



Diet, mobility and gendered violence: Integrating multi-isotope analysis with proteomic sex identification at the bi-ritual Early Iron Age cemetery of Statzendorf, lower Austria

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ABSTRACT

The Early Iron Age cemetery of Statzendorf (c. 800–400 BCE), which at discovery contained 376 burials of both cremated and inhumed individuals, offers a unique opportunity to integrate analytical approaches for these distinct burial practices. This study presents a multi-method analysis of human remains, integrating osteological, proteomic, radiocarbon, and multi-isotope data. The analysis of amelogenin peptides in 25 inhumed individuals enhanced the accuracy of sex determination, refining and correcting osteological assessments. The same and neighbouring teeth to the ones analysed for peptides were used to obtain 55 samples for isotope analysis, ensuring a securely sex-linked dataset. The analyses include carbon ($\delta^{13}\text{C}$), oxygen ($\delta^{18}\text{O}$) and strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$), and strontium concentrations ([Sr]), from dental enamel, and cremated bone. Significant differences in strontium isotope ratios were observed between males and females, alongside a correlation between strontium concentrations and social status. Women and girls were also disproportionately affected by interpersonal violence. The carbon isotope values of dental enamel revealed dietary differences, indicating that some individuals consumed more animal protein and C_4 plants, such as millet. Food sources were predominantly local, reflecting the geological variation between the lowlands of the Traisen Valley and the surrounding hilly landscape. The subtle, but notable dietary variability among individuals buried at Statzendorf suggests the emergence of social stratification and increasing social complexity during the Early Iron Age in Central Europe. This study demonstrates the potential of combining cutting-edge bioarchaeological methods to analyse cremated and skeletal human remains, providing valuable insights into the lifeways, dietary practices, and mobility of an Early Iron Age community in Austria.

1. Introduction

Analyses of human remains have offered important insights into the lives of prehistoric people, including patterns of gender differentiated

practices such as diet, migration and violence. However, the methods applied to inhumed and cremated skeletal remains differ substantially, as exposure to high temperatures during cremation changes the biochemical composition of the surviving human remains. This has

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limited the comparability between case studies and chronological periods that primarily contain inhumations or cremations.

In recent years, advances in bioarchaeological science have significantly improved the reconstruction of individuals' lifeways, whether they were buried or cremated (e.g. Cavazzuti et al. 2021, Veselka & Snoeck 2021, Waltenberger et al. 2023). Proteomic sex estimation from dental enamel has improved the accuracy of sexing in inhumations of all ages (e.g. Gowland et al. 2021, Rebay-Salisbury et al. 2025, Rebay-Salisbury et al. 2022), and it has been demonstrated that strontium isotope analysis and radiocarbon dating are also applicable to cremated remains once adequately pre-treated (e.g. Harbeck et al. 2011, Lanting & Brindley 1998, Snoeck et al. 2015, Van Strydonck et al. 2005). In this article, we combine several cutting-edge methodologies for insights into an Early Iron Age community in Austria that inhumed as well as cremated their dead.

The cemetery of Statzendorf, which has been fundamental in the early Iron Age literature for more than 100 years (Bayer 1904, Dungal 1908), exemplifies the challenges of comparing inhumations and cremations. Eponymous to the Statzendorf-Gemeinlebarn group of the eastern Hallstatt Culture (Pittioni 1954: 176), the cemetery was excavated between 1902 and 1925, and yet, findings were only fully publicized in 2006 (Rebay 2006). The excavation followed a trench-digging approach, but the documentation of the cemetery excavation was progressive for the time. The location of each grave was mapped, and the drawing shows the outline of the vessels and large stones. Some of the burials were photographed.

The cemetery of Statzendorf comprises 373 graves with 376 depositions of human remains of both inhumed and cremated individuals. The majority of the dead were cremated and scattered in the grave pit or placed in urns (Fig. 1). Around a tenth of the burials were inhumations, distributed over the entire cemetery area. The orientation of the dead does not appear to follow any fixed rules, and bodies were placed in supine position or were lying flexed on their sides (Fig. 2).

About a quarter of the graves were lined or covered with stones, and the dead were usually equipped with several vessels that were part of an extensive set of drinking and dining dishes. The most common ceramic types are handled pots, bowls, cups, and large conical necked vessels, but unusual shapes like cists and triple vessels also occur; the ceramic decoration includes creative plastic elements, white, red, black and graphite colours as well as geometrical patterns. Meat offerings were evidenced by animal bones. Bronze and iron costume items and jewellery such as dress pins, fibulae, bracelets and necklaces, belts and rings are also part of the funerary assemblages. Gendered objects include ceramic spindle whorls, which are frequently associated with female burials, as well as iron axes, lance heads and a horse harness, which are rare and typical for male burials (Rebay 2006: 160).



Fig. 1. Cremation burial D018 in situ (Photo: Prehistoric Department of the Natural History Museum, Vienna).



Fig. 2. Inhumation of a 14–16-year-old girl B104 in situ (Photo: Prehistoric Department of the Natural History Museum, Vienna).

A comprehensive publication of the archaeological documentation and materials held in the Natural History Museum in Vienna and the collection of the Herzogenburg monastery focused on differences in the burial ritual and grave equipment to reveal status differences (Rebay 2006). However, questions regarding individual life histories, gender, mobility and absolute dating remained.

In addition to establishing new osteological profiles for the available human remains, we sampled cremations and inhumations for radiocarbon dating. Inhumed individuals with dental remains were subjected to ultra-high-performance liquid chromatography-high-resolution mass spectrometry (UHPLC-HRMS) to securely identify sex-specific peptides, a proteomic method only applicable to skeletal remains that have not been exposed to the heat of cremation. Carbon, oxygen and strontium isotopes as well as strontium concentrations were measured in the enamel of up to three teeth per individual to gain a sex-specific set of measurements across an individuals' development. In cremations, we measured strontium isotope ratios and concentrations on fully calcined bone fragments. The approach aimed to clarify if cremated and inhumed individuals date to the same chronological period, if they can be considered a population of the same dietary and mobility history, and if gender was a factor in burial choices.

2. Materials and methods

In the early 20th century, the excavation focused on collecting artefacts for museum display, and the recovery of human remains was limited and highly selective. Today, the Anthropology Department of the Natural History Museum in Vienna holds skulls and only a few post-cranial bones from the inhumations, along with 16 inventory numbers of

cremated human remains, most of which have insufficient weight to allow for sampling. Our analysis was therefore limited by the availability of preserved human remains.

2.1. Osteology

Sampling for strontium isotope analysis and radiocarbon dating necessitated a re-analysis of an earlier osteological assessment (Renhart 2006) of the preserved human remains of Statzendorf at the Natural History Museum in Vienna (Appendix).

The osteological re-evaluation of inhumations included 26 individuals inventoried under 23 numbers: B133 had been recorded as a consecutive burial with two individuals, and both A089 and C077 included the dental remains of a second individual. Age estimations were corrected using tooth development and eruption (AlQahtani et al. 2010, Ubelaker 1987), the iliac auricular surface (Buckberry & Chamberlain 2002, Lovejoy et al. 1985, Osborne et al. 2004), the ossification of epiphysis (Schaefer et al., 2009), and the 'combined method', assessing and scoring ectocranial suture closure and dental wear (Acsádi & Nemeskéri 1970, Miles 2001, Rösing 1977). Body stature was estimated using separate formulae for males and females (Ruff et al. 2012). Pathological conditions and traumatic lesions on skeletal and dental remains were recorded (Grupe et al. 2015, Steckel et al. 2018) to provide insights into the overall health and possible environmental conditions experienced by the population of Statzendorf. Non-specific stress indicators such as cribra orbitalia, porotic hyperostosis, sinusitis, pleurisy and periostitis as well as, endocranial lesions were included. In this context dental and periodontal diseases (e.g. carious lesion, calculus, linear enamel hypoplasia (LEH), periapical lesion, intravital tooth loss) were also noted (Walker et al. 2009). To identify interpersonal violence, the traumatic lesions on the skeletons were recorded regarding the location, the shape and size of the trauma, as well as the timing, to distinguish between ante-mortem, peri-mortem and post-mortem lesions (Lovell 1997, Ortner 2003).

The analysis of 11 assemblages of cremated human remains attributable to grave contexts followed the guidelines of British Association for Biological Anthropology and Osteoarchaeology (Brickley & McKinley 2004), individually separating the anatomical areas of the cranium, thorax, pelvis, upper limbs, lower limbs, and unidentifiable long bone fragments. The total bone weight and the weight of the individual anatomical regions were recorded. Cremation temperatures were estimated based on colour (Wahl 1981). Sex estimation was performed based on morphological criteria following Ferembach et al. (1979), Phenice (1969), and Walker (2008), as well as metric analyses, using an adapted version of the method published by Cavazzuti et al. (2019). Age at death was estimated based on tooth eruption (AlQahtani et al. 2010), degenerative changes to the iliac auricular surface (Buckberry & Chamberlain 2002, Lovejoy et al. 1985, Osborne et al. 2004), transitional analysis (Boldsen et al. 2002), and the ossification and fusion of epiphyses (Schaefer et al. 2009).

2.2. Peptide-based sex identification

The analysis of sexually dimorphic amelogenin fragments in human dental enamel by mass spectrometry is increasingly gaining traction as a highly accurate sex estimation method in anthropology and archaeology (Buonasera et al. 2020, Madupe et al. 2025, Parker et al. 2019, Stewart et al. 2017). The method is particularly useful for sub-adult individuals (Gowland et al. 2021, Rebay-Salisbury et al. 2022), incompletely preserved skeletons, and ambiguous morphological cases (Rebay-Salisbury et al. 2025). Samples for peptide-based sex identification were taken from 25 inhumed individuals, sampling the same teeth as for isotope analysis. This not only ensures the preservation of the remaining dental surface, but also links $^{87}\text{Sr}/^{86}\text{Sr}$ ratios securely to sex, allowing inferences about gendered mobility. The identification of sex-specific peptides (Supp. Table 1) took place by ultra-high-performance liquid

chromatography-high-resolution mass spectrometry (UHPLC-HRMS), following the peptide extraction protocol described in Rebay-Salisbury et al. (2025), adapted from Stewart et al. (2017). The sampling procedure differs from that used for isotope analysis, as no enamel powder is required. Instead, it involves acid-etching a 2×2 mm area of preserved enamel, which is minimally invasive and leaves no macroscopically visible damage to the teeth.

