a substantial assemblage of exceptionally well-preserved faunal remains. These specimens were trapped between the second half of the 8th millennium BCE and the end of the 1st

Fig. 4 - ***Red circles:*** *archaeological sites investigated in this study (Gamsen, Upper Valais; La Soie and La Planta, Central Valais; Giétroz Devant Chasm, Lower Valais).* ***Yellow circles:*** *locations of farms where modern sheep are raised in Central Valais (Savièse; Knockaert et al. in preparation) and in the southern French Prealps (Carmejane, Le Chaffaut-Saint-Jurson; Blaise and Balasse 2011, pp. 3085–3093), as shown in Figures 2 and 9.*

century BCE (REYNAUD SAVIOZ *et al.* 2019, 21 30; REYNAUD SAVIOZ, BLANT 2022, 7-22). The faunal assemblage is primarily composed of Alpine ibex *(Capra ibex)* and sheep *(Ovis aries)*. The ibex, exclusively male individuals, were trapped during the Atlantic period (8th-4th millennium BCE) and likely succumbed during winter while occupying alpine pasture environments. Conversely, the trapping of domestic sheep occurred significantly later, dated to the Late Iron Age between 200 and 46 BCE (calibrated age). This later assemblage consists solely of hornless ewes and male lambs aged between 2 and 6 months, providing direct evidence for pastoral exploitation of high-altitude zones during the Iron Age by Celtic communities.

Material

The selected samples include seventeen sheep and two goats from the sites of La Planta, La Soie, and Gamsen. Additionally, two ibex and two sheep from the Giétroz Devant chasm are included. In total, thirty teeth from archaeological specimens were analysed, comprising sixteen second lower molars (M_2) and fourteen third lower molars (M_3) *(Tab. 2)*.

Countryside	Site	Period	Latitude	Altitude	ID Specimen	Species	Age-at-Death	Teeth analysed	
								M_2	M_3
Lower Valais	Gietroz Chasm	Atlantic period VIII-IV mill. BC	46.1	2178m asl	EVG D2	*Capra ibex**	2-4 years	x	x
					EVG D4	*Capra ibex**	1-2 years	x	
Central Valais	La Planta	Early Neolithic VI mill. BC	46.2	512m asl	Planta 1	*Capra hircus*	~4 years	x	x
	La Soie	Middle Neolithic V mill. BC (4 700 et 4 050 BC)	46.2	850m asl	La Soie 31	*Ovis aries**	4-6 years		x
					La Soie 65	*Ovis aries**	4-6 years	x	x
					La Soie 71	*Ovis aries**	2-6 years	x	x
					La Soie 107	*Ovis aries**	2-4 years		x
		Middle Neolithic 2 IV mill. BC (3550-3350 BC)			La Soie 89	*Ovis aries**	2-6 years	x	x
		Late Neolithic IV-III mill. BC (3350-2 950 BC)			La Soie 15	*Capra hircus**	4-6 years		x
					La Soie 16	*Ovis aries**	4-6 years	x	x
Upper Valais	Gamsen	Early Iron Age (790-600 BC)	46.3	670m asl	Gam 14	*Ovis aries**	2-4 years	x	
		Early Iron Age (600-515 BC)			Gam 11	*Ovis aries**	2-4 years	x	
		Early Iron Age (600-515 BC)			Gam 20	*Ovis aries**	2-4 years	x	
		Early Iron Age (515-450 BC)			Gam 8	*Ovis aries**	2-6 years	x	
		Early Iron Age (450-250 BC)			Gam 10	*Ovis aries**	2-6 years		x
Lower Valais	Gietroz Chasm	Late Iron Age (200-46 BC)	46.1	2178m asl	EVG 17	*Ovis aries**	2-4 years	x	x
					EVG G2	*Ovis aries**	4-6 years		x
Upper Valais	Gamsen	Roman period (80-260 AD)|	46.3	670m asl	Gam 2	*Ovis aries**	4-6 years	x	
					Gam 3	*Ovis aries**	2-4 years	x	
					Gam 4	*Ovis aries**	4-6 years	x	
					Gam 18	*Ovis aries**	4-6 years		x
					Gam 19	*Ovis aries**	4-6 years		x
		Early Middle Ages (400-1200 AD)			Gam 21	*Ovis aries**	4-6 years	x	

Tab. 2 - List of individuals selected for the isotopic analysis. For each individual, the species, estimated age at death, and sampled tooth are indicated. Tooth types are abbreviated as M_2 (second molar) and M_3 (third molar). An asterisk (*) indicates that the taxonomic identification was confirmed through ZooMS analysis (Zooarchaeology by Mass Spectrometry).

Method

Sampling and isotopic analysis

Isotopic analysis was performed on the second lobe of the left M_2 and/or M_3 of each individual. Sequential sampling of enamel from the La Soie site was conducted at the Muséum national d'Histoire naturelle (Paris, France), and samples from Gamsen, Giétroz, and La Planta at the Bioarchaeology Laboratory, University of York (York, United Kingdom). A total of 383 samples were collected, then enamel powder was pre-treated with 0.1 M acetic acid (0.1 ml/mg) for 4h, rinsed five times with distilled water and freeze-dried to eliminate contamination from exogenous carbonates. Samples from La Soie were analysed by mass spectrometry (IRMS) at the Service de Spectrométrie de Masse Isotopique du MNHN (SSMIM, Paris, France), while samples from La Planta, Gamsen, and Giétroz were analysed by IsoAnalytical (Crewe, United Kingdom). Approximately 600 µg of powder was then placed in an automated carbonate preparator (Kiel IV) coupled to an isotope mass spectrometer (Delta V Advantage). Stable carbon and oxygen isotope ratios were calibrated to VPDB using the international standard NBS 19. For all samples, isotopic composition is expressed in delta notation (δ^{18}O and δ^{13}C, in ‰), relative to the Vienna Pee Dee Belemnite (V-PDB) standard. The accuracy and repeatability of the isotopic measurements are determined using an internal laboratory calcium carbonate standard (Marbre LM normalised to NBS 19).

Taxa identification

All archaeological mandibles and teeth were taxonomically identified based on morphological criteria (PAYNE 1985, 139-147; HELMER 2000, 29-38; HALSTEAD, COLLINS 2002, 545-553; BALASSE, AMBROSE 2005, 147-166; ZEDER, PILAR 2010, 225-242; GILLIS *et al.* 2011, 2324-2339). These identifications were further supported by collagen peptide mass fingerprinting, known as ZooMS (Zooarchaeology by Mass Spectrometry), as defined by BUCKLEY *et al.* (2010, 13-20). This method enables the differentiation between sheep and goats based on variations in the peptide sequences of type I collagen (α1 and α2 chains). The methodological approach is described in the supplementary material *(Supplementary Material 1)*.

Results

The results are summarised in Table 3 and presented in detail in supplementary material *(Supplementary Material 2)*.

Taxa ID

All taxonomic identifications based on morphological criteria were confirmed by collagen peptide analysis *(Tab. 2)*.

Stable oxygen results

Intra-tooth variations in δ^{18}O values follow a sinusoidal pattern related to the seasonal cycle (*Fig. 6* and *Supplementary material 2*)[1].

