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Rethinking strontium variability beyond mobility: Strontium isotope and concentration analysis of cremated remains from Tienen (Gallo-Roman Belgium, 1-4th c.AD)

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ABSTRACT

Strontium isotope analysis ($^{87}Sr/^{86}Sr$) is a common tool for the study of mobility in archaeological populations, and has often been used in Roman contexts, to deliver more information on the mobility of the inhabitants of the Roman Empire. However, the practice of cremation within the empire and the methodological bias towards inhumation long pushed aside the study of populations who practiced cremation. Additionally, it is becoming more and more apparent that additional factors can have an influence on $^{87}Sr/^{86}Sr$ values, besides mobility, which calls for a careful reassessment of the results. This study looks at the population dynamics in the Gallo-Roman *vicus* of Tienen, through strontium isotope ($^{87}Sr/^{86}Sr$) and concentration ([Sr]) analyzes of a total of 147 cremated remains. While [Sr] values point to a general consumption of salt throughout the occupation of the *vicus* of Tienen, $^{87}Sr/^{86}Sr$ results point to limited mobility, changes in land use, and/or importations for food as an explanation for values. This study contributes to a growing field of research on mobility studies on cremations within a Roman cultural context.

1. Introduction

Strontium isotope analysis ($^{87}Sr/^{86}Sr$) is a powerful tool to study mobility of past populations, and its use has increased drastically in the last decade. Due to the age and the initial composition of bedrock, each geological unit presents a specific $^{87}Sr/^{86}Sr$ signature (Faure and Mensing, 2005). Through processes, such as weathering, the strontium from the bedrock is released into the soil, where the bioavailable fraction (termed BASr) of $^{87}Sr/^{86}Sr$ is then taken up by plants, from which it enters the food chain (Bentley, 2006; Capo et al., 1998). Additional sources of Sr in the environment are aeolian dust, sea spray, or surface waters, but the underlying bedrock of a given location is often the most significant input (Hartman and Richards, 2014; Whipkey et al., 2000; Willmes et al., 2018). The consumption of plants, animals, and water allows for Sr to enter the body, where it is incorporated into the mineral part of the skeleton, with minimal fractionation, during the formation of its different elements, by substituting for calcium (Ca) (Bentley, 2006; Lewis et al., 2017). In archaeological populations, assuming the population under study ate food from mostly local sources throughout their life, the incorporation of Sr in the skeletal tissue allows for a comparison with values recovered from the environment. This comparison makes the identification of mobility possible.

Strontium concentrations ([Sr] or Sr/Ca) measured in the body have been interpreted as dependent on the initial Sr content available in the diet (Montgomery, 2010). Therefore, [Sr] can provide indications on the type of diet consumed, with herbivorous diets presenting higher [Sr] than terrestrial carnivorous ones, for a similar region (Lewis et al., 2017). The concentration of both Ca and Sr in consumed food or water

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can influence [Sr] within body tissues. Due to the preferential intake of Ca by the body, diets rich in Ca, such as dairy-rich diets, will result in lower [Sr] in skeletal tissues (Schroeder et al., 1972). Conversely, excretion of Ca from the body by dietary elements such as salt can result in higher rates of Sr absorption, and therefore higher Sr concentrations in the skeletal tissues (Teucher et al., 2008).

In archaeological populations, the use of [Sr] in skeletal elements has highlighted the potential of that proxy to reveal the use of kelp as a fertilizer (Evans et al., 2012), differences in meat consumption (Dalle et al., 2022), or changes in salt intake between populations from different periods (Dalle et al. 2022). [Sr] therefore provides valuable insights into dietary patterns where traditional analyses, such as carbon and nitrogen isotopes, could not be applied, as is the case for cremated populations.