2.3. Radiocarbon dating

Despite the well-known difficulties associated with the Hallstatt Plateau, which make it impossible to date any sample more precisely than between c. 750 and 400 BCE (Fahrni et al. 2020, Rose et al. 2022), we hypothesised that some graves may fall into the Urnfield-Hallstatt and/or the Hallstatt-LaTène transitional period. To anchor the relative sequence in an absolute timeframe, samples were selected for their location within the cemetery and their association with material culture in the graves (A061, B142, C017, C063). The samples were chemically pretreated and prepared by the Higham Lab, University of Vienna (Brock et al. 2010, Higham et al. 2006), and measured at the VERA (Vienna Environmental Research Accelerator) AMS facility, University of Vienna (Golser & Kutschera 2017, Steier et al. 2017). Due to scheduling constraints, one sample was measured at the Keck AMS facility, University of California at Irvine (Beverly et al. 2010, Santos et al. 2007).

Sampling cremated human remains for radiocarbon dating was limited to well represented individuals with more than 40 g weight and complete calcination. This only applied to the individuals D017, D018, D019 and D020 from the south-western area of the cemetery. Since the carbon in human bone undergoes an exchange process with carbon from wood from the funerary pyre, the C14 date likely refers to a mixed signal from the human body and the firing wood, including a possible old-wood effect (Capuzzo et al. 2023, Olsen et al. 2012, Snoeck et al. 2014). Radiocarbon dates of cremated human remains were measured at the Royal Institute for Cultural Heritage at Brussels, following the pre-treatment protocols for AMS dating at the Royal Institute for Cultural Heritage (RICH) by Boudin et al. (2015), Van Strydonck et al. (2005) and Wojcieszak et al. (2020). Radiocarbon dates were calibrated using OxCal 4.4.4 (Bronk Ramsey 2009) and the INTCAL curve (Reimer et al. 2020).

2.4. Isotope analysis

Isotope analysis of carbon ($\delta^{13}\text{C}$), oxygen ($\delta^{18}\text{O}$) and strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) were conducted in 55 enamel samples from 23 inhumed individuals. We aimed at sampling three teeth per individual to achieve an optimal coverage of signals across all age ranges to adulthood (Knipper 2011: 132), and were able to do so in 12 individuals. However, in four individuals, only one tooth was available and in seven individuals, two teeth could be sampled. These included two deciduous second molars, and 53 permanent teeth comprising three canines, 18 first molars, 17 second molars, and 15 third molars (Table 1). Four bone samples were taken from cremation burials D017, D018, D019 and D020, using the same fragments as for radiocarbon dating to ensure the isotope and radiocarbon dating results obtained belong to the same individual (Sabaux et al. 2024).

In tooth enamel, carbon isotopes ($\delta^{13}\text{C}$) reflect dietary intakes (Lee-Thorp 2008) while oxygen isotopes ($\delta^{18}\text{O}$) relate mostly to the origin of the drinking water (Luz et al. 1984, Podlesak et al. 2008). In cremation, carbon and oxygen isotope ratios are linked to pyre conditions (Salesse et al. 2021, Stamataki et al. 2021, Stamataki et al. 2025). The analyses were carried out at the Archaeology, Environmental Changes & Geo-Chemistry Research Group (AMGC) at the Vrije Universiteit Brussel (VUB) on a Nu Perspective from Nu Instruments following the protocols by Spros et al. (2025) for tooth enamel and by Stamataki et al. (2021, 2025) for cremated bone fragments.

Enamel was sampled from the crowns in a vertical stripe using a low-speed drill with diamond-coated drill bits. Prior to sampling, adhering

Table 1
Isotope analyses from Statzendorf.

Grave	VUB Number	Sex	Age	Social index	Violence	Tooth (FDI)	Tooth / bone element	$^{87}\text{Sr}/^{86}\text{Sr}$	2SE	$\delta^{13}\text{C}$ (VPDB-‰)	$\delta^{18}\text{O}$ (VPDB-‰)	$\delta^{88}\text{Sr}$ (‰)
A061	STA09M1	female	25–30	71	no	16	M1	0.709435	0.000009	−15.1	−7.5	−0.438
A061	STA09M2	female	25–30	71	no	17	M2	0.709415	0.000009	−14.5	−8.7	−0.465
A061	STA09M3	female	25–30	71	no	18	M3	0.709982	0.000010	−14.4	−7.8	−0.426
A067	STA12C	female	30–40	9	no	23	C	0.710318	0.000010	−13.8	−6.8	−0.442
A067	STA12M1	female	30–40	9	no	26	M1	0.710225	0.000008	−12.6	−6.3	−0.393
A068	STA06M1	female	25–35	39	no	36	M1	0.711918	0.000007	−10.3	−6.3	−0.548
A068	STA06M2	female	25–35	39	no	37	M2	0.712704	0.000009	−10.4	−5.7	−0.435
A068	STA06M3	female	25–35	39	no	38	M3	0.712610	0.000010	−10.9	−6.2	−0.407
A070	STA11M1	male	17–21	0	no	16	M1	0.709826	0.000009	−12.3	−6.5	−0.410
A070	STA11M2	male	17–21	0	no	17	M2	0.709760	0.000007	−12.6	−6.9	−0.436
A070	STA11M3	male	17–21	0	no	48	M3	0.709426	0.000010	−12.3	−7.4	−0.410
A089	STA04C	female	30–40	22	yes	43	C	0.710707	0.000009	−10.6	−5.4	−0.479
A089	STA04M1	female	30–40	22	yes	46	M1	0.711136	0.000010	−11.4	−5.1	−0.511
A090	STA01M1	male	35–45	4	no	36	M1	0.710082	0.000007	−12.7	−5.5	−0.398
A090	STA01M2	male	35–45	4	no	37	M2	0.710150	0.000007	−11.0	−6.2	−0.321
A090	STA01M3	male	35–45	4	no	38	M3	0.710427	0.000007	−11.5	−6.3	−0.449
A094	STA05M2	male	40–50	30	no	27	M2	0.710035	0.000011	−13.8	−8.6	−0.500
A094	STA05M3	male	40–50	30	no	18	M3	0.710398	0.000010	−10.9	−6.4	−0.498
A110	STA14M1	female	30–40	19	yes	46	M1	0.709619	0.000008	−14.0	−5.1	−0.445
A110	STA14M2	female	30–40	19	yes	47	M2	0.709622	0.000007	−13.5	−5.7	−0.456
A112	STA07M1	male	30–35	0	no	46	M1	0.708894	0.000008	−13.8	−6.1	−0.501
A112	STA07M2	male	30–35	0	no	47	M2	0.708609	0.000009	−12.7	−5.7	−0.538
A112	STA07M3	male	30–35	0	no	48	M3	0.708826	0.000009	−13.3	−6.4	−0.530
A113	STA08M1	female	35–45	0	yes	36	M1	0.708778	0.000008	−14.3	−5.7	−0.575
A113	STA08M2	female	35–45	0	yes	37	M2	0.708627	0.000011	−13.5	−6.3	−0.610
A113	STA08M3	female	35–45	0	yes	38	M3	0.708738	0.000010	−13.7	−6.8	−0.517
A119	STA03M2	female	25–35	0	no	27	M2	0.710175	0.000008	−11.5	−5.9	−0.380
A119	STA03M3	female	25–35	0	no	18	M3	0.710130	0.000009	−12.0	−6.6	−0.432
B104	STA20M1	female	14–16	10	yes	46	M1	0.710359	0.000018	−15.8	−7.9	−0.244
B104	STA20M2	female	14–16	10	yes	47	M2	0.709966	0.000008	−11.8	−6.2	−0.317
B133	STA19M1	male	23–30	37	no	36	M1	0.709593	0.000016	−12.2	−5.8	−0.520
B133	STA19M2	male	23–30	37	no	37	M2	0.709461	0.000009	−13.1	−7.2	−0.426
B133	STA19M3	male	23–30	37	no	38	M3	0.710116	0.000009	−9.2	−7.8	−0.487
B139	STA10M1	male	31–40	37	no	36	M1	0.710303	0.000014	−11.6	−5.7	−0.388
B139	STA10M2	male	31–40	37	no	37	M2	0.710266	0.000011	−11.5	−6.2	−0.398
B139	STA10M3	male	31–40	37	no	38	M3	0.710052	0.000008	−12.1	−6.7	−0.393
B142	STA13M1	female	35–45	39	no	36	M1	0.710730	0.000013	−11.7	−5.9	−0.397
B142	STA13M2	female	35–45	39	no	37	M2	0.710554	0.000009	−11.8	−6.4	−0.372
B142	STA13M3	female	35–45	39	no	38	M3	0.710278	0.000009	−13.0	−6.9	−0.312
C001	STA02M1	female	25–30	90	yes	16	M1	0.710649	0.000009	−11.4	−6.1	−0.406
C001	STA02M2	female	25–30	90	yes	17	M2	0.710444	0.000012	−13.7	−7.4	−0.437
C001	STA02M3	female	25–30	90	yes	18	M3	0.711095	0.000018	−11.6	−6.3	−0.325
C016	STA16M1	female	19–30	10	yes	26	M1	0.710810	0.000009	−11.7	−5.8	−0.520
C016	STA16M2	female	19–30	10	yes	27	M2	0.710744	0.000010	−11.6	−6.0	−0.525
C016	STA16M3	female	19–30	10	yes	38	M3	0.711253	0.000009	−11.9	−6.5	−0.452
C017	STA17M1	male	19–25	20	no	36	M1	0.709519	0.000007	−11.5	−6.3	−0.503
C017	STA17M2	male	19–25	20	no	17	M2	0.709507	0.000010	−12.3	−7.2	−0.541
C017	STA17M3	male	19–25	20	no	18	M3	0.709555	0.000015	−10.8	−6.8	−0.548
C046	STA22m2	female	3–4	59	no	55	m2	0.710949	0.000012	−12.5	−5.3	−0.526
C066	STA23m2	female	5–6	20	no	55	m2	0.710788	0.000016	−13.4	−6.1	−0.442
C073	STA21M1	female	6–7	21	yes	16	M1	0.710683	0.000013	−12.2	−5.8	−0.388
C077	STA18C	female	35–45	6	no	43	C	0.710346	0.000011	−11.6	−5.5	−0.431
C078	STA15M1	female	35–45	21	yes	46	M1	0.709924	0.000010	−12.5	−6.0	−0.379
C078	STA15M2	female	35–45	21	yes	47	M2	0.710188	0.000007	−12.1	−6.8	−0.299
C078	STA15M3	female	35–45	21	yes	48	M3	0.710375	0.000007	−11.2	−6.9	−0.435
D017	MF210	–	20+	14	no	cremation	tibia	0.710572	0.000011	−20.1	−15.9	−0.374
D018	MF208	–	20+	29	no	cremation	tibia	0.711033	0.000027	−17.8	−16.3	−0.583
D019	MF211	–	20+	18	no	cremation	humerus	0.711414	0.000029	−20.7	−18.1	−0.585
D020	MF209	–	20+	22	no	cremation	diaphysis	0.711013	0.000019	−22.3	−19.8	−0.443