Across the various chrono-cultural contexts examined in this study, the analysed teeth —from the Giétroz Devant chasm (ibex and sheep), the Early Neolithic goat from La Planta (M_2 and M_3 from the same individual), the Middle II and Late Neolithic specimens from La Soie — all exhibit intra-group δ^{18}O midrange amplitudes below the MIGA-δ^{18}O threshold of 2.4‰. These results do not permit us to confidently suggest the existence of heterogeneous mobility patterns and/or herd management strategies. In contrast, sheep from the Middle Neolithic at La Soie, as well as those from the Early Iron Age and Roman Period at Gamsen, exceed this threshold, which supports the hypothesis of intra-group heterogeneity in mobility and/or herd management strategies *(Tab. 3)*.

Ibex teeth from Giétroz Devant show δ^{18}O values ranging from -9.8‰ to -5.9‰, with intra-tooth amplitude ranging from 2.8‰ to 3.9 ‰ *(Tab. 3)*. The second and third molars of the La Planta goat exhibit δ^{18}O values ranging from -8.5‰ to -3.5‰ and -11.3‰ to -4.5‰, respectively, with substantial intra-tooth amplitudes of 5.0‰ and 6.7‰. At La Soie, δ^{18}O values range from -10.7 to -4.7 ‰, with intra-tooth amplitudes ranging from 3.9 to 5.8 ‰ in the assemblage attributed to the Middle Neolithic (5th millennium BC). For the single sheep from the Middle Neolithic II (4th millennium BC), the second and third molars show values ranging from -9.8 to -3.0‰, with significant intra-tooth amplitudes of 6.5 and 5.7 ‰, respectively. In the Late Neolithic specimens, δ^{18}O values in the third molars of the goat (La Soie 15 M_3) and the sheep (La Soie 16 M_3) range from -8.1‰ to -3.5‰ and from -11.0‰ to -5.0‰, respectively, with intra-tooth amplitudes of 4.6‰ and 6.0‰. The Gamsen Early Iron Age individuals show values between -10.1 and -2.0 ‰ with intra-tooth amplitudes varying between 3.6

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[1] The sequence from La Soie16 M_2, La Soie 65 M_2 and La Soie 89 M_2 are incomplete.

Site	Sample ID	Species	Tooth	N	$\delta^{18}O$					$\delta^{13}C$			
					Min	Max	Mean	Amplitude	MIGA-$\delta^{18}O$	Min	Max	Mean	Amplitude
Giétroz chasm	EVG D2	*Capra ibex*	M2	12	-9,8	-5,9	-7,9	3,9	1,1	-11,7	-10,9	-11,2	0,8
			M3	11	-9,7	-6,9	-8,1	2,8		-11,1	-10,6	-10,9	0,5
	EVG D4	*Capra ibex*	M2	14	-9,5	-6,5	-8,0	3,0		-11,9	-11,4	-11,7	0,5
La Planta	La Planta 1	*Capra hircus*	M2	13	-8,5	-3,5	-6,2	5,0	1,8	-12,0	-11,4	-11,8	0,6
			M3	16	-11,3	-4,5	-7,3	6,7		-12,9	-12,2	-12,5	0,7
La Soie	La Soie 31	*Ovis aries*	M3	20	-10,7	-5,6	-8,1	5,1	**3,7**	-13,7	-11,6	-12,4	2,0
	La Soie 65	*Ovis aries*	M2*	7	-7,1	-4,9	-5,6	2,2		-12,2	-11,4	-11,7	0,8
			M3	16	-9,3	-4,7	-6,7	4,6		-11,8	-10,6	-11,3	1,2
	La Soie 71	*Ovis aries*	M2	12	-10,7	-4,9	-7,0	5,8		-12,2	-11,8	-12,0	0,5
			M3	18	-9,6	-4,8	-7,5	4,8		-12,7	-11,7	-12,1	1,0
	La Soie 107	*Ovis aries*	M3	18	-9,7	-5,8	-7,5	3,9		-14,2	-12,8	-13,5	1,4
	La Soie 89	*Ovis aries*	M2*	13	-9,4	-3,0	-5,4	6,5	0,8	-11,6	-11,0	-11,3	0,6
			M3	19	-9,8	-4,1	-7,0	5,7		-12,5	-11,3	-11,8	1,3
	La Soie 15	*Capra hircus*	M3	16	-8,1	-3,5	-5,5	4,6	1,4	-12,6	-11,1	-11,6	1,5
	La Soie 16	*Ovis aries*	M2*	0	-9,6	-5,0	-6,6	4,6		-12,1	-11,5	-11,9	0,5
			M3	17	-11,0	-5,0	-8,1	6,0		-12,5	-11,2	-11,7	1,4
Gamsen	Gam 14	*Ovis aries*	M2	17	-10,1	-3,2	-6,5	6,9	**3,3**	-12,6	-10,7	-11,7	1,9
	Gam 11		M2	13	-7,9	-2,0	-5,3	5,9		-13,2	-12,1	-12,6	1,1
	Gam 20		M2	13	-8,9	-4,9	-7,1	40,0		-12,9	-11,9	-12,4	1,0
	Gam 8		M2	13	-9,3	-5,7	-7,6	3,6		-12,6	-10,6	-11,5	2,0
	Gam 10		M3	9	-8,4	-3,4	-6,2	5,0	-	-14,8	-12,6	-14,0	2,2
Giétroz chasm	EVG 17	*Ovis aries*	M2	12	-10,4	-3,8	-7,2	6,7	2,0	-13,1	-12,2	-12,7	0,9
			M3	10	-9,1	-4,4	-6,7	4,6		-13,4	-11,3	-12,6	2,1
	EVG G2	*Ovis aries*	M3	9	-10,7	-5,1	-7,5	5,6		-12,8	-11,7	-12,2	1,1
Gamsen	Gam 2	*Ovis aries*	M2	9	-10,7	-5,7	-8,8	5,0	**2,8**	-13,2	-12,3	-12,6	1,0
	Gam 3		M2	13	-9,2	-4,7	-7,1	4,6		-13,1	-11,8	-12,3	1,3
	Gam 4		M2	11	-11,8	-4,5	-8,1	7,3		-12,7	-11,8	-12,1	0,9
	Gam 18		M3	13	-11,7	-5,7	-7,9	6,1		-14,0	-13,0	-13,5	1,0
	Gam 19		M3	11	-11,2	-6,7	-8,4	4,5		-12,8	-10,8	-12,0	2,0
	Gam 21		M2	8	-12,4	-4,9	-8,8	7,5	-	-13,1	-12,0	-12,6	1,0

Tab. 3 - Summary of $\delta^{18}O$ and $\delta^{13}C$ values derived from incremental sampling of enamel bioapatite in archaeological caprine. For each individual, data include site provenance, species, sampled tooth (M_2 or M_3), and isotopic parameters: minimum, maximum, mean and amplitude values. The Maximum Intra-Group Amplitude of $\delta^{18}O$ (MIGA-$\delta^{18}O$) is also reported. Groups exhibiting MIGA-$\delta^{18}O$ values above the 2.4‰ empirical threshold—indicative of intra-group isotopic heterogeneity potentially linked to diverse mobility or herding strategies—are indicated in underlined. An asterisk (*) signifies incomplete enamel isotope sequences.

and 6.9‰. The single Late Iron Age sheep shows values between -8.4 and -3.4‰, giving a significant intra-tooth amplitude of 5‰. In the Giétroz Devant chasm, sheep values range from -10.7 to -3.8‰ with high amplitudes between 4.6 and 6.7‰. For Gamsen Roman sheep, values range from -11.8 to -4.5‰ with intra-tooth amplitudes ranging from 4.5 to 7.3‰. Finally, the Early medieval sheep second molar from Gamsen shows values between -12.4 and -4.9‰, with an intra-tooth amplitude of 7.5‰, the highest of all the individuals analysed.

