Journal of Archaeological Science 180 (2025) 106294

Contents lists available at ScienceDirect

Journal of Archaeological Science

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

"Celts" up the Alps. Patterns of territorial mobility and funerary variability in Switzerland during the Late Iron Age

Zita Laffranchi [a,b], Vanessa Haussener [b], Domingo C. Salazar García [c,d], Alice Paladin [e], Stefania Zingale [e], Sönke Szidat [f], Sandra Lösch [a], Albert Zink [e], Marco Milella [a,*,1]

[a] Department of Physical Anthropology, Institute of Forensic Medicine, University of Bern, Murtenstrasse 26, 3008, Bern, Switzerland
[b] Bernisches Historisches Museum, Helvetiaplatz 5, 3005, Bern, Switzerland
[c] Departament de Prehistòria, Arqueologia i Història Antiga, Universitat de València, Avda. Blasco Ibáñez, 28, 46010, València, Spain
[d] Department of Geological Sciences, University of Cape Town, Private Bag, 7701, Rondebosch, South Africa
[e] Institute for Mummy Studies, Eurac Research, Via A.-Volta 13/A, 39100, Bolzano, Italy
[f] Department of Chemistry, Biochemistry and Pharmaceutical Sciences & Oeschger Centre for Climate Change Research, University of Bern, Freiestrasse 3, 3012, Bern, Switzerland

ARTICLE INFO

Keywords:
La Tène culture
Residential changes
Sulfur
Strontium
Oxygen
Social complexity

ABSTRACT

The European Late Iron Age (ca. 5th-1st centuries BCE) is characterized by significant economic, social, and cultural transformations, including the development and intensification of cultural and economic networks. These features make the last centuries BCE relevant for the study of human territorial mobility and its demographic and social correlates. In this study, we investigate the frequency and nature of human mobility during the Late Iron Age in one of the central regions of the La Tène cultural sphere, the area that is now Switzerland. We further address the cultural factors that may have influenced the mobility patterns. Therefore, we analyze strontium ($^{87}Sr/^{86}Sr$), oxygen ($\delta^{18}O$) and sulfur ($\delta^{34}S$) isotopic ratios from dental enamel and bone collagen in a human skeletal dataset ($N^{87}Sr/^{86}Sr = 101$; $N\ \delta^{18}O = 90$; $N\ \delta^{34}S = 121$) representing various Swiss contexts dating to the last five centuries BCE. These isotopic data are contextualized using faunal and vegetation baselines and further explored for any demographic and funerary patterns. Results reveal spatial heterogeneity in the frequency of nonlocal individuals, suggesting that both long- and short-distance residential changes were influenced by regional political and economic differences across contexts. The absence of a correlation between geographic origin and sex suggests that specific residential rules may not have been prevalent in these communities. The lack of an association between isotopic variability and funerary treatment suggests that geographic origin held limited social significance compared to sex, socioeconomic status, and community membership. These findings enhance our understanding of the demographic and cultural processes in this geochronological region highlighting the complexities and challenges of estimating past mobility patterns and geographic origin using isotopic data.

1. Introduction

The European Late Iron Age (henceforth *LIA*, 5th -1st centuries BCE) is a period featuring significant economic, social, and cultural changes. In Central Europe, these include intensified metalwork production and craft specialization, the development of centralized trade networks, and the gradual shift to settlement conglomeration, in the form of open settlements and, later, hilltop fortified structures (*oppida*) (Webley, 2018). During the LIA, earlier hierarchical social systems gave way to relatively more fluid societies, a process reflected by funerary practices that seem to put new emphasis on community membership rather than power structures (Brun, 2018, Collis and Karl, 2018, Fichtl, 2018, Metzner-Nebelsick, 2019, but see Trémeaud, 2018: 102). Related to these processes is the view, influenced by classic authors like Polybius, Titus Livius, Dionysius of Halicarnassus, Pliny the Elder, and Plutarch, of "Celtic" societies as particularly inclined to long-distance residential changes. This idea has shaped traditional discussions of the "Celtic migrations" of the 4th century BCE (Schönfelder, 2024), and the emphasis

* Corresponding author.
E-mail address: marco.milella@unipi.it (M. Milella).
[1] Present address: Department of Biology, University of Pisa, Via Derna 1, 56126 Pisa (Italy).

https://doi.org/10.1016/j.jas.2025.106294
Received 10 October 2024; Received in revised form 5 May 2025; Accepted 11 June 2025
Available online 16 June 2025

posed on the involvement of these people in trade and mercenary activities (Hauschild et al., 2013; Vitali, 1996, 2011). About the factors leading to this pronounced mobility, classical authors list increased population pressure, need for additional fertile lands, and the disruptive effects of intertribal conflict (Hauschild, 2010; Tomaschitz, 2002). Pliny (Natural History 12.5), for example, recounts that Helicon the Helvetian returned from Rome with Mediterranean goods like figs, grapes, wine, and oil. His praise of the southern region's benefits allegedly prompted the Helvetians to migrate southward.

1.1. Isotopic studies on Late Iron Age mobility

A revision of simplistic notions, such as that of the "Mobile Celts," has been prompted by the growing contribution of isotopic studies, although these remain fragmentary for this time period (Clauzel et al., 2022; Knipper et al., 2014, 2018; Laffranchi et al., 2022; Oelze et al., 2012; Piccirilli et al., 2023; Scheeres et al., 2014; Sorrentino et al., 2018). The analysis of $^{87}Sr/^{86}Sr$, $\delta^{18}O$, and $\delta^{34}S$, is widely used in archaeology to reconstruct past mobility due to their relationships with local geology ($^{87}Sr/^{86}Sr$ and $\delta^{34}S$), climate and hydrological sources ($\delta^{18}O$) (see for more details Supplementary Methods S3). The $^{87}Sr/^{86}Sr$ ratio reflects the age and composition of local bedrock (Bentley, 2006), while $\delta^{18}O$ values are shaped by environmental factors such as geography, altitude, temperature, humidity, and distance from the coast (Lightfoot and O'Connell, 2016; Rozanski et al., 1993). Sulfur isotopic ratios ($\delta^{34}S$) are also influenced by local geology, soil composition, and proximity to marine environments (Nehlich, 2015) and, although less commonly used than strontium and oxygen isotopes, have also been applied to reconstruct past mobility (e.g., Bataille et al., 2021; Laffranchi et al., 2024a; Milella et al., 2022; Paladin et al., 2020). Due to physiological and metabolic differences, the analysis of dental enamel and bone collagen provides different temporal insights into mobility. Enamel mineralizes during specific developmental periods and is unaffected by later metabolic processes (Montgomery, 2010). Consequently, its isotopic ratios reflect the environment where an individual spent their mid-to-late childhood (Humphrey et al., 2008). In contrast, bone collagen, depending on the specific bone analyzed, its turnover rate, and the element of interest, reflects isotopic signatures from a broader timeframe, typically spanning 5–20 years or more prior to death (Ebert et al., 2021; Nehlich, 2015; Richards, 2023).

The application of isotopic analyses to LIA archaeological contexts suggests a complex and regionally diverse scenario featuring variable associations between mobility, demographic, economic, and social variables (Clauzel et al., 2022; Knipper et al., 2014, 2018; Laffranchi et al., 2022; Oelze et al., 2012; Piccirilli et al., 2023; Scheeres et al., 2014; Sorrentino et al., 2018). This variability appears to be particularly elevated for the Swiss territory.

1.2. The Late Iron Age in the Swiss territory: archaeological and isotopic background

The area that is now Switzerland is of key importance for the reconstruction of "Celtic mobility." Positioned just across the Alpine range, the Swiss territory serves as a hinge between the Mediterranean world and Central Europe. The LIA is here archaeologically well represented (see also Cooper et al., 2023), with contexts including settlements like Basel-Gasfabrik, Engehalbinsel, and Mont Vully (Brönnimann et al., 2022; Ebnöther and Wyss, 2004; Kaenel et al., 2004; Martin-Kilcher, 2005), necropolises like Münsingen-Rain, Andelfingen, Solduno, Trun Darvella (Hodson, 1968; Stöckli, 1975; Tanner, 1980; Viollier, 1912) and cultic centers. Among the latter one can remember the eponymous site of La Tène, a landmark for the chronology of the European Protohistory and a pivotal find for the development of Celtic archaeology (e.g. Kaenel and Reginelli Servais, 2011; Kaeser, 2013), Tiefenau in Bern (Müller, 1990) and Le Mormont in Canton Vaud (Brunetti et al., 2019). Like elsewhere in Central Europe in this period, the transition to simpler burial forms and more homogenous grave good types suggests also for the Swiss area a progressive shift toward less differentiated societies (Curdy and Kaenel, 2006; Hofstetter, 2021 – see also Supplementary Introduction S1). At the same time, the frequent recovery among grave goods of exotic items and/or inscriptions puts this region in the midst of complex cultural, social, and economic networks (Danielisová et al., 2021; Kruta, 1979; Vitali and Kaenel, 2000).

Previous studies on territorial mobility in LIA Switzerland vary in scope and methodology, focusing on single sites (e.g., Knipper et al., 2018; Moghaddam et al., 2016), regional analyses (Moghaddam et al., 2018), and applying different isotopic analyses (e.g., strontium, oxygen or sulfur). Results are heterogeneous and suggest a regional variability in mobility patterns. For instance, Knipper et al. (2018) identify a dynamic, patrilocal system at Basel-Gasfabrik, contrasting with findings from Münsingen-Rain (Moghaddam et al., 2016; Scheeres, 2014), where no traces of such residential rule were detected. These inconsistencies underscore the need for new data to clarify mobility processes in the Swiss area, providing a more comprehensive understanding of socio-cultural dynamics during the LIA in this region.

Archaeological, anthropological, and paleodietary data indicates an association between sex, age, socioeconomic status and funerary variability in these communities (Knipper et al., 2014; 2018; Müller, 1998). Previous analyses of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopic ratios reveal significant variability in diet, possibly shaped by regional, social, and ecological factors. Dietary patterns differ across regions, reflecting diverse exploitation of C_3 and C_4 plants, as well as terrestrial and freshwater food sources (Moghaddam et al., 2018). While some contexts, like Münsingen-Rain, show dietary differences linked to sex and social status (Laffranchi et al., 2021a; Moghaddam et al., 2016), this is not consistent in other analyzed sites (Cooper et al., 2023; Moghaddam et al., 2018).

The possible social significance of geographic origin remains debated. Previous comparisons of isotopic and funerary data (Knipper et al., 2018; Scheeres, 2018; Moghaddam et al., 2016) have yielded negative or inconclusive results, failing to reveal a pattern between nonlocal origin and funerary treatment. Applying a multivariate statistical approach, based on the quantification of grave goods in each burial, may reveal nuanced patterns not identified in previous studies.

In this study we explore the demographic and sociocultural factors linked to residential mobility in LIA Switzerland, expanding the available isotopic dataset for this region by analyzing strontium ($^{87}Sr/^{86}Sr$) and oxygen ($\delta^{18}O$) from dental enamel and sulfur ($\delta^{34}S$) in bone collagen, and compare these isotopic data with sex and funerary treatment (type and number of grave goods) across different contexts. Based on these data, we address the following questions.

1) Which kind (short- or long-distance) and frequency of territorial mobility characterize different contexts from the Swiss Plateau and Alpine area, and what general patterns emerge regarding the geographic origins of nonlocals?
2) Are there sex-specific patterns in territorial mobility among these human groups?
3) Is there a correlation between an individual's nonlocal geographic origin and their funerary treatment, specifically regarding grave good variability?

2. Material and methods

2.1. Anthropological sample

Table S1 reports the regional distribution, chronology, sample size and bibliographic references for each context. These represent different areas of the Swiss territory and overall date to La Tène A-D (5th-1st c. BCE). Further information about the main archaeological contexts can be found in Supplementary Material S2. For some individuals, estimates of sex and age at death were available from previous anthropological studies (Cooper et al., 2023; Laffranchi et al., 2024a; Moghaddam et al., 2016, 2018). We double-checked previous estimates and, if needed, assessed sex and age at death for all the individuals in the study applying standard anthropological methods, as listed in Buikstra and Ubelaker (1994). We then grouped the obtained age ranges in seven classes: Fetal (F): < birth; Infants (I): birth to 3 years; Children (C): 3–12 years; Adolescents (Ao): 12–20 years; Young Adults (YA): 20–35 years; Middle Adults (MA): 35–50 years; Old Adults (OA): 50+ years. We assigned the individuals for whom preservation and/or fragmentation hampered a more precise age-at-death estimate to two broad groups: adults (Ad: ≥20 years) and nonadults (<20 years).

2.2. Mobility and dating

Before sampling, all skeletal and dental elements were first studied morphologically, photographed, and scanned by means of a high-resolution 3D scanner (Artec Spider). To minimize damage to remains, if an individual was chosen for later paleogenetic analysis (Zingale et al., 2023), the same tooth/bone fragment was first sampled for aDNA and, later for the isotopic study, to limit potential contaminations. All collected photographs and 3D models were provided to the responsible archaeological institutions and museums, together with the sampled remains and reports detailing the obtained isotopic results, as recommended by Stantis and colleagues (2024). A detailed description of all the analytical protocols applied in this study is provided in Supplementary Methods S3; we summarize here the main analytical steps.

For $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ we sampled a permanent second molar or premolar or, in their absence, a third molar of 91 and 80 individuals, respectively. We added to our datasets 10 previously published individuals from Cornaux/Les Sauges (Laffranchi et al., 2024a). We chose to sample these specific teeth as our interest was to focus on a period in the individual's life corresponding to late childhood and adolescence/early phase of adulthood (approximately up to 9 years old for M2 and up to around 16 years old for M3) (Hillson, 1996; Montgomery, 2010). For the $^{87}Sr/^{86}Sr$ baseline we processed 22 faunal samples (7 *Sus domesticus*, 6 *Caprinae*, 7 *Bos domesticus*, 2 *Equus caballus),* 16 modern plants (5 from Canton Bern, 6 from Baselland, and 5 from Canton Ticino) and 4 terrestrial snail shells (Canton Bern). We added two water samples to the ones we previously published for the river Thielle and Lake Neuchâtel (Laffranchi et al., 2024): one from the river Aare (city of Bern, sampling: November 2022), and one from the river Verzasca (Ticino: May 2022).

For the specific case of Münsingen-Rain, we added to our isotopic dataset also the previous results of $^{87}Sr/^{86}Sr$ from 34 humans and five *Sus domesticus* available in Scheeres (2014) and Hauschild et al. (2013). The final human datasets for strontium and oxygen therefore include 135 and 90 individuals, respectively. We processed the enamel samples, modern plants and terrestrial snail shells samples in the ANTARQBIO lab of the Universitat de València (Valencian Community, Spain). The mass spectrometry analyses were then conducted in the Department of Geological Sciences of the University of Cape Town (South Africa) for strontium and in the Laboratory of stable isotope analysis (LAIE) of the Institute of Environmental Science and Technology (ICTA-UAB) of the Universitat Autònoma de Barcelona (Catalonia, Spain) for oxygen. For enamel $^{87}Sr/^{86}Sr$ analyses we followed the protocols described in Pin et al. (1994), while for $\delta^{18}O$ analyses we applied the methodology proposed by Lee-Thorp and van der Merwe (1987) and modified by Koch et al. (1997), Balasse et al. (2002), and Tornero et al. (2013). The analyses of $\delta^{18}O$ (and δD) of the local water samples were done in the Stable isotopes biogeochemistry laboratory of the Andalusian Earth Sciences Institute of Granada (Spain) (see Supplementary Methods S3.1 and S3.2).