soil and possible diagenetic contaminants were removed following the procedure described by de Winter et al. (2019). The enamel powder was then pre-treated for 30 min using 0.1 M acetic acid and rinsed three times with milliQ water before being left to dry in an oven at 50 °C overnight (Pellegrini and Snoeck 2016). Approximately 1 mg of pre-treated tooth enamel was analyzed using a Nu Perspective Isotope Ratio Mass Spectrometer (IRMS) equipped with a NuCarb carbonate preparation device at the Vrije Universiteit Brussel (VUB, Brussels, Belgium). The internal standard CBA was employed (see de Winter et al. 2016), along with reference materials Iso-Analytical IA-R022 and the international standards IAEA-CO-8, IAEA-603, and NBS-18. Repeated

measurements of CBA indicate that the reproducibility errors for both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values are less than 0.3‰ (1SD). The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ results are reported relative to the international Vienna Pee Dee Belemnite (VPDB) standard. For cremated bone fragments, the samples were mechanically cleaned and then pre-treated using 1 M acetic acid and ultrasounds following Snoeck et al. (2015) and Stamataki et al. (2021, 2025). Pre-treated bone powder (30 mg; ~15 mg per duplicate) was analysed for carbon and oxygen isotopes following Stamataki et al. (2021). Samples were flushed with helium, reacted with phosphoric acid to release CO_2 , and measured using a Nu Perspective IRMS coupled with a GasPrep system at AMGC. Calibration used standards IA-R022, IAEA-

603, and IAEA-CO8. Analytical precision was better than $\pm 0.30\%$ for $\delta^{13}\text{C}$ and $\pm 0.40\%$ for $\delta^{18}\text{O}$.

Strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios reflect the geological signature of the region where an individual sourced their diet and lived their life (Bentley 2006). Strontium is incorporated in dental enamel during tooth formation (Montgomery 2010), and in bones during growth and remodelling (Budd et al. 2000), encompassing the entire lifespan (Cavazzuti et al. 2021, Frère et al. 2025). Compared to the local baseline (see Fritzl et al. 2024), these data give insights into possible origins and mobility. Strontium isotope and concentration analyses of cremated human remains and dental enamel were undertaken at AMGC, VUB, on a Nu Plasma 3 following the protocol detailed by (Boonants et al. 2025, Gerritzen et al. 2024, Snoeck et al. 2015).

Approximately 10 mg of pre-treated tooth enamel and calcined bone powder was transferred into a Teflon beaker and dissolved in 1 mL of 14 M subboiled HNO_3 . After complete dissolution, the samples were left to dry overnight on a hotplate at approximately 100 °C. For plant samples, 280 mg of material was initially digested using a Milestone UltraWAVE microwave system with 4 mL of 14 M HNO_3 and 0.5 mL of HF. Following digestion, 0.5 mL of H_2O_2 was added, and the solution was then evaporated to dryness. The strontium of the digested enamel samples and plants was extracted and purified through column chemistry using ion exchange resin (Sr-Spec, Triskem), following the protocol described in Gerritzen et al. 2024, Snoeck et al. 2015. In short, the columns and resin were rinsed with two full reservoirs of 2 M HNO_3 , followed by conditioning in 2 x 1 mL 7 M HNO_3 . Samples were loaded in four steps of 0.5 mL 7 M HNO_3 , the matrix is extracted with 5 x 1 mL of 7 M HNO_3 , and finally Sr was eluted and collected with 6 x 1 mL of 0.05 M HNO_3 . The samples were then left to dry prior to analyses on a Nu Plasma 3 MC-ICP-MS (PD017 from Nu Instruments). During this study, repeated measurements of the NIST SRM987 standard yielded $^{87}\text{Sr}/^{86}\text{Sr} = 0.710249 \pm 0.000022$ (2SD; $n = 11$), which is consistent with the mean value of 0.710252 ± 13 (2SD for 88 analyses) obtained by TIMS (Thermal Ionization Mass Spectrometry) instrumentation (Weis et al. 2006). All the sample measurements were normalised using a sample-standard bracketing method with the recommended value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.710248$ (Weis et al. 2006). Procedural blanks were considered negligible (total Sr (V) of max 0.03 V versus 10 V for analyses, i.e. $\approx 0.3\%$). For each sample the $^{87}\text{Sr}/^{86}\text{Sr}$ value is reported with a 2SE error (absolute error value of the individual sample analysis – internal error). During the course of these analyses the matrix matched standards NIST SRM1400 (bone ash) was used and returned mean $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.713128 ± 0.000040 (2SD; $n = 15$). This value is close to the long term $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.713117 ± 0.000031 (2SD; $n = 345$) obtained by Gerritzen et al. (2024). Strontium concentrations ([Sr]) were obtained on the same instrument by comparing the voltage for ^{88}Sr of each sample to the ^{88}Sr voltage of a 300 ppb [Sr] solution of NIST SRM987 (Boonants et al. 2025). A simple Rule of Three was then applied to obtain the [Sr] of the samples. The precision and accuracy of the [Sr] analyses were validated against certified standard SRM NIST 1400.

3. Results

3.1. Peptide-based sex identification

The identification of chromosomal sex by amelogenin peptides in dental enamel supplemented and corrected previous morphological sex estimates (Renhart 2006). All 25 samples analysed by mass spectrometry met the quality control threshold (Supp. Table 2) and produced reliable results (Table 3). The sex of 13 individuals (52%) was confirmed, the sex of 6 (24%) was newly identified, and the sex of another 6 (24%) was corrected. The raw mass spectrometric data were uploaded to the MassIVE repository under the accession number MSV000100046.

The four inhumed children, who were aged between three and seven at the time of their deaths, were all identified as female (C046, C066,

C073 and C077/2). C046 was found in a double grave with a stone cover. This grave contained cremated remains in an urn, as well as the east–west inhumation of a 3–4-year-old in a supine position with slightly flexed legs to the right. The ceramic assemblage from this grave includes six miniature vessels (Fig. 3). The supine inhumation of a 5–6-year-old female in Grave C066, oriented north-west to south-east and partially covered by stones, was not associated with any material culture. The 6–7-year-old female from Grave C073 was placed in a similar body position with a pair of bronze arm rings, a ceramic cup, two ceramic bowls, a handled pot, and a conical-necked vessel. The remains of a four-year-old child, recorded under the same inventory number as C077, were also identified as female.

The sex of two adult individuals was newly identified (A089/2, B133/2) and the sex of six individuals was corrected (male to female: A068, A110, A113, C077/1, C078; female to male: A094). Indeed, the grave goods in Grave A068 (an iron knife, bronze and iron fragments, animal bones, a ceramic cup, three ceramic bowls, a handled pot, a conical-necked vessel and two spindle whorls, Fig. 4) are more consistent with the identification of the 25–35-year-old individual as female than as male. Grave A089 included a 30–40-year-old individual (A089/1), and an extra mandible (A089/2) of a 35–45-year-old female that we were able to sex. The grave goods in this grave — a ceramic cup, two ceramic bowls, ceramic pot and four spindle whorls – indicate female occupants. The sex assessment of the individual in Grave A094, a 40–50-year-old north–south oriented individual in right flexed position, was corrected from female to male. He was buried with an iron knife, meat offerings, four conical-necked vessels, three ceramic cups and four ceramic bowls. The 30–40-year-old individual A110, who was also buried in a supine position with an east–west orientation, was identified as female. The bronze arm ring, conical-necked vessel, ceramic cup and Kalenderberg vessel found in the grave do not contradict this sex assessment (Fig. 5). The individual from Grave A113, a 35–45-year-old female buried in a slightly flexed position on her right side, was found in a south-southeast–north-northwest orientation with no grave goods. B104, a 14–16-year old female individual, was placed in supine position with an iron and bronze arm ring, six ceramic vessels, including a Kalenderberg jug, and a spindle whorl. The skull of the adolescent shows traces of multiple surgical interventions. Grave B133 held two consecutive burials: a male aged 23–30 in a supine position with a south-east–northwest orientation, and a female aged 16–39 in a supine position with a south–north orientation. The order of the burials and how the individuals are associated with the objects in the grave remain unclear. The grave included a bronze ring, two conical-necked vessels, a ceramic cup, two ceramic bowls, and a handled pot. Grave C077 was originally documented as containing the remains of a single individual, aged 35–45 years (C077/1), initially identified as male but now reclassified as female. The adult female was positioned in an east–west



Fig. 3. Miniature vessels and other grave goods found in Grave C046, with the inhumation of a 3–4-year-old girl (Photo: Christoph Bieber, University of Vienna).