Stable carbon results

For all archaeological individuals, $\delta^{13}C$ values range from -14.8‰ to -10.6‰, with an average of -12.1‰[2]. Ibex teeth from Giétroz Devant exhibit $\delta^{13}C$ values ranging from -11.9‰ to -10.6‰, with low intra-tooth variation (amplitude < 1‰) *(Tab. 3 and Fig. 5)*. At La Planta, $\delta^{13}C$ values from the second and third molars of a single goat range from -12.9‰ to -11.4‰, also showing low intra-tooth variation (amplitude < 1‰). At La Soie, $\delta^{13}C$ values range from -14.2 to -10.6‰, with intra-tooth amplitudes ranging from 0.5 to 2‰ in the assemblage attributed to the Middle Neolithic (5th millennium BC). For the single sheep from the Middle Neolithic 2 (4th millennium BC), the second and third molars yield values ranging from -12.5 to -11.0‰, with intra-tooth amplitudes of 0.6 and 1.3‰, respectively. The assemblage from the Late Neolithic (4th-3rd millennium BC) at La Soie provides $\delta^{13}C$ values ranging from -12.6‰ to -11.1‰, with intra-tooth variation between 0.5‰ and 1.5‰. At Gamsen, the assemblage corresponding to the Early Iron Age yields $\delta^{13}C$ values ranging from -13.2‰ to -10.6‰, with intra-tooth variation between 1‰ and 2‰. The single sheep tooth from the Late Iron Age shows $\delta^{13}C$ values between -14.8‰ and -12.6‰, with an amplitude of 2.2‰. The Roman-period assemblage (80-260 AD) exhibits $\delta^{13}C$ values ranging from -14.0‰ to -10.8‰, with intra-tooth amplitudes between 0.9‰ and 2‰. A sheep from the Early Middle Ages provides $\delta^{13}C$ values between -13.1‰ and -12.0‰, with an amplitude of 1‰. Sheep teeth from the Giétroz Devant chasm, dated to the Late Iron Age, show $\delta^{13}C$ values ranging from -13.4‰ to -11.3‰, with intra-tooth amplitudes between 0.9‰ and 2.1‰.

Within six teeth of sheep, the lowest $\delta^{13}C$ values are equal or below the threshold of -13.2 ‰, beyond which a consumption of forest resources should be considered: La Soie 31 M_3 (-13.7‰) and La Soie 107 M_3 (-14.2‰) at La Soie; Gam 10 (-14.8 ‰), EVG 17 M_3 (-13.4 ‰) at Giétroz; and Gam 2 M_2 (-13.2‰), Gam 18 M_2 (-14.0‰) at Gamsen *(Fig. 5)*.

Combined incremental $\delta^{18}O$ and $\delta^{13}C$ sequences

The $\delta^{18}O$ and $\delta^{13}C$ sequences of all archaeological individuals show a great diversity in $\delta^{18}O/\delta^{13}C$ covariation and three main patterns can be observed:

i) Most individuals show no correlation between $\delta^{18}O$ and $\delta^{13}C$ sequences *(Tab. 4)*.

ii) Six individuals demonstrated a positive correlation between $\delta^{18}O$ and $\delta^{13}C$ values with high $\delta^{13}C$ values during summer and vice a versa *(Fig. 6. A)*. This pattern is particularly evident in individuals 'La Soie 107 M_3' and 'La Soie 31 M_3' *(Fig. 7)*.

iii) In contrast, six individuals show an inverse pattern *(Fig. 6. B, Tab. 4)*.

Among the sheep exhibiting $\delta^{13}C$ values below the threshold of -13.2‰ — interpreted as indicative of forest resource consumption — two individuals ('La Soie 31 M_3' and 'La Soie 107 M_3') display positive correlations between their $\delta^{13}C$ and $\delta^{18}O$ sequences, while the others show no significant correlation.

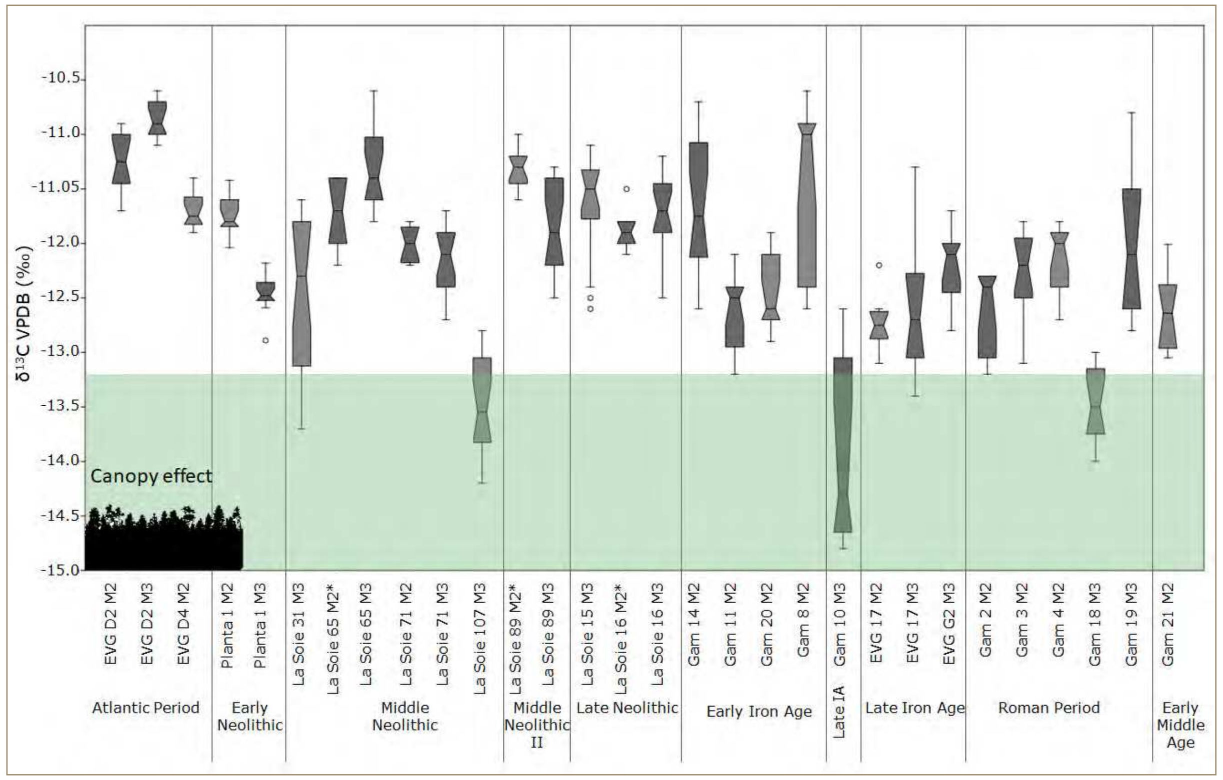

Fig. 5 - $\delta^{13}C$ (VPDB, ‰) values from enamel of archaeological caprine from the Gietroz chasm (EVG), La Planta, La Soie, Gamsen (Gam). Notched boxplots show the distribution per individual. The green shaded area marks $\delta^{13}C$ values consistent with the canopy effect — that is, values below the –13.2‰ threshold, typically reflecting diets based on resources from dense forest environments, such as C_3 plants growing under a closed canopy or animals feeding within such habitats.