We performed stable isotope analyses of sulfur ($\delta^{34}S$) on 96 individuals, sampling long bones (e.g., femur) when available and cranial bone fragments for individuals previously sampled for paleogenomic analysis or when postcranial elements were absent. This dataset includes 19 individuals who were previously excluded from the study by Moghaddam et al. (2018) due to not meeting the quality criteria for isotopic analysis. For these individuals, we repeated collagen extraction and analysis using a new bone sample. We added to this dataset data from 25 individuals from Cornaux/Les Sauges and La Tène (Laffranchi et al., 2024a). These new results expand the isotopic dataset for Late Iron Age Switzerland originally published by Moghaddam et al. (2018). In addition to $\delta^{34}S$, our bone collagen analysis also yielded stable isotope ratios of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). However, given that this study focuses on territorial mobility, and that paleodietary data and their social correlates for Late Iron Age Switzerland have already been presented and discussed by Moghaddam et al. (2018) and Cooper et al. (2023), we restrict our analysis and interpretation to $\delta^{34}S$. To better contextualize the observed human sulfur isotopic ratio variability, whenever possible, we sampled from each analyzed region and context faunal remains, for a total of 41 samples (13 *Bos taurus*, 10 *Sus domesticus*, 7 *Caprinae*, 4 *Equus caballus*, 1 *Anser anser*, 1 *Lutra lutra*, 5 *Esox lucius*). For both strontium and sulfur, we complemented our faunal datasets with published data for different chronologies in the Swiss territory (Andreetta, 2016; Laffranchi et al., 2024a; Moghaddam et al., 2018; Reitmaier et al., 2018; Rosselet-Christ et al., 2024; Scheeres, 2014; Varalli et al., 2021) (see Table 1 for details).

The collagen extraction for stable isotope analyses was performed in the Department of Physical Anthropology of the University of Bern following an acid–base–acid extraction method modified by Ambrose (1993, 1990), DeNiro (1985), and Longin (1971). The isotope ratios of carbon ($^{13}C/^{12}C$), nitrogen ($^{15}N/^{14}N$), and sulfur ($^{34}S/^{32}S$) were measured by isotope ratio mass spectrometry at Isolab GmbH, Schweitenkirchen, Germany (see Supplementary Methods S3.3 for analytical details and applied quality criteria).

The typological variability of La Tène grave goods is extremely well studied and chronologically reliable (see Supplementary Introduction S1). Since most of the analyzed burials were provided with grave goods, we therefore limited a radiocarbon analysis to skeletons from non-funerary contexts, or those provided with old and vague documentation. Fifteen samples for ^{14}C analysis come from the "catastrophic" assemblage of Cornaux/les Sauges, and we included them in a recent work on this context (Laffranchi et al., 2024a). We selected 8 additional samples from burials whose chronology was ambiguous due to absence or vague description of included grave goods. The radiocarbon analyses were carried out at the LARA laboratory at the University of Bern following Szidat et al. (2017). Radiocarbon ages were translated into calendar ages with OxCal 4.4.4 (Bronk Ramsey, 2009) using the IntCal20 calibration curve (Reimer et al., 2020) (see Supplementary Methods S3.4 for details).

2.3. Funerary analysis

Following our previous works (Alterauge et al., 2020; Laffranchi et al., 2019, 2021b; Milella et al., 2015), the comparison of isotopic and funerary data was preceded by the coding of each burial according to 41 variables representing the presence and number of different types of grave good items (see Table S2). We selected these variables following the screening of all published and archival information for each burial from each context. Depending on the type of available information, and type of item, we treated each variable as either binary (presence/absence, e.g., beads) or count data (number of items, e.g., ceramic vessels). After this preliminary step, we focused our analysis on Bern Engehalbinsel and Münsingen-Rain, the two contexts with large enough sample size and detailed archaeological documentation. Following Sparacello (2013) and Sparacello et al. (2017), we calculated for each burial a Status index.

(1) we assigned to grave good items a coefficient of status:

$$Cs(k) = \Sigma(h)[N(hk) / N(k)]$$

Table 1
Swiss Alps and Plateau: strontium and sulfur ranges of humans, faunal[a] and vegetation datasets. N: sample size; SD: standard deviation: Min, Max: minimum and maximum values. Lwr (Lower) and Upr (Upper) indicate the local isotopic range limits, calculated as Mean ± 2SD for environmental data and as the estimated 95 % density region for human data.

		$^{87}Sr/^{86}Sr$							$\delta^{34}S$‰ (VCDT)						
Region	Type of sample	N	Mean	SD	Min	Max	Lwr	Upr	N	Mean	SD	Min	Max	Lwr	Upr
Swiss Plateau	Human	133	0.70907	0.00113	0.70814	0.71795	0.70794	0.71017	233	3.4	2.8	−7.1	10.2	−1.9	8.0
Swiss Plateau	*Sus domesticus*	10	0.70883	0.00051	0.70836	0.70962	0.70781	0.70984	8	2.8	4.1	−2.4	8.3	−5.4	11.1
Swiss Plateau	*Bos taurus*	0	–	–	–	–	–	–	12	2.1	2.7	−3.8	5.8	−3.3	7.5
Swiss Plateau	*Esox lucius*	0	–	–	–	–	–	–	2	2.5	2.3	0.9	4.2	−2.0	7.1
Swiss Plateau	*Anser anser*	0	–	–	–	–	–	–	1	2.9	–	2.9	2.9	–	–
Swiss Plateau	*Equus caballus*	0	–	–	–	–	–	–	2	0.7	0.1	0.6	0.7	0.4	0.9
Swiss Plateau	*Lutra lutra*	0	–	–	–	–	–	–	1	2.4	–	2.4	2.4	–	–
Swiss Plateau	Plant	5	0.70889	0.00073	0.70823	0.70974	0.70742	0.71036	0	–	–	–	–	–	–
Swiss Plateau	*Caprinae*	5	0.70912	0.00043	0.70875	0.70980	0.70826	0.70998	8	2.7	3.8	−2.3	7.7	−4.9	10.2
Swiss Plateau	Land snail	4	0.70826	0.00006	0.70819	0.70832	0.70815	0.70838	0	–	–	–	–	–	–
Alps	Human	5	0.71252	0.00080	0.71123	0.71337	0.71233	0.71340	64	3.6	2.2	−2.0	7.7	−0.1	7.9
Alps	*Bos taurus*	15	0.70839	0.00043	0.70796	0.70977	0.70752	0.70926	10	5.8	3.4	−1.1	11.0	−1.1	12.6
Alps	*Gallus gallus domesticus*	0	–	–	–	–	–	–	2	7.2	0.9	6.6	7.8	5.4	9.0
Alps	*Cervus elaphus*	1	0.70952	–	0.70952	0.70952	–	–	3	5.5	2.6	3.1	8.3	0.3	10.8
Alps	*Lepus europaeus*	0	–	–	–	–	–	–	1	9.7		9.7	9.7	9.7	9.7
Alps	*Sus domesticus*	0	–	–	–	–	–	–	5	6.8	2.4	3.1	9.7	1.9	11.6
Alps	Plant	5	0.70925	0.00019	0.70908	0.70954	0.70888	0.70963	0	–	–	–	–	–	–
Alps	*Caprinae*	3	0.70899	0.00062	0.70858	0.70971	0.70774	0.71024	6	5.0	3.7	−0.3	9.1	−2.4	12.5

[a] Sulfur human averages include data published by Moghaddam et al. (2016, 2018). Faunal averages include published data from Varalli et al. (2021, one *B. taurus*, one *S. domesticus*, one *Caprinae* from Vaud), Andreetta (2016, three *S. domesticus*, three *Caprinae*, two *Gallus gallus domesticus*, two *Cervus elaphus*, one *Lepus europaeus* from Ticino), and Rosselet-Christ et al. (2024, two *S. domesticus*, two *Caprinae*, one *C. elaphus* sample from Valais. Strontium human averages include published data from Hauschild et al. (2013) and Scheeres (2014). Faunal averages include published data from Scheeres (2014, five *S. domesticus* from Canton Bern), Varalli et al. (2021, two *B. taurus* from Vaud), Reitmaier et al. (2018, 14 *B. taurus* from Grisons), and Rosselet-Christ et al. (2024, one *B. taurus*, one *Cervus elaphus*, three *Caprinae* from Valais).

Where N(k) is the number of burials which includes the specific item k, and N(hk) the total number of objects in the hth burial that contains the item k.

(2) we then obtained the status index of a burial [SI(h)] by summing the products of the status coefficients of the items included in the burial and their respective quantities (Sparacello, 2013; Sparacello et al., 2017).

$$SI(h) = \Sigma(k)\ [Nk \times Cs(k)]$$

In order to further evaluate the heterogeneity of the grave goods in each burial, we also calculated a Diversity Index (DI), which is the total number of different types of included grave goods divided by the total number of objects in the burial.

To account for potential biases introduced by chronology, age at death (i.e., nonadults vs adult individuals), and sex in the assessment of burial status, we employed a residual-based standardization approach. First, we coded each individual according to their biological sex and burial chronology, the latter expressed by the classic La Tène phases: A, B, C, and D. We regressed SI and, separately, RI of all available adults on burial chronology, and individual sex. The residuals from these models represent the variation in each index not explained by either chronology or sex. We applied this method rather than separately calculating indices by sex and chronological phases in order not to work on too small sample sizes.

2.4. Data analysis and statistical protocols

Our dataset includes a range of contexts, from isolated finds to large parts of necropolises, with some regions (e.g., Canton of Bern) having more consistent sample sizes than others (e.g., surroundings of Luzern). To incorporate all available data while maintaining a contextual focus, we applied a hierarchically structured research design. First, we grouped samples into two main areas: the Swiss Plateau and the Alps, following Moghaddam et al. (2018). This broad subdivision, while general, allows the inclusion of smaller contexts that would be excluded from finer-scale analyses. The distinction is mainly based on geological differences between these areas. The Swiss Plateau corresponds to the Molasse Basin, formed between the Oligocene and Miocene epochs, whereas the Alps consist of crystalline rocks (Reynard, 2021) (Fig. 1). In the second step, we refined our analysis to smaller geographic regions, approximately 40 km^2 in size, overlapping with modern Swiss cantons. Finally, we focused on two specific burial sites (Münsingen-Rain and Bern Engehalbinsel) for a detailed comparison of isotopic variability and funerary features.

The geological complexity of the Swiss territory, especially of the Molasse Basin, makes the detection of strontium and sulfur isotopic outliers particularly challenging. The Molasse comprises sedimentary rocks of diverse origins and age, leading to a highly variable isotopic signal. Considering this challenge, we decided to screen for the presence of potential nonlocals applying a mixed approach based on the screening of both environmental and human isotopic variability. Firstly, we used as proxy of the local range the mean ± 2 standard deviations of the isotopic values of pigs (for strontium and sulfur), snails and plants (for strontium), including previously published data. Pigs were screened to

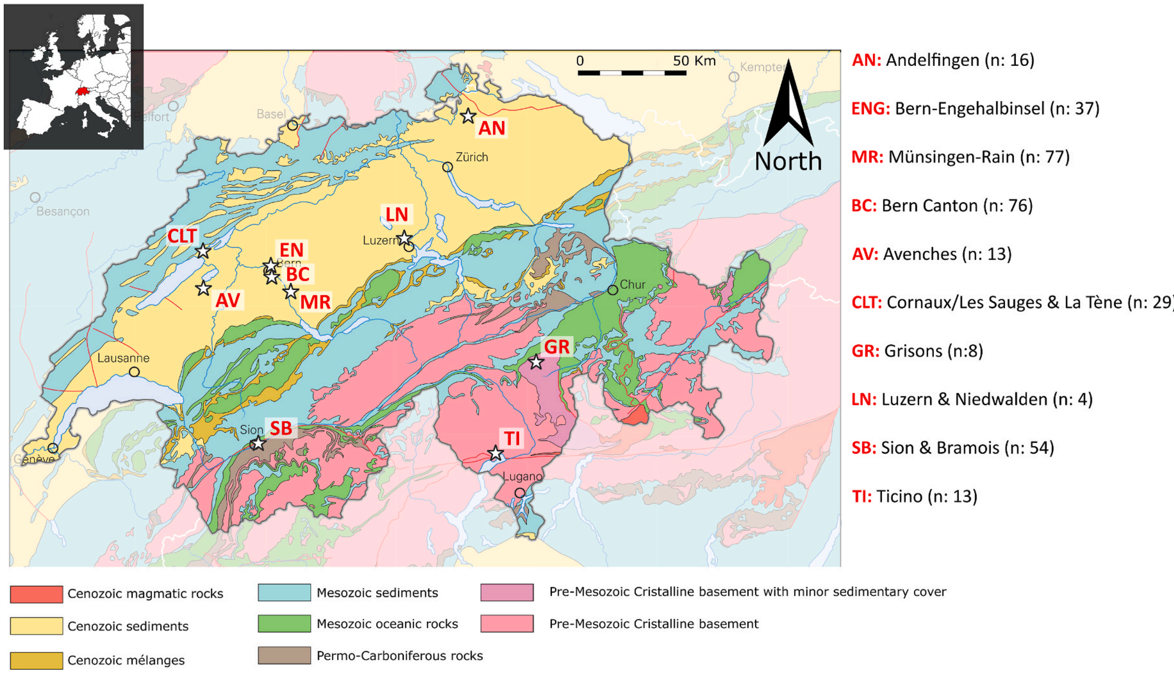

Fig. 1. Simplified geological map of Switzerland showing the distribution and sample size of the human dataset, adapted from Gouffon (2024).

exclude those with values outside the interquartile range (IQR) to address possible cases of imported animals. Out of completeness we also considered the isotopic variability of other taxa (e.g. *Caprinae*, bovids). However, given their larger foraging range, these animal isotopic values were used as broad reference points rather than strict local baselines. To approximate the local $\delta^{18}O$ isotopic signal we added to the results of the water samples collected in this study (see above) estimates of local rainfall and groundwater isotopic composition. The former is based on the range of monthly averages obtained using the Online Isotopes in Precipitation Calculator (OIPC: https://wateriso.utah.edu/waterisotopes/pages/data_access/oipc.html). For the primary analysis of the Plateau versus the Alps, we tailored estimates to the specific sample locations. For the Plateau, we combined OIPC outputs for Bern, Münsingen, Cornaux, and Avenches, while for the Alps, we used the estimate for Locarno. Groundwater oxygen isotope values, used exclusively for the second-level analysis, include the water samples collected in this study and multi-year (2010–2018) sampling range for catchments of the Sense River (Bern) and Gürbe River (Münsingen-Rain) (Staudinger et al., 2020). In order to compare our enamel carbonate values ($\delta^{18}O_C$) with the precipitation and groundwater isotopic ranges, we first converted $\delta^{18}O_C$ into the VSMOW scale using the equation of Coplen (1988), and then to drinking water ($\delta^{18}O_{DW}$) using the formula of Chenery et al. (2012) based on equation (6) of Daux et al. (2008).

We complemented these environmental data with an analysis of the central tendency of human isotopic values. This approach assumes that the majority of individuals in a given community are local, a reasonable assumption for the time period under investigation. Individuals whose isotopic values fall outside their group's central tendency may therefore be nonlocals. A similar approach has been applied, with variations, in other studies (e.g., Burton and Price, 2013; Danielisová et al., 2025; Velte et al., 2023; Wright, 2005) and offers the advantage of potentially reducing errors and uncertainties associated with environmental proxies, thereby improving the robustness of nonlocal identification in geologically heterogeneous landscapes.

To estimate the central tendency of each isotopic system, we applied a Gaussian kernel density estimation using the hdr function in the R package hdrcde (Hyndman et al., 2021), selecting the bandwidth based on Sheather and Jones (1991) and retaining the 95 % highest density region (HDR) as a probabilistic estimate of the most likely range of local human values.

For a subset of outliers selected based on their archaeological interest, we performed a dual strontium–oxygen probabilistic geographic assignments following the method and R scripts of Bataille et al. (2021) and using the assignR package (Ma et al., 2020). The analysis employed the strontium isoscape of Bataille et al. (2020) and the global $\delta^{18}O$ precipitation isoscape from Bowen and Revenaugh (2003) and Bowen et al. (2005), retrieved via assignR (function *getIsoscapes*). To facilitate visual comparison between individuals, each assignment surface (the product of the oxygen and strontium likelihood rasters) was normalized by its maximum cell value, resulting in a relative likelihood surface scaled between 0 and 1.

Posterior probability surfaces were then obtained by normalizing the same raster by the sum of all cell values (i.e., ensuring the total raster summed to 1), and the most probable regions comprising 33.3 % of the total posterior probability were mapped using the qtlRaster function in assignR (with thresholdType = "prob").

Since our enamel and collagen samples represent different life stages of an individual, we did not perform a triple (strontium-oxygen-sulfur) geographic assignment.