Fig. 4. Ceramic vessels, spindle whorls, and metal grave goods found in Grave A068, with a 25–35-year-old woman (Photo: Christoph Bieber, University of Vienna).



Fig. 5. Ceramic vessels and bronze arm ring found in Grave A110, with the inhumation of a 30–40-year-old woman (Photo: Christoph Bieber, University of Vienna).

orientation, lying on her right side with her legs slightly flexed. Additionally, the grave held the remains of a female child (C077/2). Notably, no grave goods were found associated with either individual. The individual aged 35–45 from Grave C078, who was buried in a supine position with an east–west orientation, was also now identified as female. The two bronze spiral rings, five ceramic bowls, a conical-necked vessel, two handled bowls, and animal bones align with the grave goods typically found in a woman's grave (Rebay 2006: 191–196).

3.2. Osteology

Non-specific stress indicators, such as cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia and periostitis, can reveal how individuals responded to environmental, social and nutritional pressures. Cribra orbitalia, likely a marker of nutritional stress (Brickley 2018), was observed in four out of thirteen adult females (A061, A089, C001 and C016) and one out of six adult males (B139), but not in children. Similarly, porotic hyperostosis, another skeletal marker of chronic anemia (Rinaldo et al. 2019), was found in two adult females (C001 and C078) and two adult males (A070 and B139), with no cases observed in children. Linear enamel hypoplasia, which is linked to developmental stress, was present in one adult female (A113), one adolescent girl (B104), one adult male (A070) and one adolescent boy (C017). Periostitis, which is inflammation of the outer layer of bone, was detected in two adult females (C016 and C001), one adult male (B133/1) and one adolescent boy (C017). In female C016, it appeared on the femoral and tibial shafts, showing signs of healing and ongoing bone formation, which may indicate a nutritional deficiency. The adolescent boy's

(C017) periostitis on the humerus shaft was likely linked to scurvy. Sinusitis, which is often caused by infections and poor living conditions, was identified in an adult female (C001) and two adult males (A090 and A112). Female C001 showed inflammatory changes in the maxillary sinus, while male A090 exhibited new bone structures in the frontal sinus, which may be linked to meningioma. Pathological changes to the inner layer of the skull, such as reactions at the base of the skull and new bone formation, were observed in three adult females (A061, A089/1 and C078) and one girl (C046). These adult females exhibited branching blood vessel impressions in the frontal bone, possibly resulting from a haemorrhagic-inflammatory process. The 3–4-year-old girl exhibited porotic structures and new bone formation consistent with meningitis. No males exhibited these changes. Perisinusitis, characterised by fine new bone formation near cranial venous sinuses, was found in an adult female (A061) and a girl (C046). Basal meningitis, indicated by pits and new bone formation at the skull base, was observed in an adult male (B139) and was possibly accompanied by increased intracranial pressure. Among the women, one case (A067) of possible elevated intracranial pressure was noted. Pleurisy, an inflammation of the pleural membranes, was identified in the 15–18-year-old adolescent (C017) and was linked to scurvy. Scurvy, which is caused by a deficiency of vitamin C, was evident in one adult female (C016) and one juvenile male (C017), presenting with bone changes such as periosteal reactions and new bone formation.

Traumatic lesions, which are caused by physical force or external agents, highlight the daily challenges faced by Early Iron Age communities and their vulnerability. Interestingly, only women and girls in this collection exhibit cranial or postcranial trauma. Of the 13 adult women, A089 is the only individual with healed cranial trauma. She had a remodelled fracture of the left styloid process and mandibular ramus, which is likely linked to jaw trauma. Four girls also show evidence of trauma. The 14–16-year-old girl (B104) had two healed impression fractures on the left parietal bone, which may indicate that she received wound care. The 6–7-year-old girl (C073) exhibits new bone formation on the right mandibular ramus, likely resulting from blunt force trauma. C073 also shows perimortem or postmortem injuries, including a chipped lesion on the right cranial vault and a sharp-edged, triangular injury on the right parietal bone; neither injury shows signs of healing. Four adult women (A110, A113, C016 and C078) display perimortem or postmortem injuries. A110 has radiating fracture lines on the right parietal and frontal bones with no evidence of healing. A113 has two distinct fractures: a sharp-edged linear incision on the left parietal bone, likely caused by a sharp impact, and an oblique lesion on the vertex of the left parietal bone with a missing displaced segment. C016 has a perimortem lesion on the right parietal bone featuring a straight, sharp edge and a semi-circular upper margin. C078 shows a sharp slash injury on the left parietal bone with chipping of the internal layer and loss of adjacent bone, likely resulting from the withdrawal of a weapon. She also has a small, triangular perforating lesion with radial fractures on the right parietal tuber. Adult female A119 presents a unique case involving an unusually small, rounded left temporal squama. This may be a rare anatomical variant resulting from a disturbance in embryonic development or a healed traumatic injury. Moreover, her skull is clearly asymmetrical. Only one postcranial fracture was identified. In the 25–30-year-old female individual C001, potential paralysis of the left lower limb may have led to overuse of the right side as a form of compensation. This is evidenced by an avulsion fracture and exostosis in the right tarsal bone, along with a pronounced periosteal reaction along the medial shaft of the right tibia.

All 11 assemblages of cremated human remains attributable to grave contexts had a milky-white, chalky appearance, suggesting cremation temperatures above 650–700 °C. The remains are characterised by their low weight, ranging from 4.96 to 75.92 g, and the limited representation of anatomical regions. It appears that cremated bones were not systematically collected during the excavation and that pieces of skull were preferentially selected. This restricts the ability to estimate age, sex, and

other osteological parameters, as well as limiting the skeletal elements available for sampling. All of the cremated remains were from individuals over the age of 20, and it was not possible to estimate sex (Table 2).

3.3. Radiocarbon dating

Conventional radiocarbon dates from Statzendorf span from 2560 ± 87 to 2345 ± 28 BP (Table 4). As expected, most samples cannot be dated precisely because they fall into a segment of the calibration curve known as the Hallstatt Plateau, a flat area on graphs plotting radiocarbon dating against calendar dates between c. 750 and 400 BCE (Fahrni et al. 2020, Rose et al. 2022). The dates cover a calibrated timeframe from 894 to 376 cal. BCE, utilizing the 2σ interval (95.4% probability). The KDE plots for both inhumations and cremations exhibit a similar distribution pattern with a considerable overlap (Fig. 6). The peak of the KDE curve from the inhumations begins slightly earlier than that of the cremations and displays a broader distribution. The plots indicate that both practices were performed simultaneously or in close succession, consistent with the bi-ritual character of the Statzendorf cemetery.

Fig. 7 shows a probability plot of calibrated dates ordered by the mean, with dates from cremation burials indicated in red. The grave with the highest probability to correspond to the beginning of the Hallstatt period around 800 BCE is D020, the grave closest to the end of the Hallstatt period around 400 BCE is D018. The four radiocarbon dates from cremation burials were hypothesized to date close together because of their formal similarity and spatial proximity, clustering in the south-west end of the cemetery. Interestingly, they did not all date to the end of the Hallstatt period, as expected.

Cremation D018 has the highest $\delta^{13}\text{C}$ values (-17.8‰ , compared to -20.1 , -20.7 and -22.3‰), suggesting a possible old wood effect for D017, D019 and D020 (Snoeck et al. 2014). Indeed, if 50 to 100 years are added to the model of the radiocarbon dates, it would put them all around 400 BCE (Supp. Fig. 1). The late radiocarbon date of individual D018 corresponds well to the late typo chronological assessment of the pottery in its grave. It includes a Kalenderberg-vessel that has lost its characteristic knob decoration, for example, and drinking cups with low bands in the profile. The assemblage of Grave D019 corresponds to the classic Kalenderberg style (Fig. 8).

The radiocarbon dates from inhumation graves may also fall into the entire Hallstatt period, with B142 having a higher probability to date earlier, and C017 more likely to date towards the end of the Hallstatt period. Sector B is thought to be the oldest of the cemetery, and the use of a bronze harp fibula supports an early Hallstatt date typo-chronologically. Grave C017 did not include any material culture. Radiocarbon dating confirmed that all sampled individuals date to the early Iron Age Hallstatt period and are likely to belong to the same cultural context.

3.4. Isotope analysis

Strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) of the human bone samples from Statzendorf range from 0.7086 to 0.7127, a relatively narrow span, typical for regions with mixed sedimentary and crystalline geology. A recent reconstruction of bio-available strontium baseline based on plant samples (Fritzl et al. 2024) enables linking our results to the landscape of the Traisen Valley, which is geographically divided into a valley with plains and gravel terraces, and a hill area (Fig. 9). With an elevation above sea level of 295 m, Statzendorf is clearly situated above the threshold of 235.4 m between the highlands and the lowlands. The $^{87}\text{Sr}/^{86}\text{Sr}$ of these areas differ, with ratios below 0.7093 for the valley and above this threshold for the hill area.