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[2] The sequences from La Soie16 M_2, La Soie 65 M_2 and La Soie 89 M_2 are incomplete.

Site	Period	Sample ID	Pearson's r	df	p	Interpretation
Giétroz chasm	Atlantic period VIII-IV mill. BC	EVG D2 M2	-0.59	11	**< 0.05**	Negative correlation
		EVG D2 M3	-0.11	10	> 0.05	No correlation
		EVG D4 M2	0.48	13	> 0.05	No correlation
La Planta	Early Neolithic VI mill. BC	Planta 1 M2	-0.70	12	**< 0.05**	Negative correlation
		Planta 1 M3	-0.07	15	> 0.05	No correlation
La Soie	Middle Neolithic 1 V mill. BC	La Soie 31 M3	0.80	19	**< 0.05**	Positive correlation
		La Soie 65 M2	0.86	6	**< 0.05**	Positive correlation
		La Soie 65 M3	0.02	15	> 0.05	No correlation
		La Soie 71 M2	-0.89	11	**< 0.05**	Negative correlation
		La Soie 71 M3	-0.14	17	> 0.05	No correlation
		La Soie 107 M3	0.95	17	**< 0.05**	Positive correlation
	Middle Neolithic 2 IV mill. BC	La Soie 89 M2	0.66	12	**< 0.05**	Positive correlation
		La Soie 89 M3	0.56	17	**< 0.05**	Positive correlation
	Late Neolithic IV-III mill. BC	La Soie 15 M3	0.68	16	**< 0.05**	Positive correlation
		La Soie 16 M2	-0.67	9	**< 0.05**	Negative correlation
		La Soie 16 M3	0.37	17	> 0.05	No correlation
Gamsen	Early Iron Age (790-600 BC)	Gam 14 M2	-0.71	17	**< 0.05**	Negative correlation
	Early Iron Age (600-515 BC)	Gam 11 M2	-0.23	12	> 0.05	No correlation
	Early Iron Age (600-515 BC)	Gam 20 M2	0.21	12	> 0.05	No correlation
	Early Iron Age (515-450 BC)	Gam 8 M2	-0.72	12	**< 0.05**	Negative correlation
	Late Iron Age (450-250 BC)	Gam 10 M2	0.26	8	> 0.05	No correlation
Giétroz chasm	Late Iron Age (200-46 BC)	EVG 17 M2	0.04	11	> 0.05	No correlation
		EVG 17 M3	0.40	9	> 0.05	No correlation
		EVG G2 M3	0.27	8	> 0.05	No correlation
Gamsen	Roman period (80-260 AD)	Gam 2 M2	-0.38	8	> 0.05	No correlation
		Gam 3 M2	-0.74	12	> 0.05	No correlation
		Gam 4 M2	-0.08	10	> 0.05	No correlation
		Gam 18 M3	0.05	12	> 0.05	No correlation
		Gam 19 M3	-0.60	10	> 0.05	No correlation
	Early Middle Ages (400-1200 BC)	Gam 21 M2	0.44	7	> 0.05	No correlation

Tab. 4 - Pearson correlation coefficients (r) between $\delta^{18}O$ and $\delta^{13}C$ sequences for archaeological caprine. For each individual, the correlation coefficient (r), degrees of freedom (df), and associated p-value are reported. Coefficient with p-values < 0.05 are shown in bold, indicating statistically significant correlation between $\delta^{18}O$ and $\delta^{13}C$ sequences.

Discussion

Isotopic Validation of Seasonal Vertical Mobility

All individuals (ibex and sheep) trapped at altitudes over 2000 meters, in the Giétroz Devant chasm, display $\delta^{13}C$ isotopic sequences characterised by a shifted or even inverted pattern. Based on the topographic setting, it is highly likely that these animals undertook seasonal vertical movements. In line with its behavioural ecology, the Alpine ibex—a highly specialised cliff-dwelling ungulate—performs altitudinal migrations across distinct ecological zones, generally ranging from 1,600-2,200 m asl in winter to 2,200-3,300 m asl in summer, depending on variables such as slope gradient, snow accumulation, and anthropogenic pressure (PARRINI *et al.* 2003, 411-423).

Situated within the alpine belt, the pastoral area around the chasm currently experiences substantial snow cover from November to May. Conversely, the period from June to September is snow-free, offering suitable conditions for high-altitude grazing (MeteoSwiss Open Data, Federal Office of Meteorology and Climatology, Switzerland). It is therefore highly plausible that the Iron Age sheep were trapped in the alpine pasture during the summer season, having likely originated from lower-altitude areas. The absence of correlation—or in some cases, a negative correlation—between $\delta^{13}C$ and $\delta^{18}O$ values along the tooth crowns of both ibex and sheep provides empirical support for the previously proposed model of a shift, or even reversal, in carbon isotope values with vertical mobility (KNOCKAERT *et al.* 2017, 60-74; TORNERO *et al.* 2018, 94-106): This isotopic pattern is interpreted as the result of seasonal altitudinal mobility of livestock between ecologically distinct grazing zones, each characterised by different meteoric water inputs and vegetation types.

Vertical Mobility Through Time:
From Occasional Strategy to Emerging Pattern?

Until now, for the Early and Middle Neolithic I, archaeobotanical and zooarchaeological evidence from Valais have suggested that subsistence activities were mainly concentrated in lower altitudinal zones, with a focus on herding and cultivation in valley bottoms and collinean areas (CHIQUET 2011, 217-254; DUFRAISSE 2011, 269-278; MARTIN *et al.* 2019). Despite the limited dataset, isotopic evidence from a goat at La Planta — one of the earliest Neolithic sites in Valais (UBA 25890, 6027 ± 35 BP; GALLAY *et al.* 1983 b, 43 73) — indicates that vertical mobility may already have been practised during the Early Neolithic. From the Middle Neolithic I, data from La Soie indicate the coexistence of different herding strategies: one sedentary, likely supported by fodder provisioning or the exploitation of forested environments *(Fig. 7)*, and the other characterized by seasonal altitudinal mobility. This latter pattern aligns with broader alpine palaeoenvironmental evidence. In particular, well-documented alpine pollen sequences such as Iffigsee in the Bernese Alps provide support for seasonal subalpine exploitation during the Middle Neolithic, recording recurrent forest clearances and the sustained presence of pastoral indicators (TINNER *et al.* 1999, 161–178). From the Late Neolithic at La Soie and continuing through all caprine individuals