Differences in nonlocal frequencies between males and females were tested using Fisher's

exact test, with Bonferroni correction when needed. We explored the possible association between isotopic and funerary variability by first computing for each context an Euclidean distance matrix based on the Status Index, Diversity Index, and each isotopic variable, and then running separate Mantel tests between these different matrices. This approach allowed us to evaluate whether individuals who were more similar in isotopic composition—potentially reflecting comparable mobility patterns—also exhibited greater similarities in funerary treatment. By testing these associations quantitatively, we aimed to determine whether funerary differentiation may have been influenced by factors related to geographic origin.

We performed all statistical analyses in R version 4.3.2 (R Core Team, 2023). and JMP®, Version 17 (SAS Institute Inc., Cary, NC, 1989–2023). Graphs were produced with either R or JMP and further edited with Inkscape (1.0.2–2).

3. Results

Tables S3 and S4 present the individual values for $^{87}Sr/^{86}Sr$ and $\delta^{18}O$. Table S5 presents the results for the collagen samples ($\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$) respectively. The majority of bone samples (130 out of 160: 81.2 %) met the quality criteria for collagen preservation. We excluded 18 samples that did not meet the quality criteria for sulfur, and additional 12 because they did not yield any collagen.

With the exception of two samples from Castaneda and one from Cornaux/Les Sauges that did not return results, all the other individuals sampled for radiocarbon analysis provided dates consistent with the LIA (5th-1st c BCE). The oldest date corresponds to the individual from burial 19 (TD-19/BE-17809.1.1) of Trun Darvella (472-232 cal. BCE) while the most recent one is the nonadult of burial 17 (ERB-17/BE-22522.1.2) from Engehalbinsel Reichenbachstrasse 87 (169-48 cal. BCE) (Table S6).

3.1. Regional patterns: Plateau vs Alps

The mean ±2SD strontium isotope ratio value range in the Plateau is 0.70781–0.70984 for pigs, and 0.70742–0.71036 for plants; in the Alps it is 0.70888–0.70963 for plants (Table 1). The Plateau pig ranges do not include two samples (Avenches Faubourg F-16323S and Tiefenau TIE-1S) that were excluded due to their highly radiogenic strontium signatures, strongly suggestive of a nonlocal origin of these animals.

For oxygen isotope ratio values (Table 2), the minimum-maximum range of the combined OIPC monthly estimates for Avenches, Münsingen-Rain, Bern, and Cornaux is between −13.6 ‰ and −4.0 ‰ VSMOW. The minimum-maximum OIPC monthly estimate for Locarno is between −12.9 ‰ and 3.6 ‰.

Concerning sulfur, the mean ±2SD pig range for the Plateau (−5.1 to 11.1 ‰ VCDT) is consistently wider than the one for the Alps (1.9–11.6 ‰) (Table 1).

Human strontium isotope ratio values range between 0.70814 and 0.71795 (N = 133; mean ± 1 standard deviation: 0.70907 ± 0.00113) in the Swiss Plateau, and between 0.71123 and 0.71337 (N = 5; 0.71252 ± 0.00080) in the Alps. Based on kernel density estimation, the 95 % highest density region (HDR), representing the most probable range of human values, spans 0.70794–0.71017 in the Plateau and 0.71233–0.71340 in the Alps (Table 1).

In the Plateau, three females, two males, and one nonadult (all sexed individuals referenced herein are adults) fall outside the local strontium range (Fig. 2a). These six nonlocals are in three sites: Münsingen-Rain, Bern Engehalbinsel and Cornaux/Les Sauges.

All five human samples from the Alps show strontium values outside the range for plants as well as the ranges based on published faunal datasets (Fig. 2d). Rather than considering all individuals nonlocals, this result may rather stem from a combination of the extremely small sample size and geological differences on a local scale. Therefore, a more reliable insight on mobility in this case comes from the distribution of human values. Four individuals (necropolises of Giubiasco Palasio and Locarno Solduno) fall in a relatively narrow isotopic range, between 0.71248 and 0.71337. A markedly lower value (0.71126) characterizes a male from Tenero Contra, suggesting a nonlocal geographic origin.

Human $\delta^{18}O_{DW}$ in the Swiss Plateau range between −16.0 ‰ and −7.6 ‰ VSMOW (N = 85; average ± 1 standard deviation: 11.0 ± 1.5 ‰), with the estimated 95 % range of human values between −14.0 ‰ and −8.5 ‰ (Fig. 2b–Table 2). Two adult males from Cornaux/Les Sauges (Skeleton 9 and Skeleton 23) show isotopic values lower than both the estimated precipitation range as well as the human 95 % density region. In the Alps only two individuals (both adult females from Locarno Solduno and Giubiasco Palasio) returned results for this isotopic system (respectively −7.7 ‰ and −9.6 ‰ VSMOW). Given this sample size, no central tendency was calculated and therefore plotted in Fig. 2. Both individuals, in any case, fall inside the estimated local precipitation range (Table 2).

When considering sulfur isotope ratios, human values in the Swiss Plateau range between −7.1 ‰ and 10.2 ‰ VCDT, and between −2.0 ‰ and 7.7 ‰ in the Alps. Based on kernel density estimation, the 95 % highest density region (HDR), representing the most probable range of values, spans −1.8 ‰ to 8.2 ‰ VCDT in the Plateau and −0.2 ‰ to 7.8 ‰ in the Alps (Table 1). In total, outliers for sulfur are four, one in the Plateau (an adult from Avenches of indeterminate sex), and three in the Alps (one male, two adults of unknown sex from Sion) (Fig. 2c–e). All these individuals present isotopic values that are lower than the combined pig and human ranges.

3.2. Regional patterns: smaller regions

Tables 2–4 present the averages and ranges for our second, smaller scale of analysis. We focus here on the number and sex of outliers from each context. Figs. 3–5 plot the density of human isotopic values along with faunal, vegetation, and precipitation/groundwater data. Table S7 shows the basic demographic and funerary data of the outliers from each area. For strontium, 13 individuals (out of 137: 9.5 %) are clear outliers from their respective local isotopic range. The number of nonlocals is regionally heterogeneous, with the majority being found at Münsingen-Rain (Fig. 3e: three females and one male), Cornaux/Les Sauges (Fig. 3d: five males), and Bern Engehalbinsel (Fig. 3c: two females). A particular case is that of five additional individuals from Münsingen-Rain (three females and two males, highlighted in green in Fig. 3e), showing a strontium signature clearly more radiogenic than the rest of the individuals from this context, although still inside the range of the pigs and human estimated 95 % density region. These "*possible nonlocals*" are clearly highlighted as outliers when plotting a boxplot of the human values for Münsingen-Rain.

The number of outliers for oxygen is relatively small, with two males (from Münsingen-Rain and Cornaux/Les Sauges) falling distinctly outside the local $\delta^{18}O$ range, both exhibiting particularly low values (Fig. 4c and d). To these, we may add an adolescent (F-16402) from

Table 2
Summary statistics of human $\delta^{18}O_{DW}$ values from the Swiss Plaeau, Alps, and single contexts. LS: Les Sauges; N: sample size; SD: standard deviation: Min, Max: minimum and maximum values.
Lwr (Lower) and Upr (Upper) indicate the limits of the estimated 95 % density region for human data (only for N > 3). L_{OIPC}, U_{OIPC}: endpoints of the local precipitation $\delta^{18}O_{DW}$ range (see methods).

		$\delta^{18}O_{DW}$‰ (VSMOW)							
Area/Region	N	Mean	SD	Min	Max	Lwr	Upr	L_{OIPC}	U_{OIPC}
Alps	2	−8.7	1.3	−9.6	−7.7	–	–	−12.9	−3.6
Swiss Plateau	85	−11.0	1.5	−16.0	−7.6	−14.0	−8.5	−13.6	−4.0
Avenches	3	−11.3	2.4	−14.0	−9.8	–	–	−13.2	−4.1
Bern Canton	32	−10.6	1.2	−13.3	−8.3	−13.0	−8.5	−13.6	−4.3
Cornaux/LS & La Tène	10	−12.4	1.6	−16.0	−10.8	−14.6	−10.1	−13.1	−4.0
Bern Engehalbinsel	21	−11.0	1.5	−13.7	−7.6	−13.7	−8.9	−13.6	−4.3
Münsingen-Rain	19	−11.0	1.4	−14.0	−9.2	−13.6	−8.5	−13.6	−4.3
Ticino	2	−8.7	1.3	−9.6	−7.7	–	–	−12.9	−3.6

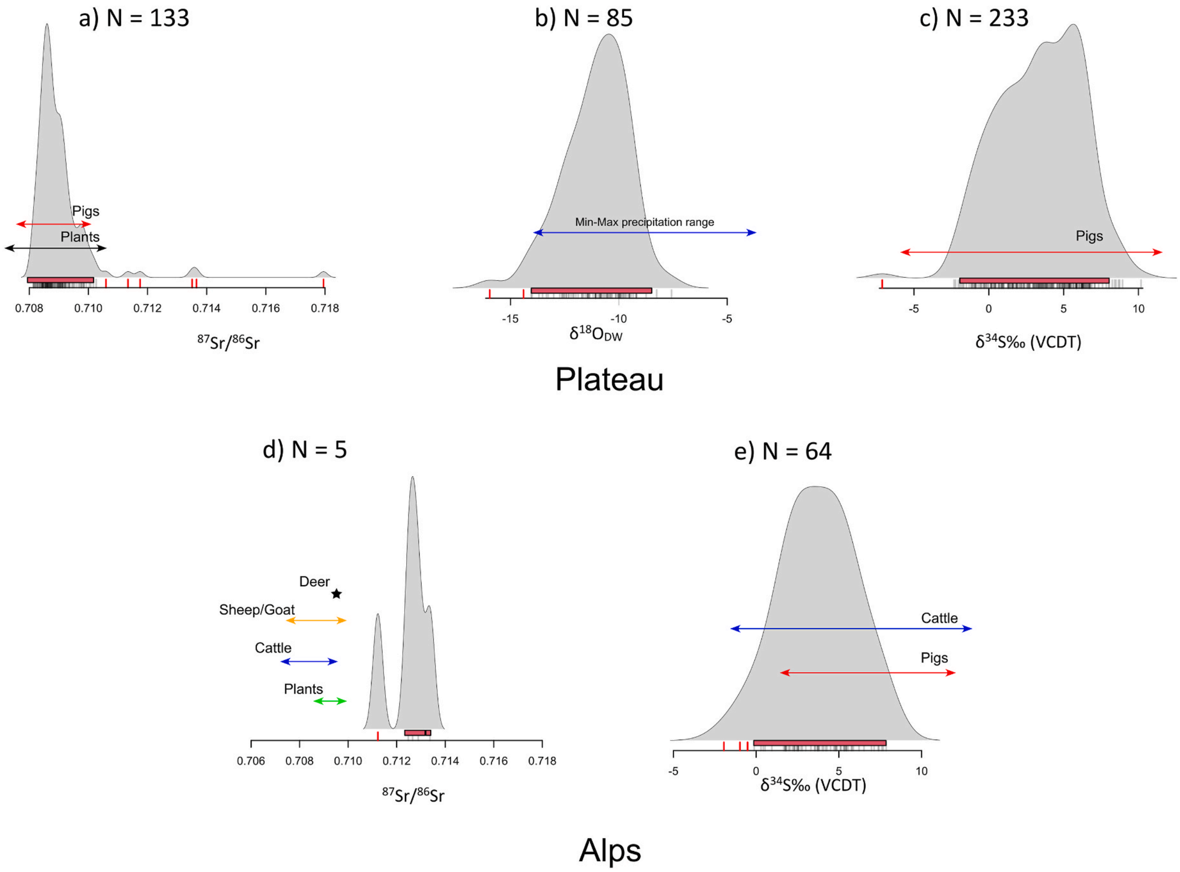

Fig. 2. Swiss Plateau (a–c) and Alps (d, e): distribution of human strontium, oxygen, and sulfur isotopic ratios. The red horizontal bars indicate the 95 % highest density region (HDR), representing the most probable range of human isotopic values based on kernel density estimation, with outliers highlighted in red. The plots display single values (star) and ranges (arrows) from local fauna, vegetation, and precipitation data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Summary statistics of human $\delta^{18}O_{DW}$ values from the Swiss Plaeau, Alps, and single contexts. N: sample size; SD: standard deviation: Min, Max: minimum and maximum values.

Lwr (Lower) and Upr (Upper) indicate the limits of the estimated 95 % density region for human data (only for N > 3).

L_{OIPC}, U_{OIPC}: endpoints of the local precipitation $\delta^{18}O_{DW}$ range (see methods).

		$^{87}Sr/^{86}Sr$						
Analyzed context	Type of sample	N	Mean	SD	Min	Max	Lwr	Upr
Bern Canton	Human	40	0.70897	0.00047	0.70814	0.70983	0.70829	0.70987
Bern Canton	*Bos taurus*	3	0.70902	0.00050	0.70851	0.70952	0.70802	0.71002
Bern Canton	*Equus caballus*	2	0.70871	0.00004	0.70868	0.70873	0.70863	0.70878
Bern Canton	*Sus domesticus*	6	0.70878	0.00051	0.70836	0.70962	0.70776	0.70980
Bern Canton	Plant	5	0.70889	0.00073	0.70823	0.70974	0.70742	0.71036
Bern Canton	*Caprinae*	1	0.70876	–	–	–	–	–
Bern Canton	Land snail	4	0.70826	0.00006	0.70819	0.70832	0.70815	0.70838
Engehalbinsel	Human	23	0.70920	0.00102	0.70834	0.71365	0.70813	0.70934
Münsingen-Rain	Human	53	0.70890	0.00138	0.70815	0.71795	0.70801	0.70990
Münsingen Entlastungsstrasse	*Bos taurus*	2	0.70877	0.00036	0.70851	0.70903	0.70804	0.70950
Münsingen Gerbegraben	*Sus domesticus*	5	0.70870	0.00053	0.70836	0.70962	0.70765	0.70975
Cornaux/Les Sauges & La Tène	Human	11	0.70990	0.00156	0.70827	0.71351	0.70757	0.71187
Cornaux/Les Sauges & La Tène	*Sus domesticus*	3	0.70871	0.00053	0.70841	0.70932	0.70766	0.70976
Cornaux/Les Sauges & La Tène	*Caprinae*	1	0.70875	–	–	–	–	–
Grisons	Human	0	–	–	–	–	–	–
Grisons	*Bos taurus*	14	0.70840	0.00045	0.70796	0.70977	0.70751	0.70930
Grisons	*Caprinae*	0	–	–	–	–	–	–
Avenches	Human	5	0.70928	0.00079	0.70814	0.71017	0.70888	0.71027
Avenches	*Bos taurus*	2	0.70928	0.00033	0.70904	0.70951	0.70861	0.70995
Avenches	*Sus domesticus*	1	0.70947	–	–	–	–	–
Avenches	*Caprinae*	3	0.70936	0.00038	0.70908	0.70980	0.70860	0.71012
Ticino	Human	5	0.71252	0.00080	0.71123	0.71337	0.71233	0.71340
Ticino	Plant	5	0.70925	0.00019	0.70908	0.70954	0.70888	0.70963

Table 4
Single contexts: sulfur ranges of humans and faunal datasets. N: sample size; SD: standard deviation: Min, Max: minimum and maximum values. Lwr (Lower) and Upr (Upper) indicate the local isotopic range limits, calculated as Mean ± 2SD for environmental data and as the estimated 95 % density region of human data. See the main text and Table 1 for details on the type, location, and references of included published data.