Fig. 10 shows $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of inhumed and cremated individuals. Multiple datapoints per individual are linked, red indicates samples from female, blue from male, and grey from unidentified (cremated) samples. The two individuals at the low end of the scale, A112, a 30–35-year-old male, and A113, a 35–45-year-old female were both found without any grave goods at the centre-east edge of the cemetery. The cremated samples cluster close together in the top third, with ratios from 0.7106 to 0.7114. The individual with the highest ratio of 0.7127 is A068, a 25–35-year-old female buried with two spindle whorls, a ceramic set, a knife and meat offerings (Rebay 2006: 60). Including only canines and second molars for comparability (i.e. one sample per individual), samples from males have a slightly lower mean $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7097 ± 0.0006 (SD; $n = 7$), compared to samples from females with a mean of 0.7103 ± 0.0010 (SD; $n = 13$). Statistical tests suggest that there is no statistically significant difference between males and females in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (t -test = 1.35, $p = 0.19 > 0.05$). Females, do however, exhibit a greater variability in their strontium isotope ratios than males, which may be archaeologically, if not statistically significant. With the exception of individuals A112 and A113, who were both buried without grave goods and probably obtained their food from the low-land of the Traisen Valley, all values can be attributed to the hilly landscape (Fritzl et al. 2024).

Focusing on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios by tooth type (Fig. 10), the results reveal that more individuals incorporate foods with higher strontium ratios with increasing age than the reverse. The strontium ratios from cremated individuals, reflecting later life, are also among the highest ratios and support this assertion. However, the values of multiple samples per individual are too close together to detect individual changes in food intake, as they range within the biologically possible variance. Interestingly, A112 and A113 show almost identical patterns.

Strontium concentrations ([Sr]) are not only tied to the geological substrate, but are also reflect dietary variability. The [Sr] values from Statzendorf range between 41 to 127 ppm in tooth enamel and 71 to 111 ppm in calcined bone. In comparison, the strontium concentrations appear low for the whole population similar to those seen in Bronze and Iron Age populations in Belgium, indicating little evidence for large amounts of salt consumption (Dalle et al. 2022). Lower concentrations may also suggest the intake of more animal protein, whereas higher

Table 2
Cremated human remains from Statzendorf.

Grave	Inventory No.	Weight (g)	Inventory	Age at Death	Sex	Pathologies and notes
A001	38248	13.03	axial skeleton, upper limbs	20 + years	unidentified	
A057	42721	17.47	cranium	20 + years	unidentified	
A065	42757	20.12	cranium	20 + years	unidentified	
C032	45143	4.96	cranium	20 + years	unidentified	
C070	45359	19.27	cranium	20 + years	unidentified	cranial hyperostosis
D017	86338	57.88	lower limbs	20 + years	ambiguous (patella $p = 0.555$)	cranial hyperostosis
D018	86356	75.92	all body areas	20 + years	unidentified	unburnt human bone fragments present
D019	86367	52.65	cranium, upper limbs, lower limbs	20 + years	unidentified	
D020	86372	40.37	upper limbs, lower limbs	20 + years	unidentified	
D021	86381	27.61	lower limbs	20 + years	unidentified	
GD09	56131	9.43	lower limbs	20 + years	unidentified	

Table 3

Proteomic sex estimations from Statzendorf.

Grave	Inventory No.	Weight (g)	Inventory	Age at Death	Sex	Pathologies and notes	Body position	Orientation	Grave goods
A001	38248	13.03	axial skeleton, upper limbs	20 + years	unidentified		supine position	west-east	two bronze rings, bronze spiral ring, bow fibula, bronze pin, 49 glass beads, bronze needle, ceramic spindle whorl, cup, four bowls, conical-necked vessel, handled pot, animal bones
A057	42721	17.47	cranium	20 + years	unidentified		supine position with legs flexed to the right	north-south	two ceramic bowls, animal bones
A065	42757	20.12	cranium	20 + years	unidentified		not recorded	not recorded	iron knife, bronze and iron fragments, animal bones, ceramic cup, three ceramic bowls, handled pot, conical necked vessel, two spindle whorls
C032	45143	4.96	cranium	20 + years	unidentified		supine position	east-west	–
C070	45359	19.27	cranium	20 + years	unidentified	cranial hyperostosis	supine position	northeast-southwest	ceramic cup, two ceramic bowls, ceramic pot, four spindle whorls
D017	86338	57.88	lower limbs	20 + years	ambiguous (patella p = 0.555)	cranial hyperostosis	–	–	–
D018	86356	75.92	all body areas	20 + years	unidentified	unburnt human bone fragments present	supine position	south-north	bone pendant, conical-necked-vessel
D019	86367	52.65	cranium, upper limbs, lower limbs	20 + years	unidentified		right side position, legs slightly flexed	north-south	iron knife, animal bones, four conical-necked vessels, three ceramic cups, four ceramic bowls
D020	86372	40.37	upper limbs, lower limbs	20 + years	unidentified		supine position	east-west	bronze arm ring, conical-necked vessel, ceramic cup, Kalenderberg vessel
D021	86381	27.61	lower limbs	20 + years	unidentified		supine position	south-north	–
GD09	56131	9.43	lower limbs	20 + years	unidentified		right side position, legs slightly flexed	southsoutheast-northnorthwest	–
A119	5782	25-Teeth-342	18	female	female	25–30	right side position, legs slightly flexed	west-east	–
B104	5848	25-Teeth-343	47	female	female	14–16	supine position	east-west	iron and bronze arm ring, Kalenderberg vessel (according to documentation), ceramic cup, bowl, conical-necked vessel
B133/1	5803–1	25-Teeth-344	38	male	male	23–30	supine position	southeast-northwest	–
B133/2	5803–2	25-Teeth-345	18	female	–	16–39	supine position	south-north	bronze ring, two conical-necked vessels, ceramic cup, two ceramic bowls, handled pot
B139	5790	25-Teeth-346	38	male	male	31–40	right side, flexed position	northeast-southwest	wild boar tusk pendant, bronze fragment, ceramic cup, two ceramic bowls, animal bones
B142	5793	25-Teeth-347	38	female	female	35–45	right side position, legs slightly flexed	east-west	iron ring, bronze harp fibula, bronze ring, glass bead, Kalenderberg vessel, ceramic cup, four ceramic bowls, spindle whorl
C001	(5797?) + 5780	25-Teeth-356	18	female	female	25–30	supine position	east-west	bronze bow fibula with amber bead, bronze harp fibula, sheet bronze belt, two bronze arm rings, five bronze rings, three bronze spiral rings, iron knife, two conical-necked vessels, ceramic cup, four ceramic bowls, Kalenderberg vessel
C016	5796	25-Teeth-348	27	female	female?	25–35	supine position	northwest-southeast	–
C017	5799	25-Teeth-349	36	male	male?	15–18	right flexed position	east-west	–

(continued on next page)

Table 3 (continued)

Grave	Inventory No.	Weight (g)	Inventory	Age at Death	Sex	Pathologies and notes	Body position	Orientation	Grave goods
C046	5801	25-Teeth-350	55	female	–	3–4	right side position, legs slightly flexed to the right	east–west	three ceramic vessels
C066	5802	25-Teeth-351	55	female	–	5–6	supine position	northwest-southeast	–
C073	5800	25-Teeth-352	16	female	–	6–7	supine position	northeast-southwest	two bronze arm rings, ceramic cup, two ceramic bowls, handeled pot, conical-necked vessel
C077/1	5798	25-Teeth-353	43	female	male?	35–45	right side position, legs slightly flexed	east–west	–
C077/2	5798	25-Teeth-354	65	female	–	4	–	–	–
C078	5795	25-Teeth-355	47	female	male	35–45	supine position	east–west	two bronze spiral rings, five ceramic bowls, conical-necked vessel, two handled bowls, animal bones

Table 4
Radiocarbon dates from Statzendorf.

Grave	NHM	Bone element	Age of ind.	Sex of ind.	Sample ID	14C Age (yr BP)	± error	Calibrated age range (1σ, 68.3% prob.)	Calibrated age range (2σ, 95.4% prob.)	Median calibrated calendar age
D018	PA86356	cremated tibia	20+	–	RICH-31799	2345	28	416–386 BCE	515–376 BCE	403 BCE
C017	AA5799	rib	15–18	male	VERA-7823	2382	40	515–398 BCE	744–387 BCE	468 BCE
A061	AA5789	radius	25–30	female	VERA-7822	2460	34	751–482 BCE	758–416 BCE	603 BCE
D017	PA86338	cremated tibia	20+	–	RICH-31791	2482	27	754–544 BCE	772–485 BCE	636 BCE
B142	AA5793	clavicle	35–45	female	UCIAMS-286,287	2495	15	757–552 BCE	770–544 BCE	629 BCE
D019	PA86367	cremated humerus	20+	–	RICH-31798	2516	26	773–569 BCE	781–544 BCE	637 BCE
D020	PA86372	cremated diaphysis	20+	–	RICH-31796	2549	25	792–596 BCE	799–565 BCE	757 BCE
C073	AA5800	rib	6–7	female	VERA-7826	2560	87	809–545 BCE	894–412 BCE	665 BCE

concentrations point to a more plant-based diet (Lewis et al. 2017).

Using only canines and second molars, [Sr] of the 13 female samples average 68.5 (41–92) ppm, while the 7 male samples have slightly higher average [Sr] (80.1 (42–127) ppm) and greater variability than females. This possibly reflects greater mobility or dietary variation. Individuals with higher social index tend to have slightly lower strontium concentrations, but this is not statistically significant (Pearson's $r = -0.32$, $p = 0.17 > 0.05$). The trend supports the hypothesis that individuals of low social status had a diet richer in strontium, possibly associated with less meat consumption and a higher diversity in diet (Fig. 11) (Burton & Wright 1995, Underwood 1977).

A clear increase in [Sr] is also observed between the M1, to the M2, M3, and the cremated bone fragments (Fig. 12). These skeletal elements represent different times of the lives of the individuals buried in Statzendorf suggesting an increase in strontium-rich foods with increasing age.