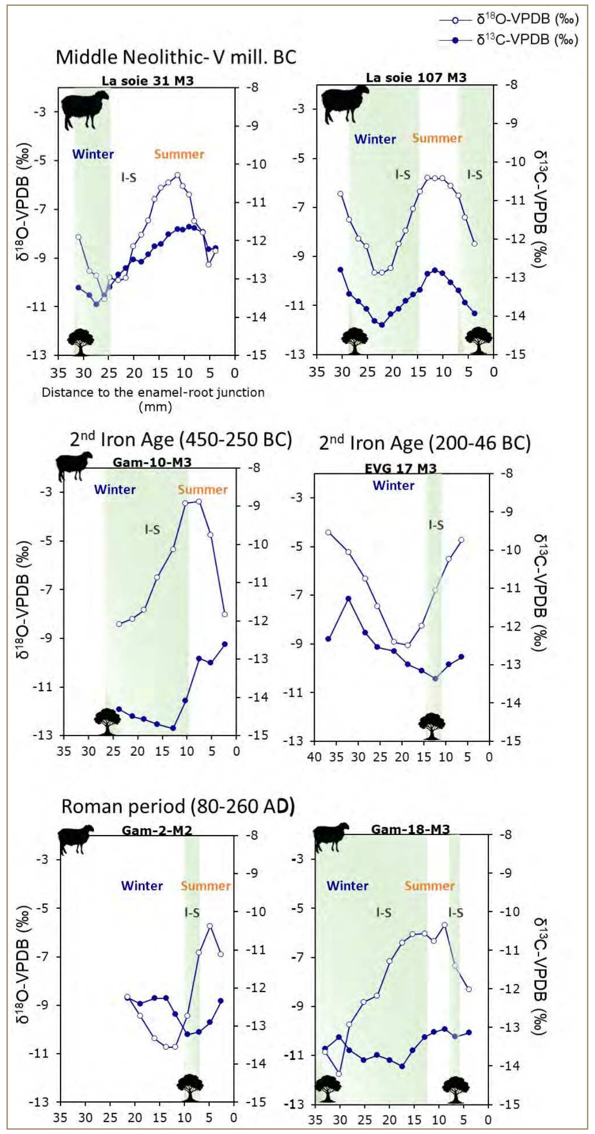

Fig. 7 - Stable isotope ($\delta^{18}O$ and $\delta^{13}C$) results from incremental sampling of second and third molars (M_2 and M_3) from individuals at La Soie and Gamsen (Gam). Low $\delta^{13}C$ values (in the green shaded area) occur during winter and/or interseasonal (I-S) periods, as inferred from $\delta^{18}O$ seasonal patterns. This asynchronous signal reflects the consumption of resources from densely forested settings.

dated from the Early Iron Age to the Early Middle Ages at Gamsen, isotopic data show a reverse pattern or no correlation between δ^{18}O and δ^{13}C sequences. These patterns suggest the use of vertical mobility strategies, possibly combined with different foddering strategies.

Although the dataset remains limited, this study thus provides the first isotopic evidence for seasonal altitudinal mobility in the Valaisan Alps—from Upper to Lower Valais—from the Early Neolithic through to the Early Middle Ages, with a marked recurrence of this practice from the beginning of the Early Iron Age. This phenomenon may be linked to the intensification of transalpine exchange networks through alpine passes during the Iron Age (CURDY, NICOD 2019, 42-44; CURDY, NICOD 2020, 497-512). Summer alpine grazing (estivage) could have formed part of broader systems of mobility and exchange involving both people and animals, connecting alpine valleys with territories on either side of the Western Alps.

Woodlands and Land use: Forest Exploitation for Pastoral Practices

In addition to the recurrent pattern of seasonal vertical mobility highlighted in this study, the diversity of ecological environments exploited for pastoral activities can also be considered. The Atlantic ibex and the Early Neolithic goat from La Planta exhibit low intra-tooth δ^{13}C variation (< 1‰). This may reflect a limited annual amplitude in dietary δ^{13}C values and the absence of marked alternation between different plant resources across the seasonal cycle (TEJEDOR-RODRÍGUEZ *et al.* 2021). Although TORNERO *et al.* (2018) reported reduced variability in plant communities at mid- and high-altitude mountain settings in the Eastern Pyrenees, YANG *et al.* (2015) documented high δ^{13}C variation in high-elevation plants at the Furka Pass (Swiss Central Alps), in locations between 2,430 and 2,500 m asl. Given the current state of knowledge, low δ^{13}C variation remains difficult to interpret regarding landscape use and further research on plant δ^{13}C values along the Valais altitudinal gradient is needed to clarify these patterns.

However, available data reveal evidence of the use of forested environments in the diet of sheep from La Soie, Gamsen, and those trapped in the Giétroz Devant chasm. The consumption of forest-derived plant resources appears to have occurred during different periods of the year *(Fig. 7)*. In the Middle Neolithic, this practice — identified in two sheep from La Soie — took place during winter months and the interseasonal and even into early summer *(Fig. 7)* and is associated with local herding strategies, suggesting the availability of wooded environments in close proximity to the site. Archaeobotanical evidence from the Valais valley floor during this period confirms the presence of species such as dogwood *(Cornus* sp.*)*, alder *(Alnus* sp.*)*, hazel *(Corylus* sp.*)*, oak *(Quercus* sp.*)*, Scots pine *(Pinus sylvestris)*, and ash *(Fraxinus* sp.*)* at elevations between 500 and 1,000 meters (MARTIN *et al.* 2019). Complementary anthracological analyses from the Petit-Chasseur site in Sion indicate the exploitation of a territory primarily located in the collinean zone, with wood gathered both from thermophilous forests dominated by Scots pine and oak, and from alluvial forests characterised by white or black alder, ash, poplar, and willow (DUFRAISSE 2011, 269-278). Wood exploitation may thus have been concomitant with silvopastoral activities or the gathering of branches and leaves, a fodder rich in nutrients and minerals (GILLIS *et al.* 2025, 87-98). This practice, identified as early as the sixth millennium BCE in the Aude Basin (TORNERO *et al.* 2020) and widely known in the Neolithic Alps (THIEBAULT 2005, 95-108; MARTIN 2014), is evidenced for the first time through the direct study of zooarchaeological remains in the Valais in this paper.

During the Late Iron Age and Roman Periods, forest resources continued to play a detectable role in pastoral economies. Isotopic data from sheep molars (EVG 17 and Gamsen 2) indicate the contribution of forest plants to their diet notably during the spring interseason *(Fig. 7)*. Grazing in forested environments during the ascent to alpine pastures, in late spring or early summer, is a well-documented practice today, notably within the context of *remuage*—the traditional seasonal herding system—still observed in various mountain regions, including the Valais (MARIETAN 1940, 14-18). Taken together, these data highlight the role of forest ecosystems as a complementary resource within alpine pastoral systems over millennia, emphasizing both continuity and adaptation in human-environment interactions beyond the Neolithic.

Adapting Pastoral Systems: Interannual Variability and Diversity of Practices

A multi-annual approach, based on the combined analysis of incremental δ^{18}O and δ^{13}C sequences from the M_2 and M_3—corresponding respectively to the first and second years of the animal's life—reveals interannual shifts in herd management practices. The variation in δ^{18}O values between the first and second winters in the Early Neolithic goat from La Planta suggests a change in altitudinal zone, likely from lower to higher elevations, potentially indicating a modification in overwintering location *(Fig. 8, A)*. Similarly, one of the sheep recovered from the Giétroz Devant chasm shows no evidence of significant forest resource intake during its first year; however, such resources were incorporated into its diet during the interseasonal period of the second year *(Fig. 8, B)*. These variations likely reflect the need for pastoral systems to remain adaptive within environments characterised by strong climatic variability (KNOCKAERT *et al.* 2017, 60-74).