		δ^{34}S‰ (VCDT)						
Analyzed context	Type of sample	N	Mean	SD	Min	Max	Lwr	Upr
Bern Canton	Human	62	4.0	2.0	−2.2	8.7	1.2	7.1
Bern Canton	*Sus domesticus*	1	−2.0					
Bern Canton	*Bos taurus*	3	2.3	0.6	1.7	2.7	1.2	3.4
Bern Canton	*Equus caballus*	2	4.2	0.1	4.1	4.3	3.9	4.5
Bern Canton	*Caprinae*	1	−2.3					
Bern Engehalbinsel	Human	37	5.5	1.1	1.6	7.1	3.6	7.4
Bern Engehalbinsel	*Sus domesticus*	1	8.0	–	–	–	–	–
Bern Engehalbinsel	*Bos taurus*	1	4.8	–	–	–	–	–
Bern Engehalbinsel	*Caprinae*	2	7.0	1.0	6.3	7.7	5.0	9.0
Münsingen-Rain	Human	76	1.0	2.2	−2.3	7.6	−2.7	6.4
Cornaux/Les Sauges & La Tène	Human	28	4.5	2.2	−1.9	8.0	1.0	8.6
Cornaux/Les Sauges & La Tène	*Sus domesticus*	3	3.5	1.4	2.0	4.8	0.7	6.3
Cornaux/Les Sauges & La Tène	*Bos taurus*	4	2.9	1.9	0.4	5.0	−0.9	6.7
Cornaux/Les Sauges & La Tène	*Esox lucius*	2	2.5	2.3	0.9	4.2	−2.0	7.1
Cornaux/Les Sauges & La Tène	*Anser anser*	1	2.9	–	–	–	–	–
Cornaux/Les Sauges & La Tène	*Equus caballus*	2	0.7	0.1	0.6	0.7	0.4	0.9
Cornaux/Les Sauges & La Tène	*Lutra lutra*	1	2.4	–	–	–	–	–
Cornaux/Les Sauges & La Tène	*Caprinae*	1	5.6	–	–	–	–	–
Sion & Bramois	Human	54	3.3	2.1	−2.0	7.6	−0.9	7.5
Andelfingen	Human	16	5.2	2.2	2.2	8.7	−2.3	8.9
Avenches	Human	10	3.8	5.2	−7.1	10.2	−2.5	12.0
Avenches	*Bos taurus*	3	−1.3	2.2	−3.8	0.5	−5.7	3.1
Avenches	*Sus domesticus*	3	2.1	5.6	−2.4	8.3	−9.0	13.2
Avenches	*Caprinae*	3	0.1	1.8	−1.2	2.2	−3.5	3.7
Ticino	Human	7	6.3	1.8	2.8	7.9	5.3	8.4
Ticino	*Bos taurus*	4	8.7	2.1	6.1	11.0	4.5	12.9
Ticino	*Gallus gallus domesticus*	2	7.2	0.9	6.6	7.8	5.4	9.0
Ticino	*Cervus elaphus*	2	6.8	2.2	5.2	8.3	2.4	11.1
Ticino	*Lepus europaeus*	1	9.7	–	–	–	–	–
Ticino	*Sus domesticus*	3	8.2	1.3	7.3	9.7	5.6	10.8
Ticino	*Caprinae*	3	7.9	1.9	5.8	9.1	–	–

Avenches Faubourg which presents a $\delta^{18}O_{DW}$ value of −14.0‰VSMOW, well outside the local OIPC range (from −13.2 ‰ to −4.1 ‰) and substantially lower than the other two individuals from this context (−10.0 ‰ and −9.8 ‰) (Table 2: no central tendency calculated due to small sample size). We highlight this result not only because the same individual is also a strontium outlier— (Fig. 3b)—a rare case of dual outlier in our dataset—but particularly due to the combination of a nonlocal isotopic signature with archaeological evidence of specific ritual practices. The individual, represented by a well-preserved, isolated splanchnocranium, was the only human remain found in the backfill of a road ditch, positioned between two post-holes interpreted as a gate's uprights, suggesting the display of the cranial element on the gate itself (Bridy, 2021).

For oxygen we can point to four *possible nonlocals*. These include two adult females from Bern Engehalbinsel and Bern Bümpliz and two adult males from Köniz and Cornaux/Les Sauges.

The number of sulfur outliers varies across different contexts (Fig. 5): four at Cornaux/Les Sauges (all males), three at Sion and Bramois (all adults of unknown sex), two at Bern Engehalbinsel (both males) and Münsingen-Rain (one male and one female), and one at Andelfingen (female), Canton of Bern (male), and Ticino (nonadult). Similarly to what is observed for strontium and oxygen, a closer examination of human isotopic distributions suggests for some contexts a more complex scenario. Münsingen-Rain and, especially, Andelfingen exhibit an approximately bimodal distribution (Fig. 5e–h) raising the possibility that we are observing two distinct groups: one local and one nonlocal. Following this criterion, nonlocals for sulfur at could actually include four males and one female at Münsingen-Rain, and two females and two males at Andelfingen. Another *possible nonlocal* can be found at Avenches (Fig. 5b): an adult of unknown sex that falls outside the human distribution but is near the lower limit of the pig range. All the mentioned *possible nonlocals* are highlighted with an asterisk in Table S7, and by green ticks in Figs. 3–5.

Fig. 6 presents, for six of these outliers, the dual-isotope (strontium and oxygen) likelihood surfaces (white to green), along with posterior probability distributions restricted to the top 33.3 % of spatial probability (white/red insets). For two individuals (MR-60 and MR-101) not analyzed for oxygen in this study, the geographic assignment was performed using δ^{18}O values from phosphate, and the corresponding estimated $\delta^{18}O_{DW}$ values, previously published by Scheeres (2014) and Hauschild et al. (2014). We selected these individuals based on their distinctive isotopic signatures or their association with noteworthy archaeological features. MR-60 exhibits the most radiogenic strontium signature at Münsingen-Rain, while ESCH-22 presents a nonlocal strontium isotope ratio value and oxygen isotope ratios distinct from the rest of the assemblage. MR-101, MR-116, and MR-70 were each associated with at least one grave good item indicative of non-local connections, and F-16402 is the exposed cranium from Avenches.

The results vary among individuals, with some (e.g., MR-60, MR-70) showing relatively localized high-probability regions while others like MR-116 and, especially, MR-101, a broader distribution across Central and Eastern Europe. The areas showing the highest probability include the Massif Central and Armorican Massif (MR-60, ESCH-22), the area between what is now Northern France and Belgium (ESCH-22), the alpine area (MR-70, MR-116, MR-101), and Central-eastern Europe (MR-101, MR-116). The result for the cranium F-16402 is the most constrained highlighting only a limited and narrow high probability areas in the Alpine and Cisalpine region.

3.3. Sex

Table 5 presents the absolute and relative frequencies of outliers by sex. These frequencies show no substantial differences across specific contexts or the entire dataset. The most notable differences are observed

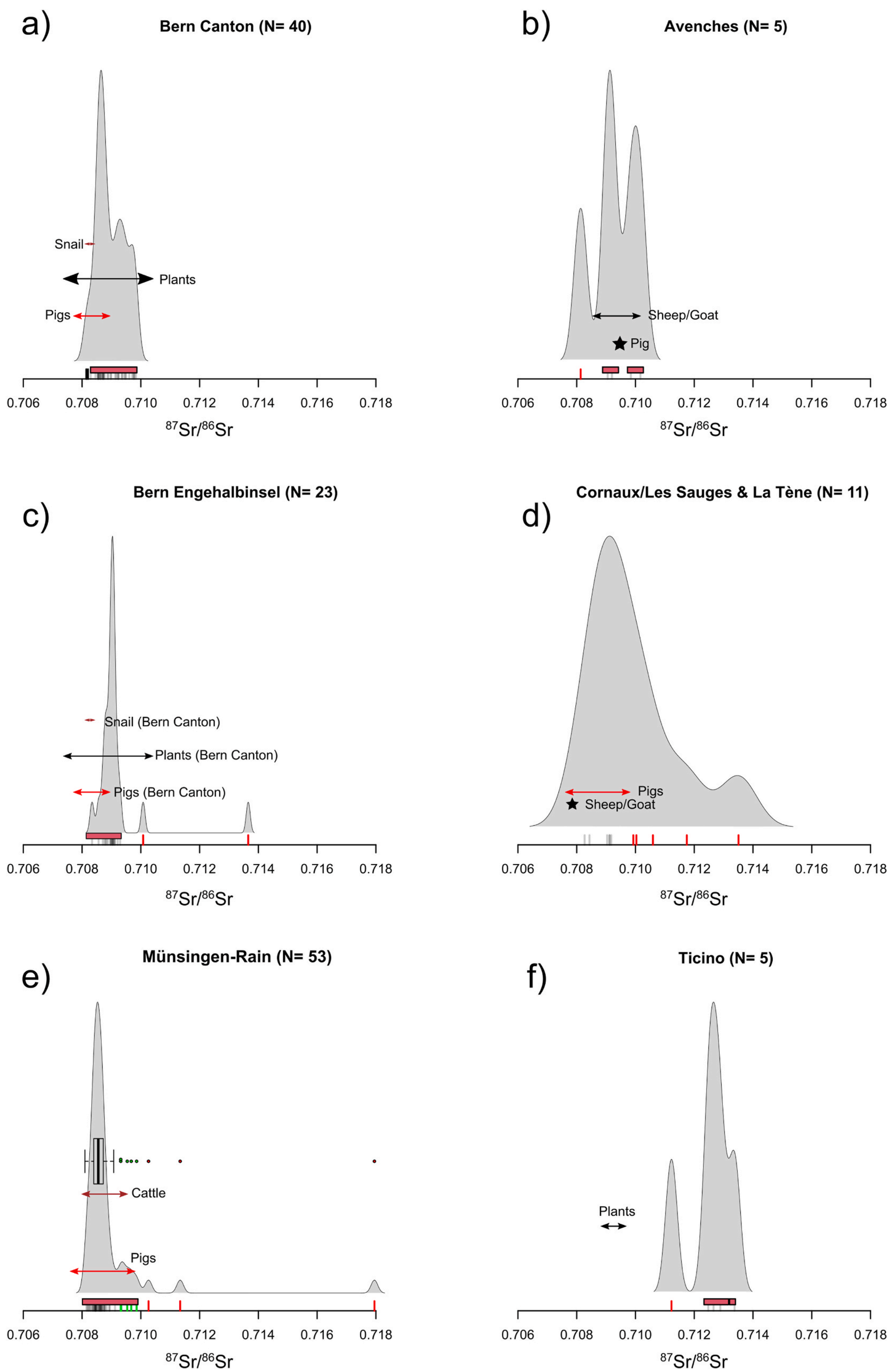

Fig. 3. Specific regional contexts: distribution of strontium isotopic ratios. The red horizontal bars indicate the 95 % highest density region (HDR), representing the most probable range of human isotopic values based on kernel density estimation, with outliers highlighted in red. The green ticks and box plot (e) indicate *possible nonlocals* at Münsingen-Rain. The plots display single values (stars) and ranges (arrows) from local fauna and vegetation data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

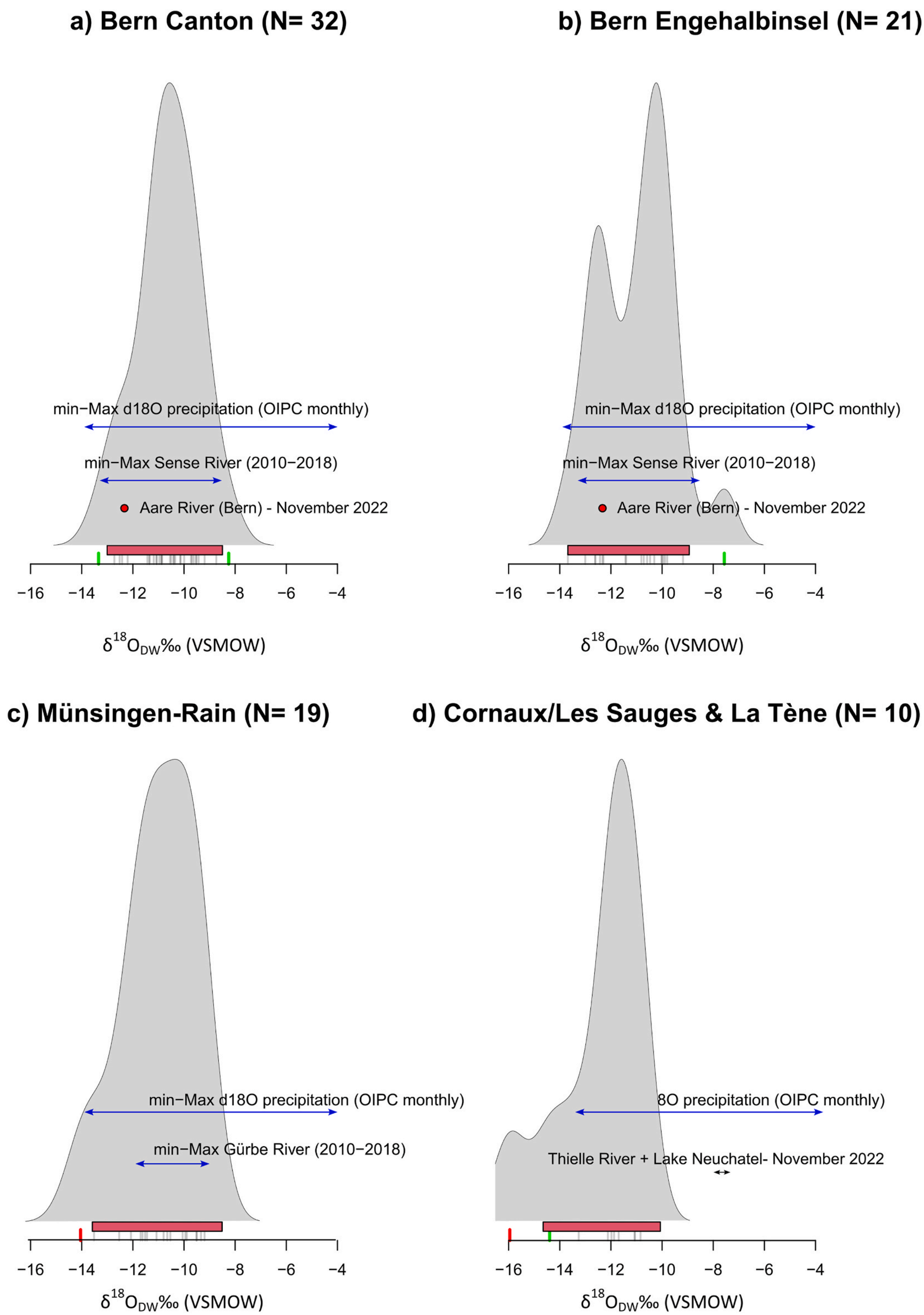

Fig. 4. Specific regional contexts: distribution of oxygen isotopic ratios. The red horizontal bars indicate the 95 % highest density region (HDR), representing the most probable range of human isotopic values based on kernel density estimation, with outliers highlighted in red and *possible nonlocals* in green. Arrows represent local isotopic ranges derived from OIPC (precipitation), published groundwater data, and water samples collected for this study. The red circle marks a single water sample from the Aare River. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

at Bern Engehalbinsel for strontium (%M: 40 %, 2/5 vs. %F: 11.8 %, 2/17), Andelfingen for sulfur (%M: 25 %, 2/8 vs. %F: 42.9 %, 3/7), and Münsingen-Rain for oxygen (%M: 10 %, 1/10 vs. %F: 0 %, 0/9). However, none of these differences are statistically significant.