Oxygen isotopes ($\delta^{18}\text{O}$) reflect drinking water consumption during childhood, when enamel was formed, and may indicate an origin in specific regions, altitudes and climates (O'Connell 2023). The results from Statzendorf range from -8.7 to -5.1‰ , which are consistent with the area around Statzendorf (Bowen 2022, Bowen & Revenaugh 2003) and suggest no long-distance mobility with the possible exception of two individuals: the 25–30-year-old female A061 (-8.7‰) and the 40–50-year-old male A094 (-8.6‰). These lower values are consistent with higher altitudes, possibly in the Alps (Fig. 13).

Carbon isotopes ($\delta^{13}\text{C}$) were also measured from dental enamel. Values range from -15.8 to -9.2‰ . The general variation suggests a mixed diet with variable animal and carbohydrates components that are mostly C_3 with some contributions of C_4 plants (Varalli et al. 2021). Using only canines and second molars to represent individuals, male values range from -13.8 to -11‰ , whereas female values range from -14.5 to -10.4‰ . With almost identical means, females show a slightly higher variability ($\text{SD} = 1.31$ vs. 0.94‰). This suggests little difference in dietary intake between the sexes. $\delta^{13}\text{C}$ values from children's samples under six years cluster tightly between -13.5 and -12.2‰ , whereas adolescents and adults' samples spread across the full range. Once again, two individuals stand out, the 14–16-year old female B104 with the lowest value (-15.8‰ – note the individual with the second lowest value is A061 who also had the lowest $\delta^{18}\text{O}$ values) and the 23–30-year old male B133 with the highest value (-9.2‰). These two individuals also have lower $\delta^{18}\text{O}$ values. Individuals with a higher social index tend to have slightly lower $\delta^{13}\text{C}$ values, but the correlation is weak.

The strongest pattern in the dataset is the positive correlation between $\delta^{13}\text{C}$ values and $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios (Fig. 14). This pattern suggests variations in dietary practices among individuals, with potentially two main sources of foods, one with low carbon and strontium isotope ratios (e.g. C_3 crops cultivated in the valley) and one with higher carbon and strontium isotope ratios (e.g. C_4 crops or animals grown or raised in the direct vicinity of Statzendorf). C_4 plants, such as millet had been introduced to Bronze Age Central Europe starting around c. 1600

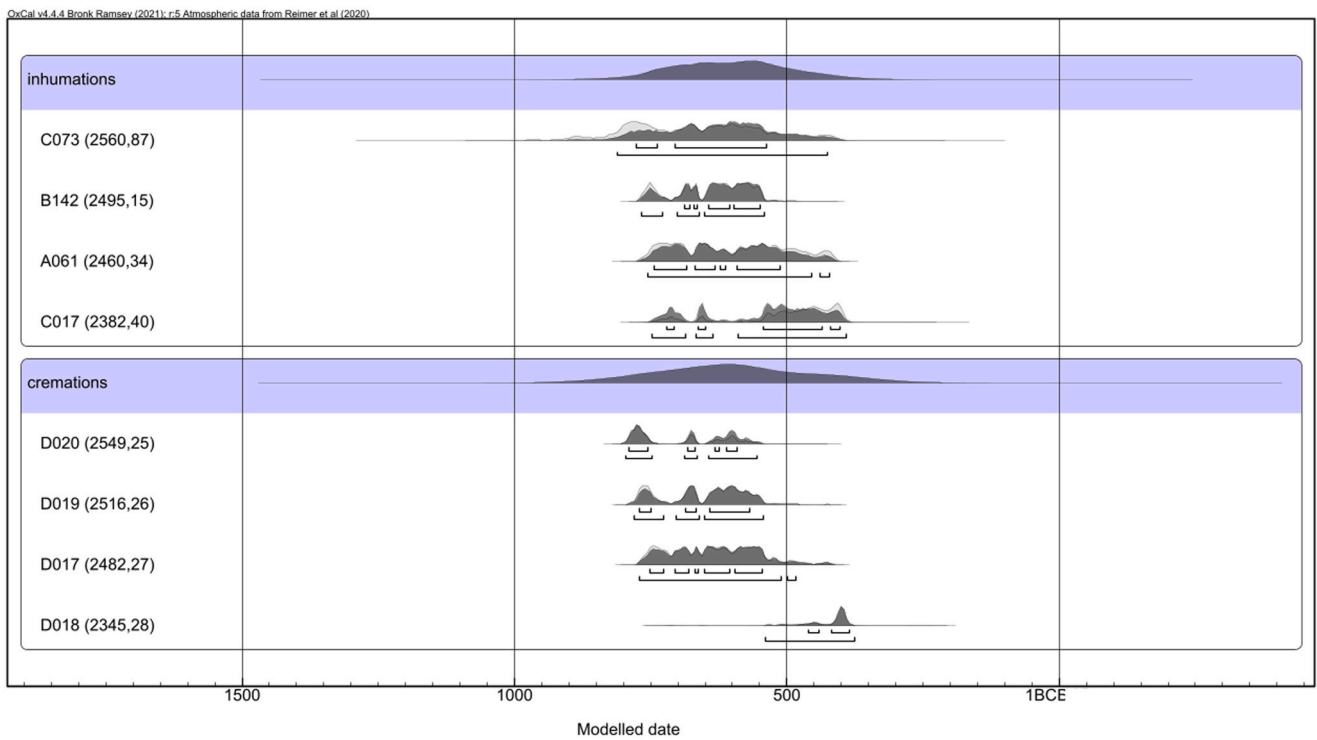


Fig. 6. KDE plots of radiocarbon dates from inhumations and cremations.

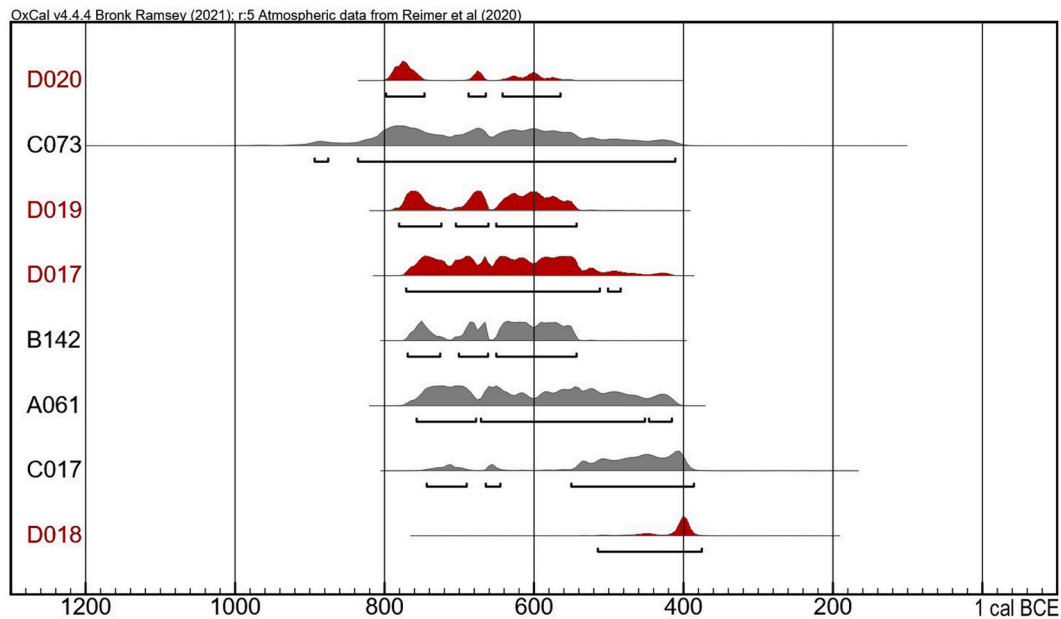


Fig. 7. Calibrated radiocarbon dates from inhumations (grey) and cremations (red).

BCE (Filipović et al. 2020), and was firmly established in the Hallstatt diet. This is evidenced, for example, by the presence of millet in faeces found in Hallstatt salt mines (Maixner et al. 2021), and bone chemistry signals from Magdalenska gora in Slovenia (Murray & Schoeninger 1988). Together, these findings imply that the individuals from Statzendorf were not only sourcing their food from diverse geographic locations but were also consuming a variety of foodstuffs, reflecting a complex and varied dietary strategy.

4. Bioarchaeological biographies

The rich and complex datasets enable us to focus on specific burials at Statzendorf and construct detailed narratives about the lives of these individuals. Individual A068 was a young woman, aged 25–35 years, whose burial reflects a life of relative abundance and significance. She was interred with a range of grave goods, including two spindle whorls, a ceramic set, a knife, and meat offerings, indicating her role in domestic and possibly craft-related activities. Isotope analysis reveals that she likely lived in the hilly landscape around Statzendorf, as evidenced by



Fig. 8. Ceramic assemblage found in cremation Grave D019 (Photo: Christoph Bieber, University of Vienna).

her high $^{87}\text{Sr}/^{86}\text{Sr}$ – the highest in the group. Her elevated carbon isotope ($\delta^{13}\text{C}$) values suggest a diet richer in C4 plants, such as millet, or a greater reliance on animal protein compared to others in her community. These details paint a picture of a woman who may have been well-integrated into her environment, with access to resources and a diet that set her apart from many of her contemporaries.

Individual B104 was a young adolescent girl, aged 14–16 years, whose burial reflects both a life of hardship and a degree of social status. She was laid to rest in a supine position, in east–west orientation, and accompanied by notable costume elements, an iron and bronze arm ring, as well as six ceramic vessels – one of which was a distinctive Kalenderberg jug. Despite the well-equipped burial, her health during life was poor. Linear enamel hypoplasia on her teeth points to significant stress during development, and her skull bears evidence of multiple surgical interventions, including trepanation, suggesting attempts to treat severe medical conditions. In her first molar, isotope analysis reveals the lowest carbon isotope ($\delta^{13}\text{C}$) values among the individuals studied, indicating a diet primarily reliant on C3 plants and limited animal protein, whereas the second molar signals are considerably higher. Her life included physical challenges and an improving childhood diet, and her burial indicates she was valued within her community.