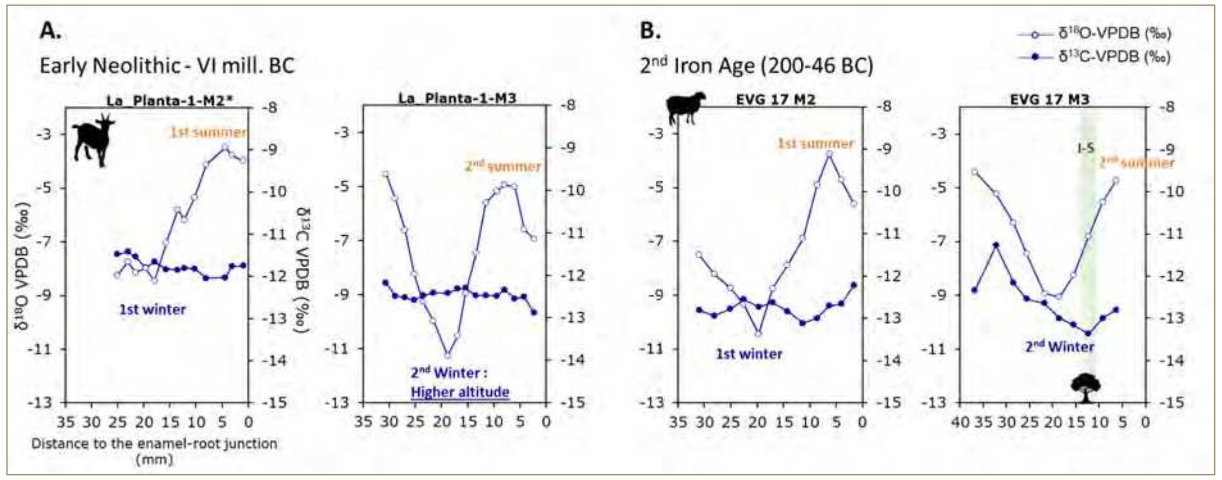

Fig. 8 - Incremental analyses of δ^{18}O and δ^{13}C from tooth enamel of an M_2–M_3 pair, A. Goat from La Planta (Early Neolithic); B. Sheep from the Late Iron Age at Giétroz.

The diversity of herding strategies is further reflected in the intra-site heterogeneity of oxygen and carbon isotope values observed between individuals, potentially indicating the cumulative influence of multiple overlapping processes. The exploitation of both exclusively herbaceous resources and a combination of herbaceous and forest resources within a single archaeological assemblage—as documented at La Soie, Gamsen, and in the sheep trapped in the Giétroz Devant chasm—suggests the implementation of flexible pastoral practices, embedded within complex and dynamic climatic, environmental, and territorial frameworks *(Fig. 5)*.

It is also important to emphasise that sheep from the Middle Neolithic (5th millennium BCE) at La Soie, as well as those from Early Iron Age and Roman contexts at Gamsen, exceed the MIGA-δ^{18}O threshold of 2.4‰—a value beyond which heterogeneity in mobility patterns and/or herd management strategies can be considered *(Tab. 3)*.

Possible Long-Distance Mobility and Non-Local Animals Origins within Herds

In addition to seasonal herding, intra herd variability in δ^{18}O may derive from the inclusion of non local animals. By plotting mean δ^{18}O values per individual in boxplots that also show reference sets from modern sheep raised in known locations (Valais and the Southern French Prealps; Fig. 2, Fig. 9), we observe that several archaeological individuals exhibit higher mean δ^{18}O values than the δ^{18}O range estimated for the Central Valais based on extrapolated data from modern sheep (KNOCKAERT *et al.* in prep.). Such deviations suggest either time spent at lower altitudes and/or closer proximity to the sea, or origins from other ecological zones. A chronological approach shows that the ibexes dated from the Atlantic Period trap at Giétroz Devant fall within the estimated range for the Central Valais δ^{18}O area. Subsequently, all Neolithic groups include specimens with higher mean δ^{18}O values. This trend becomes particularly pronounced during the Early Iron Age, when all individuals from Gamsen lie outside the range defined for the Central Valais. In contrast, during the Roman Period and the Early Middle Ages, most individuals again plot within the local δ^{18}O interval *(Fig. 9)*.

Several case scenarios are noteworthy: as previously mentioned, the goat from La Planta appears to have undergone a substantial shift in ecological zone between its first and second year of life, suggesting origin in a different ecological zone. During the Late Neolithic at La Soie, the goat (La Soie 15 M_3) and the sheep (La Soie 16 M_3), recovered from the same pit and likely strictly contemporaneous, do not seem to have occupied the same ecological zones in their second year of life; the goat likely residing at a lower altitude.

Finally, the sheep Gam 11 M_2 exhibits a particularly high mean δ^{18}O value, close to that of modern sheep raised in the French Prealps *(Fig. 4 and Fig. 9)*, which suggests an origin at a lower altitude and/or nearer the coast.

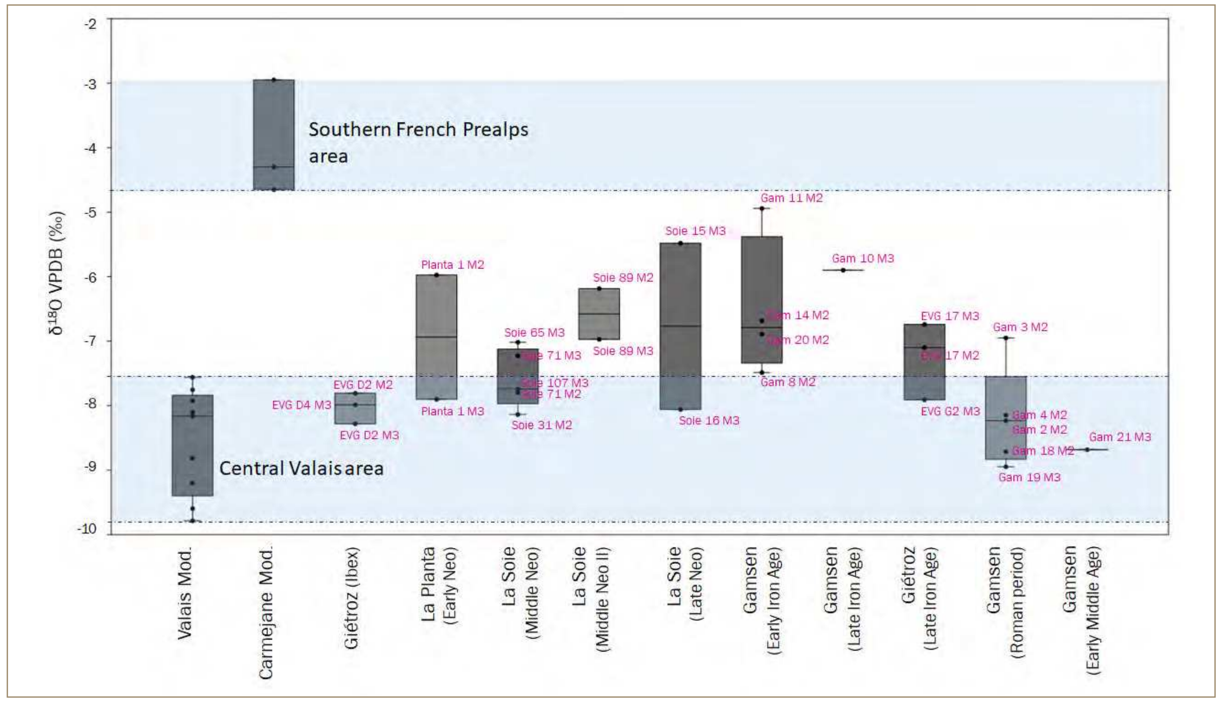

Fig. 9 - Boxplot of mean $\delta^{18}O$ values for each individual within the chronological spatial units of the study. The shaded areas delineate the estimated $\delta^{18}O$ range reconstructed from modern sheep enamel samples, reflecting indirectly current environmental and altitudinal conditions within the Central Valais region and the French Southern Alps. (Based on KNOCKAERT et al. in prep. and BLAISE, BALASSE 2011, 3085 3093).