3.4. *Funerary variability*

Table S8 reports the Status and Diversity Indices for the adult individuals at Münsingen-Rain and Bern Engehalbinsel. Figs. S1 and S2 present the plots of funerary versus isotopic distances for both contexts, along with the results of the Mantel tests. These results clearly indicate

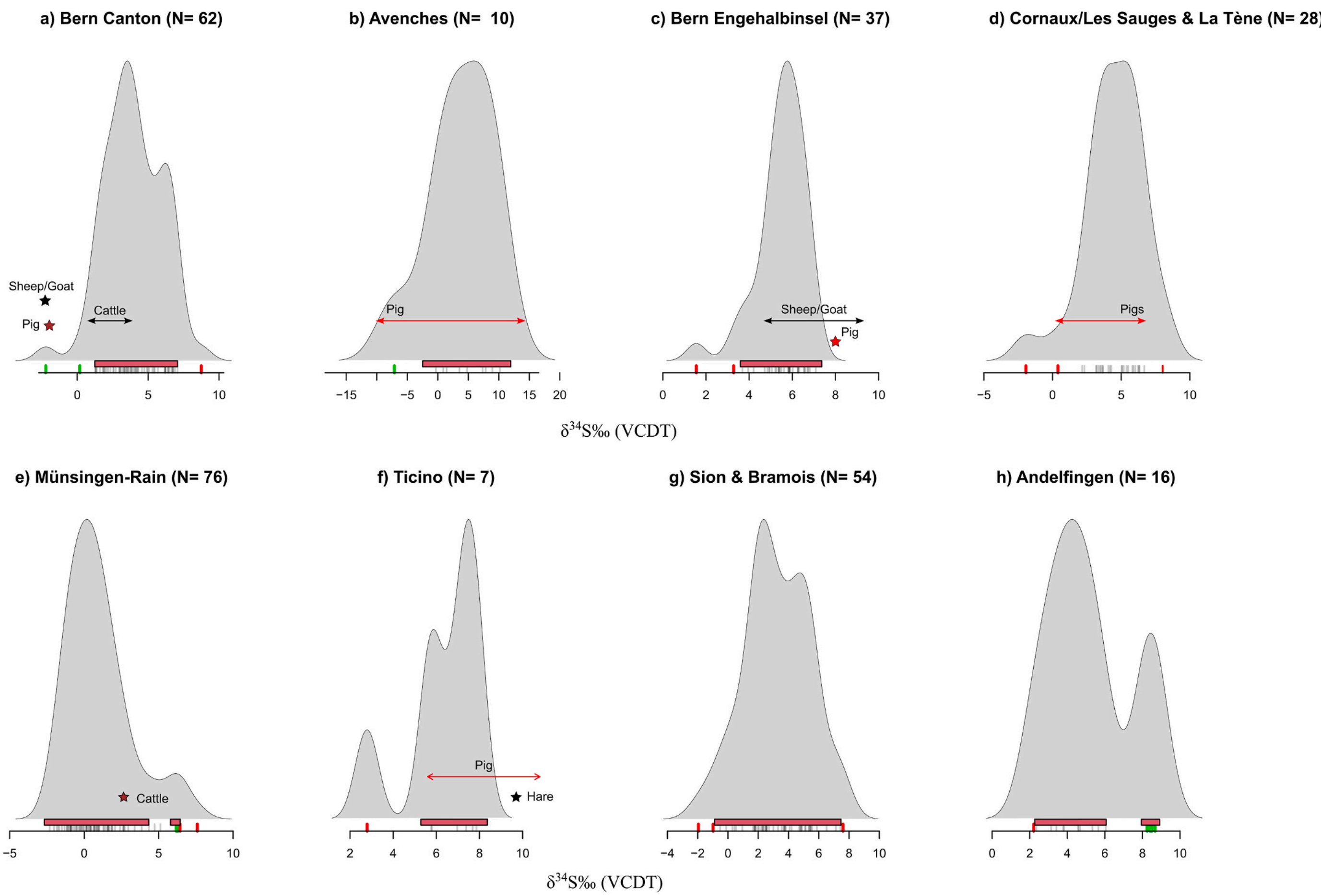

Fig. 5. Specific regional contexts: distribution of sulfur isotopic ratios. The red horizontal bars indicate the 95 % highest density region (HDR), representing the most probable range of human isotopic values based on kernel density estimation, with outliers highlighted in red and *possible nonlocals* in green. The plots show single values (stars) and ranges (arrows) from local fauna data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

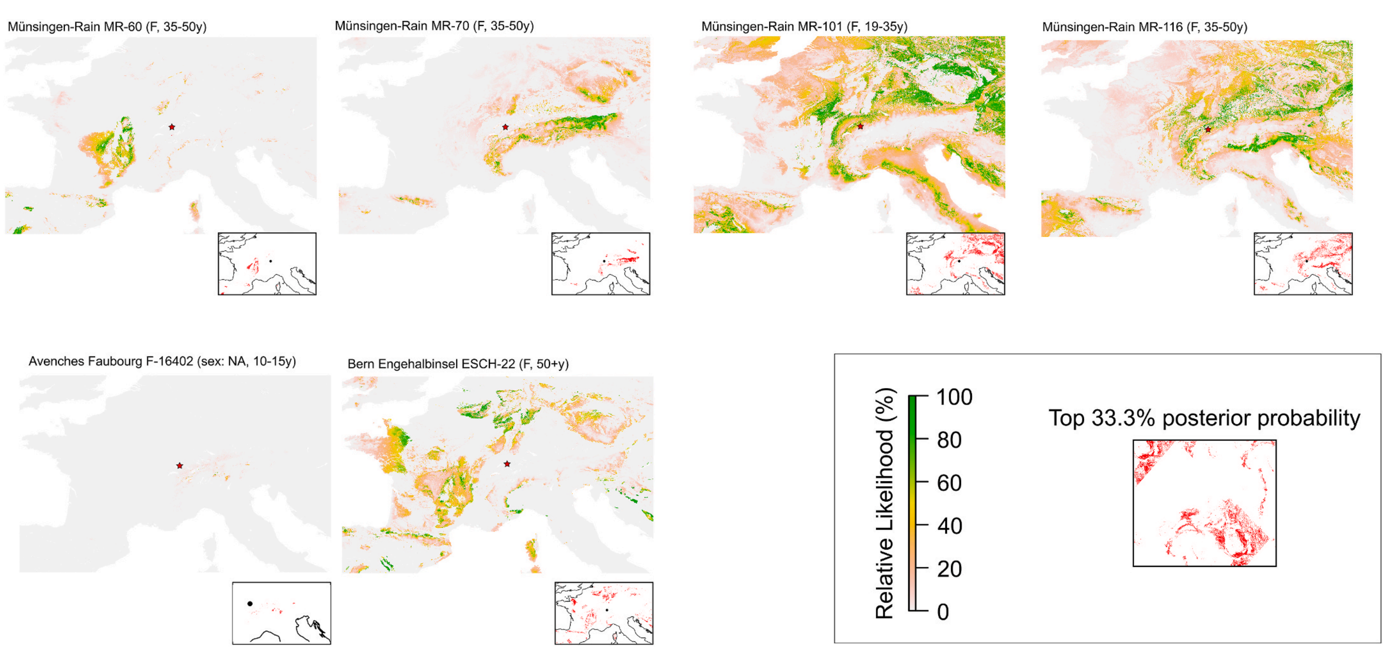

Fig. 6. Dual isotope ($^{87}Sr/^{86}Sr$ and $\delta^{18}O$) geographic assignments for selected individuals. Main maps show relative likelihood surfaces. Inset maps highlight the top 33.3 % of the posterior probability using a probability-based threshold.

Table 5
Number and relative frequency (%) of outliers in each sex.
nF, nM: number of analyzed females and males; F_{out}, M_{out}: number of female and male outliers. FET= Fisher exact test
The analysis includes only adults and, for each context, the possible nonlocals as well (see Table S6).

	$^{87}Sr/^{86}Sr$					$\delta^{34}S$‰ (VCDT)					$\delta^{18}O_{DW}$‰ (VSMOW)				
Analyzed context	nF	nM	F_{out} (%)	M_{out} (%)	p (FET)	nF	nM	F_{out} (%)	M_{out} (%)	p (FET)	nF	nM	F_{out} (%)	M_{out} (%)	p (FET)
Andelfingen	–	–	–	–	–	7	8	3 (42.9)	2 (25.0)	0.608	–	–	–	–	–
Avenches	2	1	0 (0)	0 (0)	–	2	1	0 (0)	0 (0)	–	1	1	0 (0)	0 (0)	–
Bern Canton	26	9	0 (0)	0 (0)	–	36	14	0 (0)	2 (14.3)	–	21	8	1 (4.8)	1 (12.5)	0.483
Cornaux/Le Sauges & La Tène	0	10	–	4 (40.0)	–	0	20	0 (0)	4 (20.0)	–	0	9	–	2 (22.0)	–
Engehalbinsel	17	5	2 (11.8)	2 (40.0)	0.210	21	12	2 (9.5)	2 (16.7)	0.610	16	4	1 (6.3)	0 (0)	1.000
Münsingen-Rain	20	27	5 (25.0)	4 (14.9)	0.465	29	37	2 (6.9)	3 (8.1)	1.000	9	10	0 (0)	1 (10.0)	1.000
Sion & Bramois	–	–	–	–	–	18	26	0 (0)	0 (0)	–	–	–	–	–	–
Ticino	3	2	0 (0)	1 (50.0)	1.000	3	2	0 (0)	0 (0)	–	2	0	0 (0)	–	–
Total	*68*	*54*	*7 (9.3)*	*11 (17.7)*	0.204	116	120	*7 (6.0)*	*13 (10.8)*	0.244	*49*	*32*	2 (4.0)	4 (12.5)	0.203

that these variables are completely uncorrelated. A more detailed view is provided in Fig. S3, which shows for both sites a rather random distribution of the Status and Diversity indices. For completeness, Fig. S4 presents an overview of carbon and nitrogen isotopic values for these two contexts (data from Moghaddam et al., 2016, 2018, and this study; see Table S5), along with the status index and potential nonlocality of each individual. Although no clear pattern emerges among these variables, two females from Münsingen-Rain (MR-70 and MR-101) warrant attention: MR-70 exhibits a markedly higher $\delta^{13}C$ ratio alongside a nonlocal strontium value, while MR-101 combines an elevated $\delta^{13}C$ value with a high-status index.

4. Discussion

Before discussing our results, we must first address the primary limitations of this study. The geological complexity of the Swiss Plateau, as previously mentioned, presents significant challenges for detecting nonlocals and estimating their geographic origin. This issue is exacerbated by the lack of detailed strontium and sulfur isoscapes for Switzerland. Caution is also necessary when, as in this study, modern precipitation and groundwater data are used as proxies for local $\delta^{18}O_{DW}$. This approach has well-documented limitations (e.g., Bataille et al., 2020; Lightfoot and O'Connell, 2016), as isotopic values of precipitation have likely shifted over the past two millennia. Additionally, local individuals may have accessed water sources with a 'non-local' isotopic signature, such as rivers originating at high altitudes, and cooking and brewing practices could have further influenced the $\delta^{18}O$ of ingested water. The intrinsic error associated with applying conversion equations to estimate drinking water $\delta^{18}O$ values from human tissues must also be acknowledged (Daux et al., 2008; Pederzani and Britton, 2019; Pollard et al., 2011), as it further compounds the broader uncertainties inherent in oxygen isotope-based mobility studies. Another source of uncertainty is the differing sample sizes across the analyzed contexts, with some necropolises and/or regions represented by only a few individuals, while others are represented by relatively large numbers. A clear example of this is the small sample size of the contexts from the Alpine area, an issue affecting especially strontium analysis and primarily due to the poor preservation of dental and skeletal remains in the region. This problem restricts our ability to draw robust conclusions about Alpine mobility patterns, and calls for caution when interpreting the results for this geographical area. Another challenge lies in selecting the criteria for defining local isotopic ranges and pinpointing outliers. Although we exercised caution and considered various factors to minimize false positives, our approach has limitations that likely led to an underrepresentation of nonlocals. This fact is particularly relevant for the Plateau, where short-distance residential changes—likely more common in the analyzed period—may go undetected isotopically, while long-distance mobility is more prominently emphasized. This limitation may account for the *possible nonlocals* identified in several contexts, who may have originated from nearby areas distinct from their final burial locations. Expanding environmental isotopic datasets across diverse geographical regions may improve the spatial resolution and accuracy of provenance analyses in the future, enabling a more precise identification of nonlocals and their geographic origin (cf. Brönnimann et al., 2018).

It is also important to emphasize the differing temporal resolutions provided by our isotopic data. While isotopic ratios from dental enamel offer insights into an individual's childhood, bone collagen reflects a broader temporal window, particularly in our case, due to the low turnover rate of cranial bones. Consequently, we chose not to integrate these data into a combined triple isotopic probabilistic geographic assignment. Although our analysis of different tissues can provide chronological insights into residential changes - such as individuals exhibiting non-local strontium and/or oxygen signatures alongside a local sulfur signal - a finer temporal resolution would require additional analyses. These may include intra-individual sampling of teeth with varying developmental timelines, bones with different turnover rates, and incremental sampling of dental enamel and dentine (e.g., Boethius et al., 2022; Coffin et al., 2022; Depaermentier et al., 2023; Frei et al., 2017; Knipper et al., 2018; Laffranchi et al., 2022; Lamb et al., 2014; Pérez-Ramallo et al., 2022).

Regarding our first research question, the results of this study suggest both short- and long-distance mobility in the analyzed contexts, with frequency of nonlocals overall low but heterogeneous on a local basis. Some geographic areas, like the Massif Central and the alpine area, emerge as important source of incomers.

Archaeological and anthropological data suggest that during the Late Iron Age, the Swiss Plateau had a higher population density compared to the Alps (Cooper et al., 2023; Hofstetter, 2021, Pauli-Gabi and Steiner, 2002). The Plateau also featured economically, culturally, and religiously significant centers, such as the *Brenodor* oppidum at Bern Engehalbinsel (see Supplementary Material S2.2). Similarly, despite the absence of archaeological traces of an associated settlement, the type and variability of grave goods at Münsingen-Rain suggest a community engaged in extensive trade networks and characterized by complex socioeconomic differentiation (see Supplementary Material S2.1) (Hodson, 1968; Müller, 1998). Larger, economically significant locations attract potential movers for various reasons, including better economic opportunities and the presence of kin or other social networks in the area (Boyd, 1989). Additionally, increased mobility around major centers may have created a self-reinforcing effect, providing potential migrants with more information about their target destinations (Anthony, 1990; Van Hear et al., 2017). Given the central roles of Bern Engehalbinsel and possibly Münsingen-Rain in trade, craftsmanship, and religious activities, it is unsurprising that these sites exhibit higher frequencies of nonlocals compared to the rest of our dataset. This observation aligns with those by Knipper et al. (2018) regarding the elevated frequency (37 %: 20/54) of nonlocals at the proto-urban center of Basel-Gasfabrik. At the same time, we need to stress that, compared with this context, the frequencies of nonlocals observed in our study are much lower. Methodological and contextual factors may explain this discrepancy. In particular, by examining two teeth per individual, these authors detected lifetime residential changes that single-tooth analysis, like ours, could miss. Additionally, economic, social, and political factors, along with Basel-Gasfabrik' s location at key trade routes, may explain the higher residential mobility rates observed there.

The results of the probabilistic geographic assignment are interesting, as they align with the known spread of the La Tène culture across continental Europe. In particular, the strong connections to the alpine/subalpine region and the area corresponding to what is now Central France are intriguing, suggesting long-distance residential mobility, as already highlighted by previous studies (Knipper et al., 2018; Laffranchi et al., 2024a), further supporting the idea that such extended mobility was not uncommon for this period.

At the same time, as mentioned above, our data suggest the presence of short-distance residential changes, statistically represented by the *possible nonlocals* highlighted in the study. Caution is needed when interpreting these ambiguous cases, but we believe that considering them as actual nonlocals, or, following Depaermentier et al. (2020, 2021) "*microregional*", returns a more realistic scenario than one where mobility is exclusively characterized by long-distance residential changes.

Turning to the second research question, our analyses failed to highlight a contrast in mobility between males and females. Mobility studies frequently try to compare sex-specific isotopic variability with those expected based on different social systems and residence patterns (e.g., Bentley et al., 2004, Cintas-Peña et al., 2023; Depaermentier et al., 2020; Knipper et al., 2018; Pearson et al., 2023; Sjogren et al., 2020). Focusing on the European Late Iron Age, the high frequency of male individuals showing a local isotopic signature suggested to Knipper et al. (2018) the presence of a patrilocal residential rule at Basel-Gasfabrik. Conversely, no patterning between sexes was detected at other La Tène contexts in Germany, Italy, and Czech Republic (Laffranchi et al., 2022; Scheeres et al., 2013, 2014). Our results would therefore align with these latter studies. This may be due to several factors including, besides possible social norms, the limited and small-scale mobility within the analyzed communities, as well as the chronological resolution of our data. We cannot exclude that more evident differences in mobility between sexes may emerge after analyzing different dental samples from the same individuals and/or incorporating in the future the analyses of other variables (e.g., Lead, Neodymium, Hydrogen).