Individual A061 was a young woman, aged 25–30 years, whose burial reflects both a life of hardship and high social status. Her grave assemblage included two bronze rings, a bronze spiral ring, a bow fibula, a bronze pin, glass beads, a bronze needle, a ceramic spindle whorl, a cup, four bowls, a conical-necked vessel, a handled pot, and animal bones. These grave goods suggest she held a prominent role within her community, possibly tied to textile craft-related activities. Despite her social standing, A061's health condition tells a different story. Cribra orbitalia, perisinusitis, and pathological changes in her skull suggest unspecific stress and a possible hemorrhagic-inflammatory condition, indicating significant health challenges during her life. Isotope analysis provides further insight into her origins and diet. Her lower $\delta^{18}\text{O}$ values suggest she may have lived at higher altitudes, possibly in the Alps, while her low $\delta^{13}\text{C}$ values indicate a diet primarily reliant on C3 plants, with limited access to animal protein. A life marked by physical struggles and dietary limitations ended with a burial reflecting wealth and recognition within her community.

The burial of individual A094, a man aged 40–50 years, suggests a life of modest status yet shared origins with Individual A061. Similar to the young woman, his lower $\delta^{18}\text{O}$ values point to an early life spent at higher altitudes, possibly in the Alps, indicating a similar geographic background. His third molar, which captured isotopic signals during adolescence, carries a more local signature, indicating integration into the community. He was buried in a north–south orientation, lying in a right-flexed position, accompanied by grave goods that included an iron knife, meat offerings, four conical-necked vessels, three ceramic cups, and four ceramic bowls. While his burial was less elaborate than A061's, the presence of multiple items still reflects a degree of recognition within his community.

Individual B133/1, a 23–30-year old laid to rest in supine position, oriented southeast-northwest, was found as part of a consecutive burial alongside a 16–39-year-old female. The grave contained an array of goods, including a bronze ring, two conical-necked vessels, a ceramic cup, two ceramic bowls, and a handled pot, but it is unclear which items were specifically associated with him. Pathological evidence indicates that he experienced periostitis, an inflammation of the outer bone layer, which may have been caused by infection, injury, or other stressors during his life. Isotope analysis reveals intriguing details about his diet. His carbon isotope ($\delta^{13}\text{C}$) values were the highest among studied

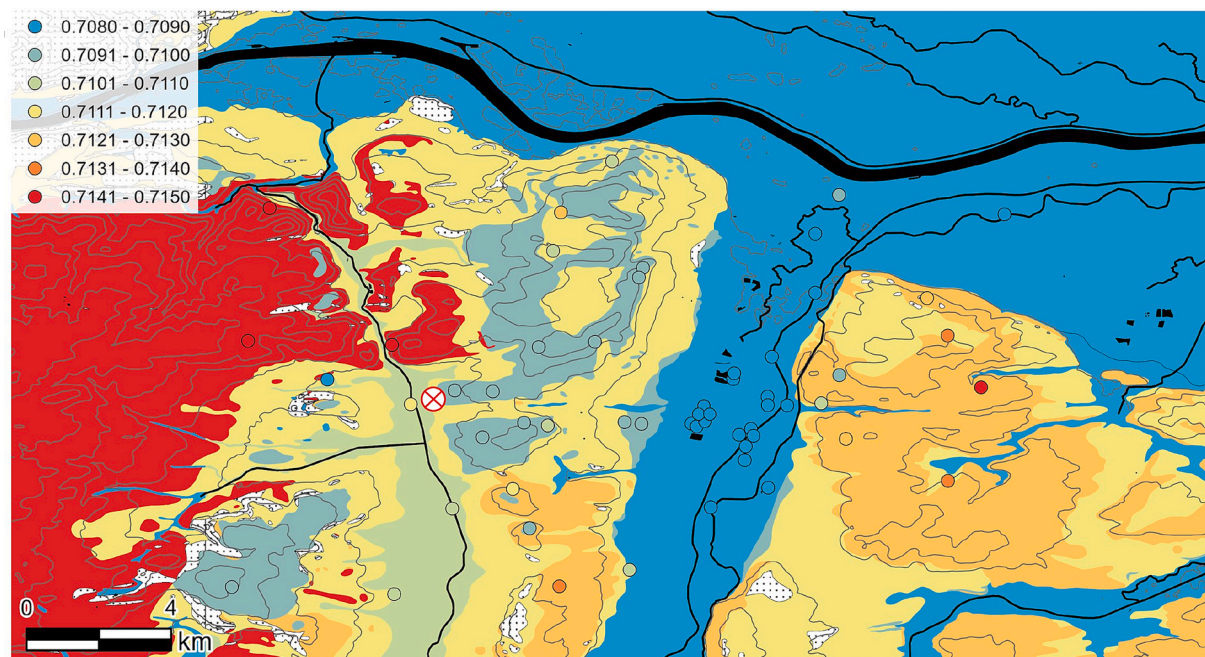


Fig. 9. Map of bio-available strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios in the Traisen Valley, with the geographical location of Statzendorf (after Fritzl et al. 2024).

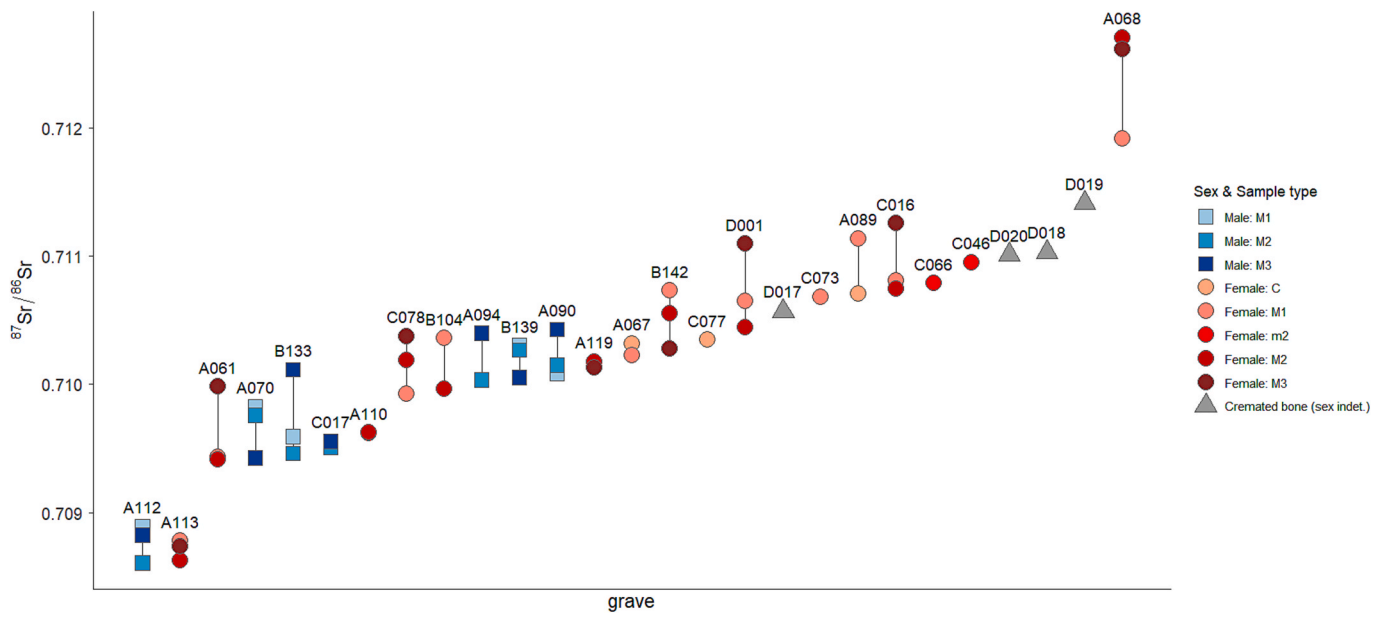


Fig. 10. Strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios of inhumed and cremated individuals by sex and sample type (red: female, blue: male; C = canine, m1 = first deciduous molar, M1 = first permanent molar, M2 = second permanent molar, M3 = third permanent molar).

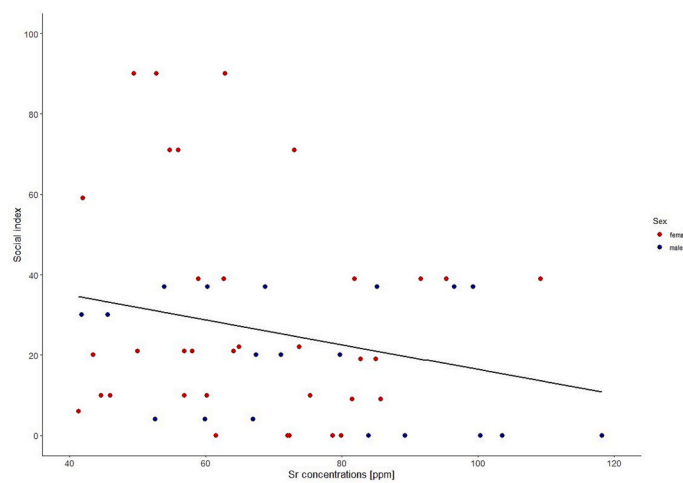


Fig. 11. Strontium isotope concentrations and social index (red: females, blue: males).