The introduction of non local individuals into a herd is a well documented zootechnical practice aimed at maintaining genetic diversity within the livestock population (GROENEVELD *et al.* 2010, 6-31; RAMOROKA *et al.* 2025). The tendency observed for individuals spending time in different environments during the Early Iron Age may be linked to the intensification of cultural exchanges and migrations in the region during this period in particular with the expansion of the Golasecca culture across a broad territory including Swiss Ticino and the Po Plain in Italy, which may also have led to the movement of animals—representing living economic heritage.

Conclusion

This study provides the first comprehensive overview of livestock management strategies integrating resource use and herd mobility across a broad chronological span from the Early Neolithic to the Early Middle Ages in the Valais region. Through the unique case study of the Giétroz Devant chasm, it offers an empirical validation of a model for seasonal vertical mobility based on stable isotope analysis of archaeological caprine tooth enamel, establishing a valuable reference framework for future research.

The observed inverse or absent correlation between $\delta^{18}O$ and $\delta^{13}C$ values in individuals from Giétroz Devant closely corresponds to patterns documented in modern transhumant pastoral systems. Notably, this isotopic signature was also detected in specimens from the Early Neolithic site of La Planta, indicating that vertical mobility was practised as early as the 6th millennium BCE. The persistence of this strategy through the Middle and Late Neolithic, as well as into the Early Iron Age, underscores its fundamental role in Alpine pastoralism.

Additionally, high $\delta^{18}O$ values in some Early Iron Age individuals suggest the introduction of non-local animals, reflecting increased cultural exchange and mobility during this period. The study further highlights the importance of forested environments within pastoral strategies, with evidence for the incorporation of forest resources into sheep diets during winter and transitional seasons, demonstrating the resilience and ecological adaptability of these systems.

Together, these findings reveal the complexity and flexibility of prehistoric Alpine pastoralism, emphasising the significance of vertical mobility and interregional interactions in shaping human-environment dynamics over millennia. Ongoing sequential strontium isotope analyses will support a multi-isotopic and geospatial approach to refine our understanding of the networks and territories involved in these complex livestock management systems.

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Supplementary Materials

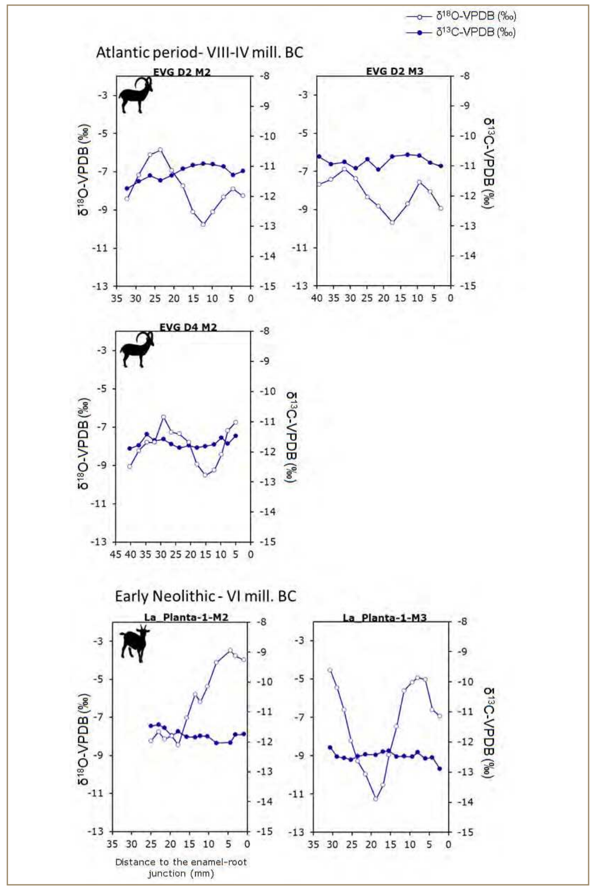
Supplementary Material 1

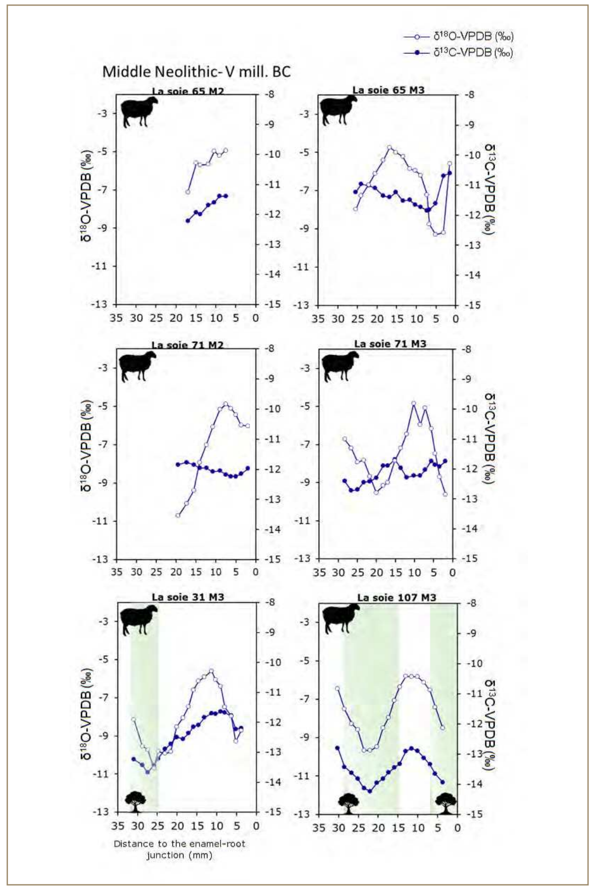
ZooArchaeology by Mass Spectrometry Approach