Regarding our last research question, our data suggest that the geographic origin of an individual was not among the factors influencing how they were buried. This result aligns with those obtained by other similar analyses on Iron Age contexts (Knipper et al., 2018; Laffranchi et al., 2019, 2021; Moghaddam et al., 2016; Scheeres et al., 2014), and may be influenced by a series of factors. First, since funerary rituals are enacted by the survivors, they may be more informative about the beliefs and social structure of the deceased's community or family than of the individual themselves (Parker Pearson, 1999). This may have been especially relevant during the Late Iron Age given the mentioned focus on community values and membership of funerary practices during this time period (Collis and Karl, 2018; Fichtl, 2018; Metzner-Nebelsick, 2019). Furthermore, if burial features were actually influenced by the social perception of the deceased, other factors such as gender, age, socioeconomic status, familial or social connections, may have been more relevant. A lack of distinctive burial features for nonlocals could also suggest cultural or familial ties between incomers and the host community. This scenario might apply to some of the *possible nonlocals* in our study, particularly if they were, as we postulated, linked to short-distance residential changes. Finally, our analysis of funerary variability is inherently limited to the physical aspects of the ritual, as it relies exclusively on the examination of grave goods and burial features. Nonetheless, it is important to acknowledge that gestural and vocal elements of funerary rituals, though archaeologically invisible, may have been central and influenced by the deceased's geographic and cultural origins (Laffranchi et al., 2024b). If we shift from the broad perspective offered by the use of indices to a finer scale of analysis and consider single cases, we may indeed identify instances where individual grave goods suggesting cultural connections beyond the Swiss Plateau align with nonlocal isotopic values. This seems the case for four females included in our probabilistic geographic assignment: MR-101, MR-116, and MR-70 from Münsingen-Rain, and ESCH-22 from Engehalbinsel-Schärloch.

Among the objects from MR-101, one of the richest burials at Münsingen-Rain, is a top-modern fibula (first example of a LTC1 type), with typological parallels to Bohemia and Bavaria (Müller and Lüscher, 2004). While this hypothesis is primarily supported by isotopic geographic assignment based on strontium and oxygen, the exceptionally high $\delta^{13}C$ value of this individual (−16.4 ‰ VPDB; see Fig. S4) provides additional evidence. Carbon isotope data from Early and Late Iron Age sites in southwestern Germany and Bohemia indicate an increasing reliance on C_4 plants (Le Huray and Schutkowski, 2005; Oelze et al., 2012; Vytlačil et al., 2024), reinforcing this connection. MR-116 was buried with a gold finger ring of a typology linked to northern Italy and that finds parallels in the 'Celtic' necropolis of Casalecchio di Reno (Bologna) (Waldhauser, 1998). At Münsingen-Rain, only five female individuals were interred with gold rings, possibly indicating high social status (Jud, 1998). Notably, the probabilistic geographic assignment highlights the cisalpine region as one of the highest-probability origin areas (Fig. 6).

MR-70 was buried with a Certosa-type bronze fibula, characteristic of the southern Alpine and northern Italian cultural sphere (Martin-Kilcher, 1973). While in this case the isotopic data are less clear, it is nonetheless interesting to observe that the highest-probability geographic areas include the eastern Alps and the Alpine region to the north of the Po valley.

Another, although less clear, example of co-presence of nonlocal isotopic and funerary data is the female ESCH-22 from the Engehalbinsel, for which combined $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ suggest an origin from a rather variable set of regions to the west of the Swiss Plateau. The problem in this case is the archaeological documentation of this burial, rather fragmentary. This hampers to confidently associate the individual to specific grave goods. It is however worth noting that among the artifacts published by Stähli (1977) for Engehalbinsel Schärloch (where ESCH-22 was found) are a bronze brooch of the Mötschwil type, distributed as far as Bavaria and possibly Bohemia, and two glass arm rings datable to the LT C2 stage (Müller, 1996; Jud and Ulrich-Bochsler, 2014; Stähli, 1977).

These observations, if compared with the results obtained by the analysis of funerary indices, underscore the need to integrate statistical and qualitative analyses, as broad-scale approaches may obscure the complexity of individual mobility and cultural interaction. If we assume that the "exotic" items were worn in life by the deceased—a hypothesis that remains uncertain—this would suggest that a different geographic and cultural affiliation was (at least materially) expressed through single objects rather than through a distinctly different or elaborate burial. Funerary rituals, focused on the expression of shared community values, norms, and symbols, may have prioritized collective identity over individual origins, explaining the consistent burial practices observed for nonlocals. In this context, geographic origin appears to have been subtly embodied in life rather than explicitly marked in death.

While the above considerations may apply to data from settlements or necropolises, they are only marginally relevant to Cornaux/Les Sauges. The latter is indeed a non-funerary context that yielded a substantial number of nonlocals (9 out of 20: 45 %) (Laffranchi et al., 2024a). The osteological and archaeological evidence suggests that these individuals died due to the collapse of a wooden bridge while they were crossing it. The high number of isotopic outliers and male predominance indicate they may have been part of a specialized group like traders or soldiers, offering a rare insight into mobility and socio-economic roles.

Another non-funerary case of interest is the cranium from Avenches Faubourg archaeologically interpreted as displayed on a gate (Bridy, 2021). Combined strontium and oxygen values suggest a childhood spent in a southern alpine area or cisalpine region (north of the Italian peninsula). The exposure of heads and/or cranial remains is attested historically (e.g. Diodorus Siculus: *Bibliotheca Historica*) and documented archaeologically by numerous finds from southern Gaul, Belgium, Germany, and Switzerland in a range of contexts including oppida, sanctuaries, as well as domestic spaces (e.g. Brunaux et al., 1985; Ciesielski et al., 2011; Rousseau, 2012).

The individual's nonlocal origin may suggest a trophy head from a vanquished warrior or a raid victim, with the latter scenario potentially more consistent with their young age at death. Alternatively, as proposed by Bridy (2021), the cranium may represent a relic—retrieved and displayed post-burial (cf. Rousseau, 2012). Under this hypothesis, the individual could have been a community member who migrated to Avenches after being born elsewhere. Further examination of the archaeological context, combined with additional molecular analyses, could provide deeper insights into this intriguing case.

5. Conclusions

Our data reveal spatial heterogeneity in the frequencies of nonlocal individuals among analyzed Late Iron Age Swiss contexts, potentially linked to regional political and economic differences. Isotopic variability indicates residential changes over both short and long distances, possibly involving areas such as the alpine and subalpine regions, and the area that is now Central-eastern France. The lack of a clear correlation between mobility, sex, and funerary treatment provides new insights into the social dynamics of residential changes in La Tène cultures. By expanding the isotopic dataset for Late Iron Age Switzerland and applying diverse statistical methods, this study enhances our understanding of mobility during this period, highlighting its complexity within a key area of the La Tène cultural sphere. From a broader perspective, our findings emphasize that past mobility cannot be reduced to a singular trend but represents a mosaic of regional and scale-related variability. Ongoing paleogenetic analyses will further assess biological kinship between nonlocals and host community members, shedding light on familial and social ties influencing mobility. Additional isotopic studies, including multi-tissue analyses and an expanded faunal and vegetation dataset, could refine our understanding of nonlocal individuals' origins and improve the resolution of mobility reconstructions in the Swiss territory.

CRediT authorship contribution statement

Zita Laffranchi: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vanessa Haussener:** Writing – review & editing, Data curation. **Domingo C. Salazar García:** Writing – review & editing, Methodology, Data curation. **Alice Paladin:** Writing – review & editing. **Stefania Zingale:** Writing – review & editing. **Sönke Szidat:** Writing – review & editing, Data curation. **Sandra Lösch:** Writing – review & editing, Resources. **Albert Zink:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition. **Marco Milella:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Data availability statement

The data supporting the findings of this study are available within the article and the included supplementary material. R scripts related to this work are available in Zenodo (https://doi.org/10.5281/zenodo.14748931).

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used OpenAI's ChatGPT in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by a Swiss National Science Foundation Grant to MM (Grant Number: 10531FL_197103/1) and by a grant from the Autonomous Province of Bolzano-Alto Adige—Department of Innovation, Research, University and Museums (Funding Decree n.9/2021) to AZ. DCSG acknowledges funding from the Generalitat Valenciana (CIDEGENT/2019/061).

The authors thank the Editor, Associate Editor, and anonymous reviewers for their insightful comments and constructive suggestions.

The following people and institutions provided access to the specimens and/or archaeological documentation: Manuel Buess, Anja Gerth, Stefan Aebersold (Archaeological Service Canton Bern); the team at Bernisches Historisches Museum; Denis Genequand, Hugo Amoroso, Aurélie Schenk, Daniel Castella, (Site et Musée romain d'Avenches), Anne Claire Fabre (Naturhistorisches Museum Bern), Marc Antoine Kaeser, Géraldine Delley, Célestine Leuenberger (Laténium Park and Museum), Sonia Wüthrich (Office du patrimoine et de l'archéologie de Neuchâtel, section archéologie), Luisa Mosetti, Rossana Cardani Vergani, Moira Morinini Pè (Ufficio Beni culturali Canton Ticino); Anna Kienholz and Simon Kurmann (Archaeological Service Canton Luzern). We thank the Archaeological Services of the Cantons of Grisons and Thurgau, and Véronique Dasen (Université de Fribourg) for providing useful archaeological information. Nicole Saviot, Simone Häberle, and Rafael M. Martínez Sánchez helped us identify animal species and suggested archaeozoological bibliography. We thank Stefano Bernasconi for the useful information on the geology of Switzerland. Antonio Delgado Huertas and Arsenio Granados Torres analyzed the water samples included in this study. We also thank Carlos Tornero for his assistance during the preparation of dental enamel for Oxygen analyses and Petrus Le Roux and Pau Comes for their help with the strontium and oxygen analyses.

We are grateful to Clément Bataille for providing the sulfur and strontium isoscapes as well as numerous suggestions on the probabilistic geographic assignment, and to Jessica Bottinelli (swisstopo) for providing the map used in Fig. 1.

Gabriele Arenz, Manuela de la Cruz Cordoba supported the laboratory preparation of the samples. Lara Indra helped with the collection of vegetation and water samples. Chris Knüsel, Felix Müller, and Dimitri Kunz provided useful information, suggestions, and encouragement.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2025.106294.

References

Alterauge, A., Meier, T., Jungklaus, B., Milella, M., Lösch, S., 2020. Between belief and fear - reinterpreting prone burials during the Middle Ages and early modern period in German-speaking Europe. PLoS One 15, e0238439. https://doi.org/10.1371/journal.pone.0238439.

Ambrose, S.H., 1993. Isotopic analysis of paleodiets: methodological and interpretive considerations. In: MK, S. (Ed.), Investigations of Ancient Human Tissue: Chemical Analyses in Anthropology. Gordon and Breach, Langhorne, Pennsylvania, pp. 59–130.

Ambrose, S.H., 1990. Preparation and characterization of bone and tooth collagen for isotopic analysis. J. Archaeol. Sci. 17, 431–451. https://doi.org/10.1016/0305-4403(90)90007-R.

Andreetta, A., 2016. Anthropologie et archéologie des cimetières du moyen-âge au sud des alpes des suisses. PhD thesis. University of Bern, Switzerland.

Anthony, D.W., 1990. Migration in archeology: the baby and the bathwater. Am. Anthropol. 92, 895–914. https://doi.org/10.1525/aa.1990.92.4.02a00030.

Balasse, M., Ambrose, S.H., Smith, A.B., Rpice, T.D., 2002. The seasonal mobility model for prehistoric herders in the South-western Cape of South Africa assessed by isotopic analysis of sheep tooth enamel. J. Archaeol. Sci. 29, 917–932. https://doi.org/10.1006/jasc.2001.0787.

Bataille, C.P., Crowley, B.E., Wooller, M.J., Bowen, G.J., 2020. Advances in global bioavailable strontium isoscapes. Palaeogeogr. Palaeoclimatol. Palaeoecol. 555, 109849. https://doi.org/10.1016/j.palaeo.2020.109849.

Bataille, C.P., Jaouen, K., Milano, S., Trost, M., Steinbrenner, S., Crubézy, É., Colleter, R., 2021. Triple sulfur-oxygen-strontium isotopes probabilistic geographic assignment of archaeological remains using a novel sulfur isoscape of western Europe. PLoS One 16 (5), e0250383. https://doi.org/10.1371/journal.pone.0250383.

Bentley, R.A., 2006. Strontium isotopes from the Earth to the archaeological skeleton: a review. J. Archaeol. Method Theor 13, 135–187. https://doi.org/10.1007/s10816-006-9009-x.

Bentley, R.A., Price, T.D., Stephan, E., 2004. Determining the 'local' 87Sr/86Sr range for archaeological skeletons: a case study from Neolithic Europe. J. Archaeol. Sci. 31, 365–375. https://doi.org/10.1016/j.jas.2003.09.003.

Boethius, A., Ahlström, T., Kielman-Schmitt, M., Kjällquist, M., Larsson, L., 2022. Assessing laser ablation multi-collector inductively coupled plasma mass spectrometry as a tool to study archaeological and modern human mobility through strontium isotope analyses of tooth enamel. Archaeol. Anthropol. Sci. 14, 97. https://doi.org/10.1007/s12520-022-01556-9.

Bowen, G.J., Revenaugh, J., 2003. Interpolating the isotopic composition of modern meteoric precipitation. Water Resour. Res. 39 (10). https://doi.org/10.1029/2003WR002086.

Bowen, G.J., Wassenaar, L.I., Hobson, K.A., 2005. Global application of stable hydrogen and oxygen isotopes to wildlife forensics. Oecologia 143 (3), 337–348. https://doi.org/10.1007/s00442-004-1813-y.

Boyd, M., 1989. Family and personal networks in international migration: recent developments and new Agendas. Int. Migrat. Rev. 23, 638–670. https://doi.org/10.1177/019791838902300313.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360. https://doi.org/10.1017/s0033822200033865.

Brönnimann, D., Knipper, C., Pichler, S.L., Röder, B., Rissanen, H., Stopp, B., Rosner, M., Blank, M., Warnberg, O., Alt, K.W., Lassau, G., Rentzel, P., 2018. The lay of land: strontium isotope variability in the dietary catchment of the Late Iron Age proto-urban settlement of Basel-Gasfabrik, Switzerland. J. Archaeol. Sci.: Report 17, 279–292. https://doi.org/10.1016/j.jasrep.2017.11.009.

Brönnimann, D., Rissannen, H., Spichtig, N., Wimmer, J., Gottardi, C., Knipper, C., Kühn, M., Müller-Kissing, M., Pichler, S., Rentzel, P., Stopp, B., Vach, W., Warnberg, O., Alt, K.W., Schibler, J., Röder, B., Lassau, G., 2022. Wissenschaftlicher Bericht: Die jüngerlatènezeitliche Zentralsiedlung Basel-Gasfabrik im Fokus: Ausgewählte Ergebnisse der interdisziplinären Forschung. Jahresbericht der Archäologischen Bodenforschung Basel-Stadt 2021, 116–152.

Brun, P., 2018. Funerary practices. In: Haselgrove, C., Rebay-Salisbury, K., Wells, P.S. (Eds.), The Oxford Handbook of the European Iron Age. Oxford University Press, Oxford, pp. 1237–1261.

Brunaux, J.-L., Méniel, P., Poplin, F., 1985. Gournay: Les fouilles sur le sanctuaire et l'oppidum (1975-1984). Rev. Archeol. Picardie 4, 1–268.

Brunetti, C., Méniel, P., Nitu, C., 2019. Mormont I-Les structures du site du Mormont (Eclepens et La Sarraz, Canton de Vaud) fouilles 2006-2011, Lausanne.

Buikstra, J.E., Ubelaker, D.H., 1994. Standards for data collection from human skeletal remains. In: Proceedings of a Seminar at the Field Museum of Natural History, Arkansas Archaeological Survey Research Series, Arkansas.

Burton, J.H., Price, T.D., 2013. Seeking the local Sr/Sr ratio to determine geographic origins of humans. Acs Sym Ser 1147, 309–320.

Chenery, C.A., Pashley, V., Lamb, A.L., Sloane, H.J., Evans, J.A., 2012. The oxygen isotope relationship between the phosphate and structural carbonate fractions of human bioapatite. Rapid Commun. Mass Spectrom. 26 (3), 309–319. https://doi.org/10.1002/rcm.5331.

Ciesielski, E., Duday, H., Girard, B., Roure, R., Martin, A., Agusti, B., 2011. La pratique des têtes coupées et les dépôts d'armes en Gaule méditerranéenne et dans le nord-est de la Péninsule Ibérique. In: Roure, R., Pernet, L. (Eds.), Des rites et des Hommes. Les pratiques symboliques des Celtes, des Ibères et des Grecs en Provence, en Languedoc et en Catalogne. Éditions Errance, Paris, pp. 113–145.

Cintas-Peña, M., Garrido Pena, R., Herrero-Corral, A.M., Flores Fernández, R., Waterman, A.J., Díaz-Zorita Bonilla, M., Díaz-del-Río, P., Peate, D.W., 2023. Isotopic evidence for mobility in the copper and bronze age cemetery of humanejos (parla, madrid): a diachronic approach using biological and archaeological variables. J. Archaeol. Method Theor 31, 1152–1184. https://doi.org/10.1007/s10816-023-09633-6.