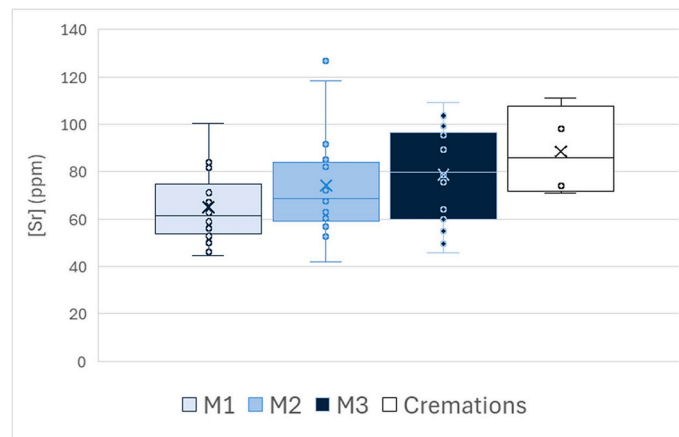


Fig. 12. Strontium concentrations ([Sr]) for different skeletal elements (first, second and third molars, cremations).

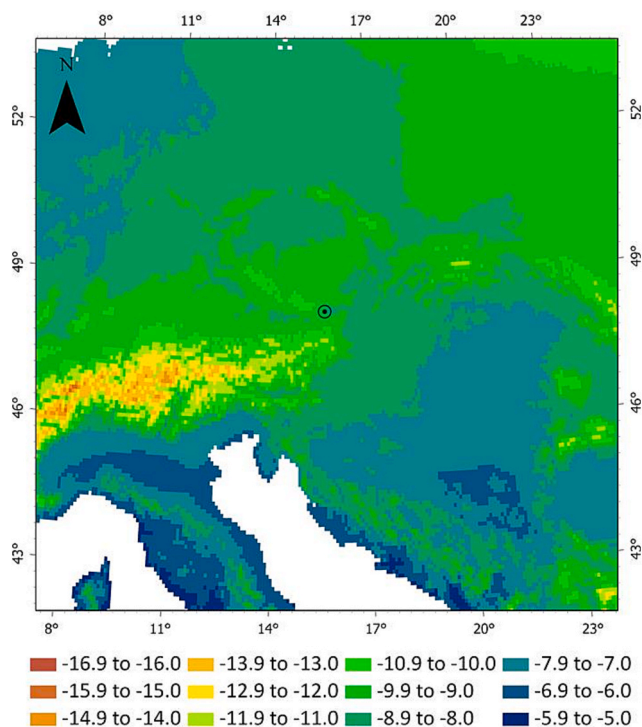


Fig. 13. Location of Statzendorf highlighted over a grid of modern annual $\delta^{18}\text{O}$ trends in precipitation (Bowen 2022, Bowen & Revenaugh 2003, IAEA/WMO 2015) (map: Hannah James).

individuals, suggesting he consumed a diet rich in C_4 plants such as millet or animal protein, especially during adolescence, when his third molar developed. This dietary pattern might reflect his social status and access to specific resources during this formative stage of life.

A112 and A113, a male aged 30–35 years and a female aged 35–40 years, were inhumed in close proximity at the centre-east edge of the cemetery. The male was interred lying on his back in south-north orientation, while the female was positioned slightly flexed on her right side, oriented from southeast to northwest. The male exhibited signs of sinusitis, while the female displayed linear enamel hypoplasia, indicative of developmental stress, as well as perimortem fractures on the skull. Neither burial included any grave goods. The striking similarity in their isotopic patterns suggests a shared life, marked by common dietary practices and geographic origins. Both individuals exhibited the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios among the cemetery population, pointing to a life spent in the lowlands of the Traisen Valley, where their food was likely sourced. Their mixed diets included contributions from

both C_3 and the C_4 plant millet, yet their isotope values indicate a greater reliance on C_3 plants and a lower intake of animal protein compared to others in the community. This fits the low status expressed in the burial ritual. The shared dietary and environmental markers hint at a close connection between A112 and A113, perhaps as companions or kin.

5. Conclusion

This bioarchaeological investigation of human remains from Statzendorf, with its 376 burials—approximately one-tenth of which are inhumations—offered a unique opportunity to integrate datasets from both inhumations and cremations. Analytical approaches to cremated bones and teeth from inhumations have advanced significantly in recent years and are now increasingly applied on a larger scale. However, these analyses typically require distinct methodologies and are therefore rarely applied to one archaeological context.

Cremated human remains were assessed via bioarchaeological methods, radiocarbon dated, and analyzed for $^{87}\text{Sr}/^{86}\text{Sr}$. Inhumed individuals were also macroscopically analyzed based on their morphology, with four samples subjected to radiocarbon dating. Due to the Hallstatt plateau, the dates did not significantly refine the chronology; however, they do indicate that more precise dating is possible at the beginning and end of the period. The results also confirm a Hallstatt date for individuals buried without grave goods and establish that both cremation and inhumation were practiced simultaneously during the Early Iron Age.

The analysis of amelogenin peptides in 25 individuals significantly improved the accuracy of sex identification, securely linking isotopic analyses to sex. Here, we use amelogenin-derived data on sex as a proxy for gender (Rebay-Salisbury, 2024), as recent studies have confirmed a close link between sex and gender in Bronze and Iron Age Central European communities (Rebay-Salisbury et al. 2025). The comparison between the grave good assemblages and the results of peptide-based sex identification yielded a stronger correlation compared to previous morphological sex estimations. Gender-typical grave goods found in some of the graves at Statzendorf include spindle whorls, bronze jewelry, and certain types of vessels associated with women. In contrast, male graves are more challenging to identify based on objects alone, as tools and weapons are very rare (Rebay 2006: 193).

Girls and women buried in the cemetery of Statzendorf were disproportionately affected by healed and fatal injuries, reflecting exposure to physical violence or accidents in their environment. At least in part, the discrepancy between females and males in the levels of traces of interpersonal violence can be attributed to the uneven preservation of skeletal remains and possibly a cultural tendency to inhumate girls rather than cremate them. However, these factors do not fully account for the

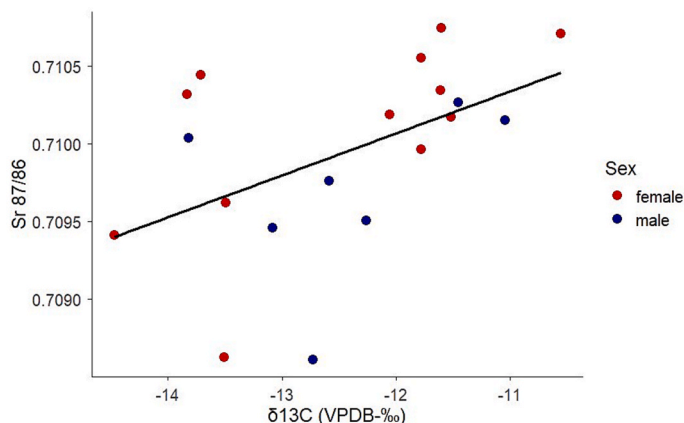


Fig. 14. Correlation between $\delta^{13}\text{C}$ values and $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios.

observed differences. Notably, evidence of violence is also present in well-equipped, high-status graves, indicating that this pattern is more closely linked to gender than to social status.

The biochemical analysis included $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and [Sr] measurements from multiple teeth per individual (55 teeth, 7 males, 16 females), providing insights into developmental ages and the osteobiographies of the deceased. The data from Statzendorf does not indicate high levels of long-distance mobility, as observed at sites like Magdalenenberg near Villingen (Oelze et al. 2012) or Basel-Gasfabrik (Knipper et al. 2018), both of which are considered central places of regional elites during the Iron Age. However, two individuals have low oxygen values that could be consistent with an origin in the higher altitudes of the Alps.

The evidence from Statzendorf suggests a community that relied on locally sourced diets, with geological variations between the lowland valley and upland hills reflected in the strontium isotope ratios. The evidence of dietary variability, with some individuals consuming more animal protein and C4 plants like millet, reflects a community with access to diverse food sources and a complex subsistence strategy. Males seem to have a more restricted area from which they source their diet, and variations in carbon isotopes also suggest subtle dietary differences, with some individuals consuming more animal protein and C4 plants than others. These dietary differences may be influenced by age and gender, and also by the growing expression of social status through burial rituals. While Late Bronze Age burial practices emphasize uniformity and reveal minimal distinctions among individuals within cemeteries (Sørensen & Rebay-Salisbury 2023), Early Iron Age communities appear increasingly complex and stratified. This is reflected in the highly varied grave goods, both in quality and quantity, as well as in the diversity of burial practices, ranging from simple cremation deposits to monumental burial mounds (Nebelsick et al. 1997, Rebay-Salisbury 2016). Furthermore, the disproportionate evidence of interpersonal violence among women and girls, even those in high-status graves, provides critical insights into the gendered dynamics of violence and vulnerability in this period.

The Statzendorf cemetery thus serves as a vital case study for exploring the intricate relationships between gender, status, diet, and violence in prehistoric Europe.

CRedit authorship contribution statement

Katharina Rebay-Salisbury: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Lukas Waltenberger:** Formal analysis, Investigation, Visualization, Writing – review & editing. **Michaela Fritzl:** Investigation, Visualization, Writing – review & editing. **Hannah Skerjanz:** Data curation, Investigation, Writing – review & editing. **Domnika Verdianu:** Investigation, Writing – review & editing. **Leslie Quade:** Investigation, Writing – review & editing. **Michaela Spannagl-Steiner:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Michael Wolf:** Data curation, Formal analysis, Investigation, Writing – review & editing. **Fabian Kanz:** Investigation, Methodology, Resources, Writing – review & editing. **Anneminne Frère:** Investigation, Writing – review & editing. **Christophe Snoeck:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2026.105740>.

Data availability

All primary data (osteological assessments, proteomic assignments, and isotopic measurements) and metadata are available in the publication and supplementary materials. The mass spectrometry proteomics data have been deposited to the MassIVE repository (<https://massive.ucsd.edu>) under the accession number MSV000100046. Isotope data will be deposited in the open-access online IsoArch database (<https://isoarch.org/>).

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