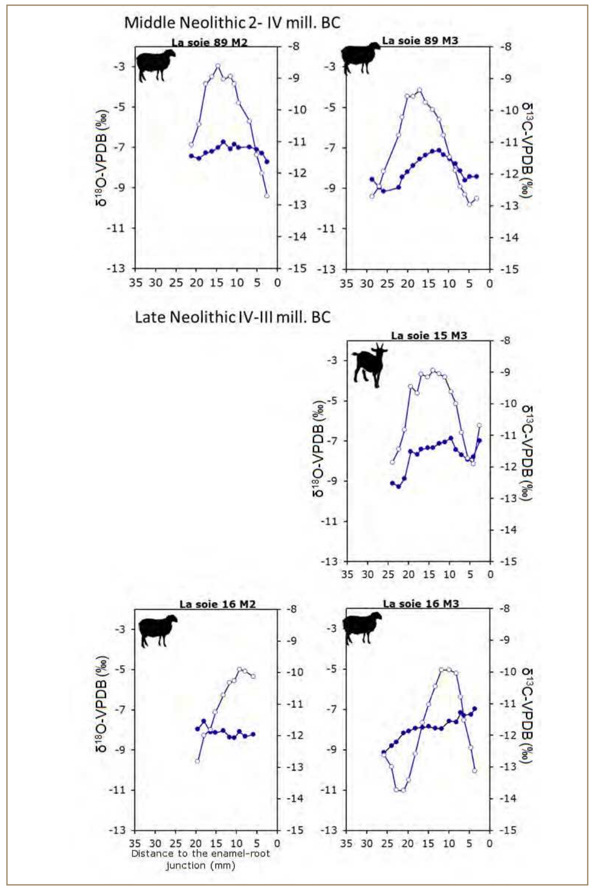
Approximately 10-30 mg of bone chips were demineralised in 250µl of 0.6M hydrochloric acid at 4˚C for a period ranging from 24 hours to one week depending on the mineralisation level of the sample. The remaining bone was rinsed three times in 50mM ammonium bicarbonate (NH_4HCo_3) buffer pH 8.0 (Ambic). Then insoluble collagen was gelatinized by heating at 65˚ C in 100µl of Ambic for 1 hour. Following gelatinization, the samples were centrifuged to precipitate insoluble contaminants and non-gelatinized protein and a 50µl aliquot of supernatant was treated with 1µl of 0.5 µg-¹ of trypsin solution and incubated at 37˚C for 18 hours. After centrifugation, 1µl of 5% trifluoroacetic acid (TFA) was used to stop trypsin digestion. Then target peptides were extracted and purified using 100 µL of Pierce C18 ZipTips with washing (0.1% TFA and UHQ water) and conditioning (0.1% TFA in 50:50 acetonitrile and UHQ water) solutions. 1µl of sample solution was spotted in triplicate onto a MALDI 384 target plate with 1µl of α-cyano-4-hydroxycinnamic acid (matrix solution) and allowed to dry. Each spot was analysed by reflectron mode MALDI-MS using a calibrated MALDI-TOF MS instrument to measure the mass to charge ratios (m/z) of the isolated peptides. MALDI analysis was carried out using MALDI-TOF MS (a Bruker Ultrafex III) at the University of York. Replicates were averaged using the open-source software mMass (www.mmass.org) and compared to a database of known m/z markers (BUCKLEY *et al.* 2010, 13-20)

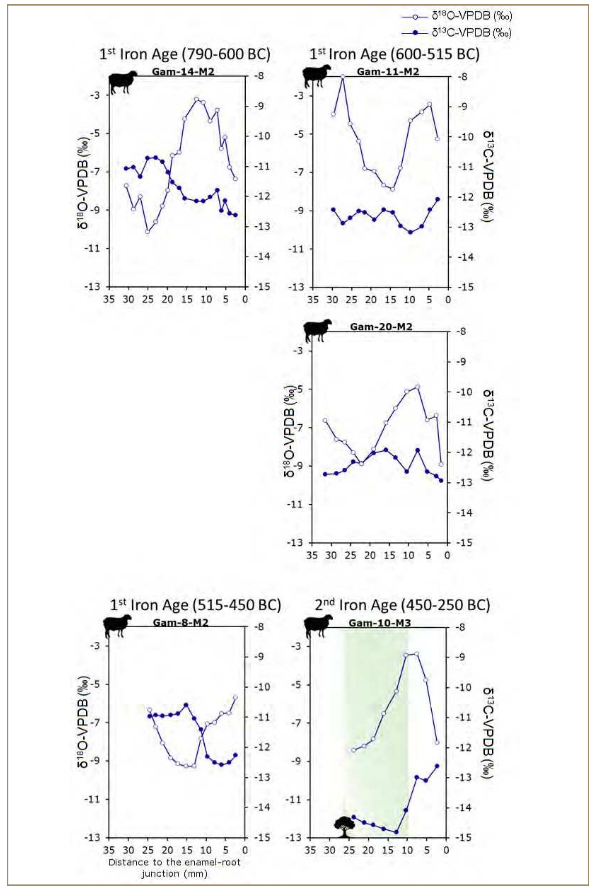
Supplementary Material 2

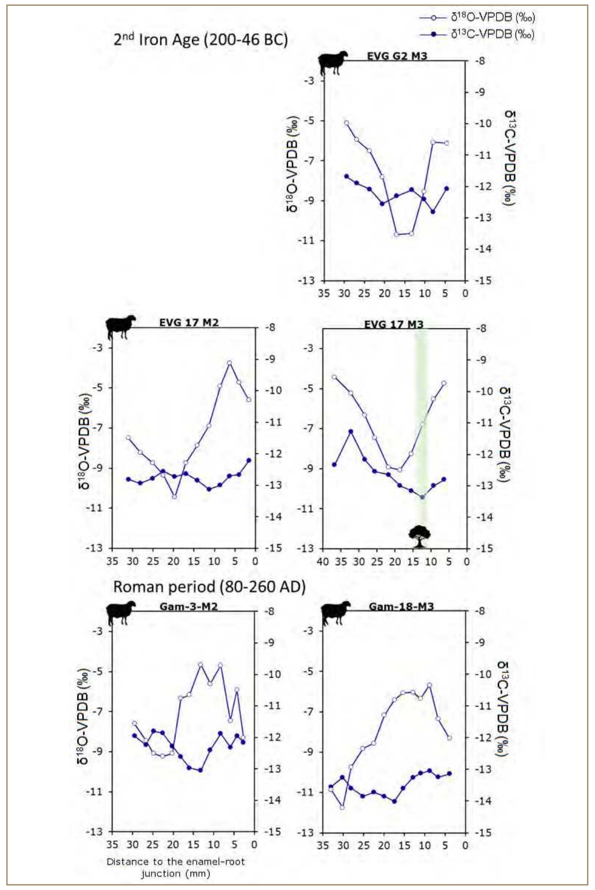
Results from the sequential $\delta^{18}O$ and $\delta^{13}C$ analyses of second (M_2) and third molars (M_3) of archaeological caprines from Giétroz Devant Chasm, La Planta, La Soie, and Gamsen. Each sample is spatially located within the tooth crown based on its distance from the enamel–root junction in millimeters.

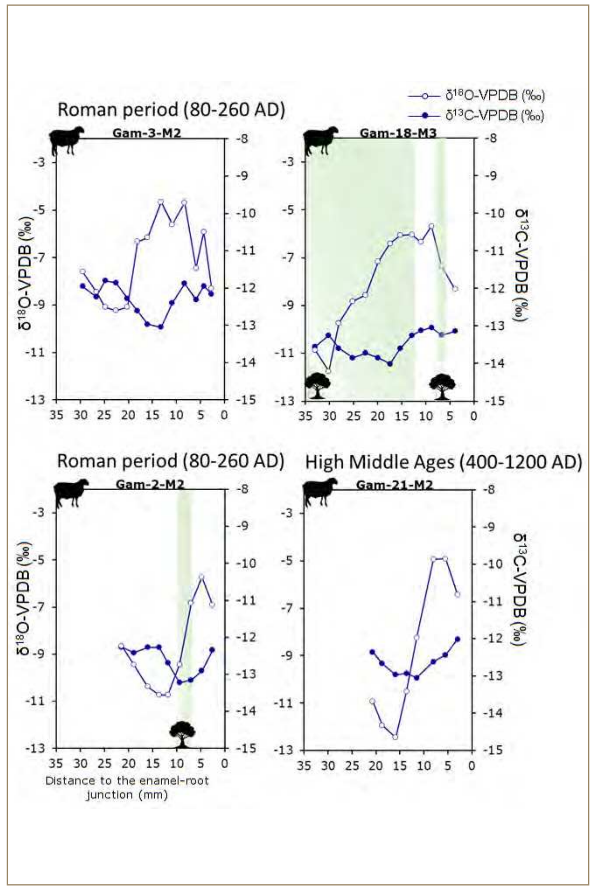












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