Clauzel, T., Richardin, P., Ricard, J., Prilaux, G., Martin, J.E., Amiot, R., Fourel, F., Nguyen Van, A., Arnaud-Godet, F., Vinçon-Laugier, A., Flandrois, J.P., Lécuyer, C., 2022. Geographic origin and social status of the Gallic warriors from Ribemont-sur-Ancre (France) studied through isotope systematics of bone remains. Int. J. Osteoarchaeol. 33, 39–50. https://doi.org/10.1002/oa.3172.

Coffin, J., Dolphin, A.E., Jackes, M., Yakymchuk, C., Perrin, T., 2022. Exploring childhood mobility in Neolithic Southern France (Roquemissou) using incremental analyses of Sr isotope ratios in tooth enamel. J. Archaeol. Sci.: Report 42, 103417. https://doi.org/10.1016/j.jasrep.2022.103417.

Collis, J., Karl, R., 2018. Politics and power. In: Haselgrove, C., Rebay-Salisbury, K., Wells, P.S. (Eds.), The Oxford Handbook of the European Iron Age. Oxford University Press, Oxford, pp. 927–946.

Cooper, C., Milella, M., Lösch, S., 2023. The Late Iron Age in Switzerland: a review of anthropological, funerary, and isotopic studies. Archaeol. Anthropol. Sci. 15, 137. https://doi.org/10.1007/s12520-023-01838-w.

Coplen, T.B., 1988. Normalization of oxygen and hydrogen isotope data. Chem. Geol. Isot. Geosci. 72 (4), 293–297. https://doi.org/10.1016/0168-9622(88)90042-5.

Curdy, P., Kaenel, G., 2006. Les Celtes de l'âge du fer. In: Gallay, A. (Ed.), Des Alpes au Léman : images de la préhistoire. Infolio, Gollion, pp. 261–325.

Danielisová, A., Pajdla, P., Bursák, D., Strnad, L., Trubac, J., Kmosek, J., 2021. Claiming the land or protecting the goods? The Duchcov hoard in Bohemia as a proxy for 'Celtic migrations' in Europe in the 4th century BCE. J. Archaeol. Sci. 127. https://doi.org/10.1016/j.jas.2020.105314.

Danielisová, A., Nordfors, U., Kertes, S., Wessman, A., Ackerman, L., Oinonen, M., Etu-Sihvola, H., Arppe, L., 2025. Multi-isotopic evidence reveals the emergence of a cosmopolitan community at the Luistari cemetery in Eura, Finland, during the early Medieval period (600–1130 CE). Archaeol. Anthropol.Sciences 17, 58. https://doi.org/10.1007/s12520-024-02147-6.

Daux, V., Lécuyer, C., Héran, M.A., Amiot, R., Simon, L., Fourel, F., Martineau, F., Lynnerup, N., Reychler, H., Escarguel, G., 2008. Oxygen isotope fractionation between human phosphate and water revisited. J. Hum. Evol. 55 (6), 1138–1147. https://doi.org/10.1016/j.jhevol.2008.06.006.

DeNiro, M.J., 1985. Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. Nature 317, 806–809. https://doi.org/10.1038/317806a0.

Depaermentier, M.L.C., Kempf, M., Banffy, E., Alt, K.W., 2020. Tracing mobility patterns through the 6th-5th millennia BC in the Carpathian Basin with strontium and oxygen stable isotope analyses. PLoS One 15, e0242745. https://doi.org/10.1371/journal.pone.0242745.

Depaermentier, M.L.C., Kempf, M., Bánffy, E., Alt, K.W., 2021. Modelling a scale-based strontium isotope baseline for Hungary. J. Archaeol. Sci. 135. https://doi.org/10.1016/j.jas.2021.105489.

Depaermentier, M.L.C., Krause-Kyora, B., Hajdas, I., Kempf, M., Kuhn, T., Spichtig, N., Schwarz, P.A., Gerling, C., 2023. Bioarchaeological analyses reveal long-lasting continuity at the periphery of the Late Antique Roman Empire. iScience 26, 107034. https://doi.org/10.1016/j.isci.2023.107034.

Ebnöther, C., Wyss, S., 2004. Brenodor - Brenodurum im Brennpunkt: Fakten, Fragen und Perspektiven. Zu den Ergebnissen der Sondierungen von 2000 im Vicus Reichenbachwald (Bern-Engehalbinsel). Jahrbuch der Schweizerischen Gesellschaft für Ur- und Frühgeschichte 87, 282–296. https://doi.org/10.5169/seals-117795.

Ebert, C.E., Rand, A.J., Green-Mink, K., Hoggarth, J.A., Freiwald, C., Awe, J.J., et al., 2021. Sulfur isotopes as a proxy for human diet and mobility from the preclassic through colonial periods in the Eastern Maya lowlands. PLoS One 16 (8), e0254992. https://doi.org/10.1371/journal.pone.0254992.

Fichtl, S., 2018. Urbanization and oppida. In: Haselgrove, C., Rebay-Salisbury, K., Wells, P.S. (Eds.), The Oxford Handbook of the European Iron Age. Oxford University Press, Oxford, pp. 717–740.

Frei, K.M., Villa, C., Jorkov, M.L., Allentoft, M.E., Kaul, F., Ethelberg, P., Reiter, S.S., Wilson, A.S., Taube, M., Olsen, J., Lynnerup, N., Willerslev, E., Kristiansen, K., Frei, R., 2017. A matter of months: high precision migration chronology of a Bronze Age female. PLoS One 12, e0178834. https://doi.org/10.1371/journal.pone.0178834.

Gouffon, Y. (Ed.), 2024. Tectonic Map of Switzerland 1:500 000, Explanatory Notes. Federal Office of Topography Swisstopo, Wabern.

Hauschild, M., 2010. Keltische Wanderungen nach Italien – das Bild der antiken Sagen und Quellen. In: Schönfelder, M. (Ed.), Kelten! Kelten? Keltische Spuren in Italien, Begleitbuch zur Ausstellung im Römisch-Germanischen Zentralmuseum 19. Mai bis 1. Verlag des Römisch-Germanischen Zentralmuseums, Mainz, Mainz, pp. 14–16. August 2010.

Hauschild, M., Schönfelder, M., Scheeres, M., Knipper, C., Alt, K.W., Pare, C., 2013. Nebringen, Münsingen und Monte Bibele – Zum archäologischen und bioarchäometrischen Nachweis von Mobilität im 4./3. Jahrhundert v Chr. Archaol. Korresp. 43, 345–364.

Hillson, S., 1996. Dental Anthropology. Cambridge University Press, Cambridge.

Hodson, F.R., 1968. The La Tène Cemetery at Münsingen-Rain. Verlag Stämpfli & CIE AG Bern, Bern.

Hofstetter, T., 2021. D(IS) M(ANIBUS) S(ACRUM) - an overview of funerary behaviours on the territory of present-day Switzerland from late protohistory to early medieval times through the study of material remains, textual sources and funerary inscriptions. Journal of Ancient History and Archaeology 8, 5–60. https://doi.org/10.14795/j.v8i3.657.

Hyndman, R.J., Einbeck, J., Mp, W., 2021. Hdrcde: highest density regions and conditional density estimation. https://pkg.robjhyndman.com/hdrcde/. https://pkg.robjhyndman.com/hdrcde/.

Jud, P., 1998. Untersuchungen zur Struktur des Gräberfeldes von Münsingen-Rain. In: Müller, F. (Ed.), Münsingen-Rain, ein Markstein der keltischen Archäologie. Funde, Befunde und Methoden im Vergleich. Akten Internationales Kolloquium Das keltische Gräberfeld von Münsingen Rain 1906-1996. Schriften des Bernischen Historischen Museums 1, Bern, pp. 123–144. Münsingen/Bern, 9.-12. Oktober 1996.
Jud, P., Ulrich-Bochsler, S., 2014. Bern, Reichenbachstrasse. Die Gräber aus dem Oppidum auf der Engehalbinsel Bern. Archäologischer Dienst des Kantons Bern, Bern.
Kaenel, G., Carrard, F., Chaix, L., Curdy, P., 2004. L'oppidum du Mont Vully : un bilan des recherches 1978-2003, Fribourg. Academic Press ; Service archéologique de l'Etat de Fribourg, Fribourg.
Kaenel, G., Reginelli Servais, G., 2011. La reprise des études du site de La Tène: bilan intermédiaire. Annuaire d'Archéologie Suisse 94, 215–221.
Kaeser, M.A., 2013. La Tène, de la découverte du site à l'éponymie du second âge du Fer européen. Les prospections de Friedrich Schwab et les recherches archéologiques antérieures à la Correction des Eaux du Jura. In: Lejars, T. (Ed.), La Tène: La collection du Musée Schwab (Bienne, Suisse), pp. 21–53. Lausanne.
Knipper, C., Meyer, C., Jacobi, F., Roth, C., Fecher, M., Stephan, E., Schatz, K., Hansen, L., Posluschny, A., Höppner, B., Maus, M., Pare, C.F.E., Alt, K.W., 2014. Social differentiation and land use at an Early Iron Age "princely seat": bioarchaeological investigations at the Glauberg (Germany). J. Archaeol. Sci. 41, 818–835. https://doi.org/10.1016/j.jas.2013.09.019.
Knipper, C., Pichler, S.L., Brönnimann, D., Rissanen, H., Rosner, M., Spichtig, N., Stopp, B., Rentzel, P., Röder, B., Schibler, J., Lassau, G., Alt, K.W., 2018. A knot in a network: residential mobility at the Late Iron Age proto-urban centre of Basel-Gasfabrik (Switzerland) revealed by isotope analyses. J Archaeol Sci-Rep 17, 735–753. https://doi.org/10.1016/j.jasrep.2017.12.001.
Koch, P.L., Tuross, N., Fogel, M.L., 1997. The effects of sample treatment and diagenesis on the isotopic integrity of carbonate in biogenic hydroxylapatite. J. Archaeol. Sci. 24, 417–429. https://doi.org/10.1006/jasc.1996.0126.
Kruta, V., 1979. Duchcov-Münsingen: nature et diffusion d'une phase laténienne. In: Duval, P.M., Kruta, V. (Eds.), Les mouvements celtiques du Ve au Ier siècle avant notre ère. Actes du XXVIIIe colloque organisé à l'occasion du IXe Congrès International des Sciences Préhistoriques et Protohistoriques, pp. 81–115. Editions du C.N.R.S, Paris.
Laffranchi, Z., Cavalieri Manasse, G., Salzani, L., Milella, M., 2019. Patterns of funerary variability, diet, and developmental stress in a Celtic population from NE Italy (3rd-1st c BC). PLoS One 14, e0214372. https://doi.org/10.1371/journal.pone.0214372.
Laffranchi, Z., Milella, M., Lombardo, P., Langer, R., Lösch, S., 2021a. Co-occurrence of malignant neoplasm and Hyperostosis Frontalis Interna in an Iron Age individual from Münsingen-Rain (Switzerland): a multi-diagnostic study. International Journal of Paleopathology 32, 1–8. https://doi.org/10.1016/j.ijpp.2020.10.008.
Laffranchi, Z., De Lotto, M.B.A., Delpino, C., Lösch, S., Milella, M., 2021b. Social differentiation and well-being in the Italian Iron Age: exploring the relationship between sex, age, biological stress, and burial complexity among the Picenes of Novilara (8th-7th c. BC). Archaeol. Anthropol. Sci. 13. https://doi.org/10.1007/s12520-021-01449-3.
Laffranchi, Z., Granados-Torres, A., Lösch, S., Zink, A., Dori, I., Delgado-Huertas, A., Milella, M., 2022. "Celts" up and down the Alps. Insights on mobility patterns in the pre-Roman/Celtic population from Verona (NE Italy, 3rd-1st c. BCE): a multi-isotopic approach. American Journal of Biological Anthropology 178, 513–529. https://doi.org/10.1002/ajpa.24523.
Laffranchi, Z., Zingale, S., Indra, L., Coia, V., Garcia, D.C.S., Paladin, A., Kaeser, M.A., Delley, G., Szidat, S., Loesch, S., Zink, A., Milella, M., 2024a. Geographic origin, ancestry, and death circumstances at the Cornaux/Les Sauges Iron Age bridge, Switzerland. Sci. Rep. 14, 12180. https://doi.org/10.1038/s41598-024-62524-y.
Laffranchi, Z., Zingale, S., Tecchiati, U., Amato, A., Coia, V., Paladin, A., Salzani, L., Thompson, S.R., Bersani, M., Dori, I., Szidat, S., Loesch, S., Ryan-Despraz, J., Arenz, G., Zink, A., Milella, M., 2024b. "Until death do us part". A multidisciplinary study on human- Animal co- burials from the Late Iron Age necropolis of Seminario Vescovile in Verona (Northern Italy, 3rd-1st c. BCE). PLoS One 19, e0293434. https://doi.org/10.1371/journal.pone.0293434.
Lamb, A.L., Evans, J.E., Buckley, R., Appleby, J., 2014. Multi-isotope analysis demonstrates significant lifestyle changes in King Richard III. J. Archaeol. Sci. 50, 559–565. https://doi.org/10.1016/j.jas.2014.06.021.
Lee-Thorp, J.A., van der Merwe, N.J., 1987. Carbon isotope analysis of fossil bone apatite. South Afr. J. Sci. 83, 712–715.
Le Huray, J.D., Schutkowski, H., 2005. Diet and social status during the La Tène period in Bohemia: carbon and nitrogen stable isotope analysis of bone collagen from Kutná Hora-Karlov and Radovesice. J. Anthropol. Archaeol. 24, 135–147. https://doi.org/10.1016/j.jaa.2004.09.002.
Lightfoot, E., O'Connell, T.C., 2016. On the use of biomineral oxygen isotope data to identify human migrants in the archaeological record: intra-sample variation, statistical methods and geographical considerations. PLoS One 11 (4), e0153850. https://doi.org/10.1371/journal.pone.0153850.
Longin, R., 1971. New method of collagen extraction for radiocarbon dating. Nature 230, 241–242. https://doi.org/10.1038/230241a0.
Ma, C., Vander Zanden, H.B., Wunder, M.B., Bowen, G.J., 2020. assignR: an R package for isotope-based geographic assignment. Methods Ecol. Evol. 11 (8), 996–1001. https://doi.org/10.1111/2041-210X.13426.
Martin-Kilcher, S., 1973. Zur Tracht- und Beigabensitte im keltischen Gräberfeld von Münsingen-Rain (Kt. Bern). Zeitschrift für schweizerische Archäologie und Kunstgeschichte. Band 30, 26–39. Heft 1.
Martin-Kilcher, S., 2005. Bern-Engehalbinsel: Oppidum und Vicus Brenodurum. Funde aus einem zentralen Heiligen Platz. In: Kaenel, G., Martin-Kilcher, S., Wild, D. (Eds.), Colloquium Turicense. Siedlungen, Baustrukturen und Funde im 1. Jh.v.Chr. zwischen oberer Donau und mittlerer Rhone. Cahiers d'archéologie romande, Zürich, pp. 59–66.
Metzner-Nebelsick, C., 2019. Central Europe. In: Haselgrove, C., Rebay-Salisbury, K., Wells, P.S. (Eds.), The Oxford Handbook of the European Iron Age. Oxford University Press, Oxford, pp. 217–274.
Milella, M., Mariotti, V., Belcastro, M.G., Knusel, C.J., 2015. Patterns of irregular burials in western Europe (1st-5th century A.D.). PLoS One 10, e0130616. https://doi.org/10.1371/journal.pone.0130616.
Milella, M., Caspari, G., Laffranchi, Z., Arenz, G., Sadykov, T., Blochin, J., Keller, M., Kapinus, Y., Lösch, S., 2022. Dining in tuva: social correlates of diet and mobility in southern siberia during the 2nd-4th centuries CE. American Journal of Biological Anthropology 178, 124–139. https://doi.org/10.1002/ajpa.24506.
Moghaddam, N., Müller, F., Hafner, A., Lösch, S., 2016. Social stratigraphy in Late Iron Age Switzerland: stable carbon, nitrogen and sulphur isotope analysis of human remains from Munsingen. Archaeol. Anthropol. Sci. 8, 149–160. https://doi.org/10.1007/s12520-014-0221-4.
Moghaddam, N., Müller, F., Lösch, S., 2018. A bioarchaeological approach to the Iron Age in Switzerland: stable isotope analyses (δ13C, δ15N, δ34S) of human remains. Archaeol. Anthropol. Sci. 10, 1067–1085. https://doi.org/10.1007/s12520-016-0441-x.
Montgomery, J., 2010. Passports from the past: exploring human mobility through strontium isotope analysis of tooth enamel. Ann. Hum. Biol. 37 (3), 325–346. https://doi.org/10.3109/03014461003649297.
Müller, F., 1990. Der Massenfund von der Tiefenau bei Bern: zur Deutung latènezeitlicher Sammelfunde mit Waffen. In: Verlag Schweizerische Gesellschaft für Ur- und Frühgeschicht. Basel.
Müller, F., 1996. Latènezeitliche Grabkeramik aus dem Berner Aaretal. Jahrbuch der Schweizerischen Gesellschaft für Ur- und Frühgeschichte 76, 43–66.
Müller, F., 1998. Münsingen-Rain, ein Markstein der keltischen Archäologie. Funde, Befunde und Methoden im Vergleich. Verlag Bernisches Historisches Museum, Bern.
Müller, F., Lüscher, G., 2004. Die Kelten in der Schweiz, pp. 126–127. Stuttgart.
Nehlich, O., 2015. The application of sulfur isotope analyses in archaeological research: a review. Earth Sci. Rev. 142, 1–17. https://doi.org/10.1016/j.earscirev.2014.12.002.
Oelze, V.M., Koch, J.K., Kupke, K., Nehlich, O., Zauner, S., Wahl, J., Weise, S.M., Rieckhoff, S., Richards, M.P., 2012. Multi-isotopic analysis reveals individual mobility and diet at the Early Iron Age monumental tumulus of Magdalenenberg, Germany. Am. J. Phys. Anthropol. 148, 406–421. https://doi.org/10.1002/ajpa.22063.
Parker Pearson, M., 1999. The Archaeology of Death and Burial. Texas A&M University Press, College Station, TX.
Pauli-Gabi, T., Steiner, L.F.W., 2002. Agglomérations et urbanisme. In: Flutsch, L., Niffeler, U., Rossi, F. (Eds.), Quand la Suisse n'existait pas: le temps des Romains. La Suisse du Paléolithique à l'aube du Moyen-Âge, pp. 75–134. Basel.
Pearson, J., Evans, J., Lamb, A., Baird, D., Hodder, I., Marciniak, A., Larsen, C.S., Knusel, C.J., Haddow, S.D., Pilloud, M.A., Bogaard, A., Fairbairn, A., Plug, J.H., Mazzucato, C., Mustafaoglu, G., Feldman, M., Somel, M., Fernandez-Dominguez, E., 2023. Mobility and kinship in the world's first village societies. Proc. Natl. Acad. Sci. U. S. A. 120, e2209480119. https://doi.org/10.1073/pnas.2209480119.
Pederzani, S., Britton, K., 2019. Oxygen isotopes in bioarchaeology: principles and applications, challenges and opportunities. Earth Sci. Rev. 188, 77–107. https://doi.org/10.1016/j.earscirev.2018.11.005.
Pérez-Ramallo, P., Grandal-d'Anglade, A., Organista, E., Santos, E., Chivall, D., Rodríguez-Varela, R., Götherström, A., Etxeberria, F., Ilgner, J., Fernandes, R., Arsuaga, J.L., Le Roux, P., Higham, T., Beaumont, J., Koon, H., Roberts, P., 2022. Multi-isotopic study of the earliest mediaeval inhabitants of Santiago de Compostela (Galicia, Spain). Archaeol. Anthropol. Sci. 14. https://doi.org/10.1007/s12520-022-01678-0.
Piccirilli, E., Sorrentino, R., Lugli, F., Bortolini, E., Silvestrini, S., Cavazzuti, C., Conti, S., Czifra, S., Gyenesei, K., Kohler, K., Tanko, K., Vazzana, A., Jerem, E., Cipriani, A., Gottarelli, A., Belcastro, M.G., Hajdu, T., Benazzi, S., 2023. New insights on Celtic migration in Hungary and Italy through the analysis of non-metric dental traits. PLoS One 18, e0293090. https://doi.org/10.1371/journal.pone.0293090.
Pin, C., Briot, D., Bassin, C., Poitrasson, F., 1994. Concomitant separation of strontium and samarium Neodymium for isotopic analysis in silicate samples, based on specific extraction chromatography. Anal. Chim. Acta 298, 209–217. https://doi.org/10.1016/0003-2670(94)00274-6.
Pollard, A.M., Pellegrini, M., Lee-Thorp, J.A., 2011. Technical note: some observations onthe conversion of dental enamel δ (18) o(p) values to δ(18) o(w) to determine human mobility. Am. J. Phys. Anthropol. 504, 2007–2009. https://doi.org/10.1002/ajpa.21524.
R Core Team, 2023. R: a language and environment for statistical computing. https://www.R-project.org/.
Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Ramsey, C.B., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C., van der Plicht, J., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S.M., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The Intcal20 northern hemisphere radiocarbon age calibration curve (0-55 cal Kbp). Radiocarbon 62, 725–757. https://doi.org/10.1017/Rdc.2020.41.
Reitmaier, T., Doppler, T., Pike, A.W.G., Deschler-Erb, S., Hajdas, I., Walser, C., Gerling, C., 2018. Alpine cattle management during the bronze age at ramosch-mottata, Switzerland. Quat. Int. 484, 19–31. https://doi.org/10.1016/j.quaint.2017.02.007.

Reynard, E., 2021. Landscapes and Landforms of Switzerland, World Geomorphological Landscapes. Springer International Publishing, Cham.
Richards, M.P., 2023. Sulphur isotope ratios of archaeological human collagen as a mobility indicator. In: Price, T.D. (Ed.), Isotopic Proveniencing and Mobility. Interdisciplinary Contributions to Archaeology. Springer, Cham. https://doi.org/10.1007/978-3-031-25722-3_8.
Rozanski, K., Araguas-Araguas, L., Gonfiantini, R., 1993. Isotopic patterns in modern global precipitation. Geophys. Monogr. 78, 1–36. https://doi.org/10.1029/GM078p0001.
Rosselet-Christ, D., Goude, G., Besse, M., Honegger, M., Kottas, G., Gios, M., Desideri, J., 2024. First Swiss alpine agropastoral societies: contribution of isotope analysis to the study of their diet and mobility. J Archaeol Sci-Rep 57. https://doi.org/10.1016/j.jasrep.2024.104585.
Rousseau, E., 2012. Pratique des têtes coupées chez les gaulois : les données archéologiques. In: Boulestin, B., Henry-Gambier, D. (Eds.), Crânes trophées, crânes d'ancêtres et autres pratiques autour de la tête: problèmes d'interprétation en archéologie. Actes de la table ronde pluridisciplinaire, musée national de Préhistoire, Les Eyzies-de-Tayac (Dordogne, France), 14-16 octobre 2010, vol.2415. BAR International Series, Oxford: Archaeopress.
Scheeres, M., 2014. High Mobility Rates during the Period of the "Celtic Migrations"? 87Sr/86Sr and δ18O Evidence from Early La Tène Europe. University of Mainz.
Scheeres, M., Knipper, C., Hauschild, M., Schonfelder, M., Siebel, W., Pare, C., Alt, K.W., 2014. "Celtic migrations": fact or fiction? Strontium and oxygen isotope analysis of the Czech cemeteries of Radovesice and Kutna Hora in Bohemia. Am. J. Phys. Anthropol. 155, 496–512. https://doi.org/10.1002/ajpa.22597.
Scheeres, M., Knipper, C., Hauschild, M., Schönfelder, M., Siebel, W., Vitali, D., Pare, C., Alt, K.W., 2013. Evidence for "Celtic migrations"? Strontium isotope analysis at the early La tene (LT B) cemeteries of nebringen (Germany) and Monte Bibele (Italy). J. Archaeol. Sci. 40, 3614–3625. https://doi.org/10.1016/j.jas.2013.05.003.
Schönfelder, M., 2024. Celtic migrations and the spread of La Tène Culture. Archeol. Rozhl. 76, 97–113. https://doi.org/10.35686/ar.2024.5.
Sheather, S.J., Jones, M.C., 1991. A reliable data-based bandwidth selection method for kernel density estimation. J. Roy. Stat. Soc. B 53, 683–690. https://doi.org/10.1111/j.2517-6161.1991.tb01857.x.
Sjogren, K.G., Olalde, I., Carver, S., Allentoft, M.E., Knowles, T., Kroonen, G., Pike, A.W. G., Schroter, P., Brown, K.A., Brown, K.R., Harrison, R.J., Bertemes, F., Reich, D., Kristiansen, K., Heyd, V., 2020. Kinship and social organization in Copper Age Europe. A cross-disciplinary analysis of archaeology, DNA, isotopes, and anthropology from two Bell Beaker cemeteries. PLoS One 15, e0241278. https://doi.org/10.1371/journal.pone.0241278.
Sorrentino, R., Bortolini, E., Lugli, F., Mancuso, G., Buti, L., Oxilia, G., Vazzana, A., Figus, C., Serrangeli, M.C., Margherita, C., Penzo, A., Gruppioni, G., Gottarelli, A., Jochum, K.P., Belcastro, M.G., Cipriani, A., Feeney, R.N.M., Benazzi, S., 2018. Unravelling biocultural population structure in 4th/3rd century BC Monterenzio Vecchio (Bologna, Italy) through a comparative analysis of strontium isotopes, non-metric dental evidence, and funerary practices. PLoS One 13, e0193796. https://doi.org/10.1371/journal.pone.0193796.
Sparacello, V.S., 2013. The Bioarchaeology of Changes in Social Stratification, Warfare, and Habitual Activities Among Iron Age Samnites of Central Italy. The University of New Mexico.
Sparacello, V.S., Vercellotti, G., d'Ercole, V., Coppa, A., 2017. Social reorganization and biological change: an examination of stature variation among Iron Age Samnites from Abruzzo, central Italy. Int J Paleopathol 18, 9–20. https://doi.org/10.1016/j.ijpp.2017.07.003.
Stähli, B.S., 1977. Die Latène-Gräber von BernStadt. In: Schriften des Seminars für Urgeschichte der Universität Bern, vol. 3. Bern.
Stantis, C., Schaefer, B.J., Correia, M.A., Alaica, A.K., Huffer, D., Plomp, E., Di Giusto, M., Chidimuro, B., Rose, A.K., Nayak, A., Kendall, E.J., 2024. Ethics and applications of isotope analysis in archaeology. American Journal of Biological Anthropology, e24992. https://doi.org/10.1002/ajpa.24992.
Staudinger, M., Seeger, S., Herbstritt, B., Stoelzle, M., Seibert, J., Stahl, K., Weiler, M., 2020. The CH-IRP data set: a decade of fortnightly data on δ^2H and δ^{18}O in streamflow and precipitation in Switzerland. Earth Syst. Sci. Data 12, 3057–3066. https://doi.org/10.5194/essd-12-3057-2020.
Stöckli, W.E., 1975. Chronologie der Jüngeren Eisenzeit im Tessin. In: Verlag Schweizerische Gesellschaft für Ur- und Frühgeschicht. Basel.
Szidat, S., Vogel, E., Gubler, R., Lösch, S., 2017. Radiocarbon dating of bones at the LARA laboratory in bern, Switzerland. Radiocarbon 59, 831–842. https://doi.org/10.1017/Rdc.2016.90.
Tanner, A., 1980. Das Latènegräberfeld von Trun-Darvella. Historisch-Archäologischer Verlag, Zürich.
Tomaschitz, K., 2002. Die Wanderungen der Kelten in der antiken literarischen Überlieferung. In: Verlag der Österreichischen Akademie der Wissenschaften. Wien.
Tornero, C., Balasescu, A., Ughetto-Monfrin, J., Voinea, V., Balasse, M., 2013. Seasonality and season of birth in early Eneolithic sheep from Cheia (Romania): methodological advances and implications for animal economy. J. Archaeol. Sci. 40, 4039–4055. https://doi.org/10.1016/j.jas.2013.05.013.
Trémeaud, C., 2018. Genre et hiérarchisation dans le monde nord-alpin, aux âges du Bronze et du Fer, vol.2912. BAR International Series, Oxford.
Van Hear, N., Bakewell, O., Long, K., 2017. Push-pull plus: reconsidering the drivers of migration. J. Ethnic Migrat. Stud. 44, 927–944. https://doi.org/10.1080/1369183x.2017.1384135.
Varalli, A., Desideri, J., David-Elbiali, M., Goude, G., Honegger, M., Besse, M., 2021. Bronze Age innovations and impact on human diet: a multi-isotopic and multi-proxy study of western Switzerland. PLoS One 16, e0245726. https://doi.org/10.1371/journal.pone.0245726.
Velte, M., Czermak, A., Grigat, A., Haas-Gebhard, B., Gairhos, A., Toncala, A., Trautmann, B., Haberstroh, J., Paffgen, B., von Heyking, K., Lösch, S., Burger, J., Harbeck, M., 2023. Between Raetia Secunda and the dutchy of Bavaria: exploring patterns of human movement and diet. PLoS One 18, e0283243. https://doi.org/10.1371/journal.pone.0283243.
Viollier, D., 1912. Fouille exécutées par les soins du Musée National. VII. Le cimetière gallo-helvète d'Andelfingen (Zurich). Indicateur d'antiquités suisses: Nouvelle série 14, 16–57. https://doi.org/10.5169/seals-158989.
Vitali, D., 1996. Celtes cisalpins, celtes transalpins: quelques réflexions sur le rôle de I'ltalie du nord dans I'origine des oppida. In: Groenen, M. (Ed.), La Préhistoire au Quotidien. Melánges offerts à Pierre Bonenfant. Millon J., Grenoble, pp. 323–345.
Vitali, D., 2011. I Celti in Italia tra scambi e movimenti migratori. In: Marzatico, F., Gebhard, R., Glairscher, P. (Eds.), Le grandi vie della civiltà, relazioni e scambi fra il Mediterraneo ed il centro Europa dalla Preistoria alla Romanità, Castello del Buonconsiglio, Trento, pp. 287–289.
Vitali, D., Kaenel, G., 2000. Un Helvète chez les Etrusques vers 300 av. J.-C., ArS 23, 115–122.
Vytlačil, Z., Danielisová, A., Velemínský, P., et al., 2024. Dietary changes seen through the isotope analysis of the La Tène burial site of Prosmyky (Bohemia, 4th-3rd century BCE). Archaeol. Anthropol. Sci. 16, 86. https://doi.org/10.1007/s12520-024-01994-7.
Waldhauser, J., 1998. Die Goldfingerringe von Münsingen-Rain und ihre Vergleichsstücke aus Flachgräberfeldern im Gebiet zwischen dem schweizerischen Mittelland und dem Karpatenbecken. In: Müller, F. (Ed.), Münsingen-Rain, ein Markstein der keltischen Archäologie. Funde, Befunde und Methoden im Vergleich. Akten Internationales Kolloquium «Das keltische Gräberfeld von Münsingen Rain 1906-1996», Münsingen/Bern. Schriften des Bernischen Historischen Museums 1, Bern, pp. 85–122, 9.-12. Oktober 1996.
Webley, L., 2018. Households and communities. In: Haselgrove, C., Rebay-Salisbury, K., Wells, P.S. (Eds.), The Oxford Handbook of the European Iron Age. Oxford University Press, Oxford, pp. 693–716.
Wright, L.E., 2005. Identifying immigrants to Tikal, Guatemala: defining local variability in strontium isotope ratios of human tooth enamel. J. Archaeol. Sci. 32 (4), 555–566, 1016/j.jas.2004.11.011.
Zingale, S., Laffranchi, Z., Paladin, A., Meiseleder, L., Lösch, S., Arenz, G., Salzani, L., Dori, I., Müller, F., Haussener, V., Kaeser, M.A., 2023. Reconstructing the genetic history of the Late Iron Age "Celtic" groups from north and south of the Alps (4th-1st century BCE) (CELT. UD ALPS). Am J Biol Anthropol 180, 202. https://doi.org/10.1002/ajpa.24731.