The *civitas* Tungrorum was an administrative region of the Roman Empire, covering modern eastern Belgium, the southern parts of the Netherlands, northern Luxembourg and small areas of northern France and western Germany. Following the defeat and destruction of the Eburones and the Aduatuci by Julius Caesar in the 1st c. BC, the territory became part of Gallia Belgica (Raepsaet, 2013; Roymans et al., 2020). Around the turn of the 1st century BCE/AD, Germanic groups from the eastern bank of the Rhine, among which the Tungri, were allowed to settle in the depopulated territory of the later *civitas* (Raepsaet, 2013). At the end of the 1st c. AD, the *civitas* became part of Germania Inferior.

Throughout the early phases of the Roman period, the *civitas* saw the development of a system of rural and villa settlements, producing agricultural surplus for local markets and the subsistence of administrative, military and craft centers, with Tongeren being the capital of the *civitas* (Lepot and Pigière, 2013; Roymans and Derks, 2011). Several lines of evidence regarding cattle morphology, specialization of crop production, equipment or storage structures point to an intensification of agriculture in the *civitas* (Bakels, 2009; Kooistra, 1996; Pigière, 2017; Roymans and Derks, 2011; Roymans, 1996). This was allowed by the environment of the region, displaying a fertile loess area in the south, particularly suited for agricultural purposes. Additionally, the *civitas* was well integrated to the empire through the river and road systems, among which was the road Cologne-Boulogne.

With the crisis of the 3rd century, several aspects of life and the economy were disrupted within the *civitas* (Brulet, 2008). While the centers located close to the major roads and rivers remained occupied, many agglomerations declined and were gradually abandoned in parallel of a demographic drop (de Brue et al., 2017; Deforce et al., 2020; Van Thienen, 2020). In this context of crisis, the economy shifted to more self-sufficient one, which accompanied a decline in the villa system and the agricultural exploitation of the *civitas* (Bakels, 2009; Bitter, 1991; Van Thienen, 2020).

This study focuses on the Grijpenveld cemetery of the *vicus*, or small agglomeration, of Tienen, a Gallo-Roman site in Belgium in use for 3 centuries (1-3rd c. AD), where cremation was the main funerary treatment. In addition, samples from the adjacent Avendoren tumulus (2nd c. AD) were also analysed for comparison. The chronological sub-divisions of the site based on the material culture mark Tienen as an ideal case to investigate trends in mobility, diet, and food-sourcing, from its founding to the end of a Roman settlement, through $^{87}Sr/^{86}Sr$ and [Sr] analysis. The Grijpenveld cemetery also presents an excellent opportunity to further enquire about the lives of *vicus* residents and in more provincial contexts, which has been investigated in recent studies using $^{87}Sr/^{86}Sr$ analyses for populations in the Roman Empire (Emery et al., 2018; Stark et al., 2022). Additionally, it also presents the opportunity to look into the salt consumption of Gallo-Roman populations, following the conclusions of Dalle et al. (2022) suggesting that salt consumption (as condiment, preservative and/or garum) increased dramatically during the Roman period.

With the increased connectivity witnessed within the Roman Empire, $^{87}Sr/^{86}Sr$ analysis has been often employed to investigate the mobility of numerous populations within its borders. However, $^{87}Sr/^{86}Sr$ analysis on Roman populations more often focuses on populations from important political and commercial centers (e.g. Killgrove, 2010; Prowse et al., 2007), military installations (e.g. Chenery et al., 2011; Eckardt et al., 2015), and from Italian (e.g. Killgrove and Montgomery, 2016; Milella et al., 2019; Salesse et al., 2021) or English contexts (Budd et al., 2004; Eckardt et al., 2015; Montgomery et al., 2009; Powell, 2014; Shaw et al., 2016). There is thus a lack of studies on other populations from different parts of the empire. This is needed to obtain a more complete picture of mobility within the borders of the territory under Roman rule. The vast majority of $^{87}Sr/^{86}Sr$ analysis on Roman populations so far has focused on inhumed individuals as well, as tooth enamel was long considered the only suitable material for this type of analysis (Hoppe et al., 2003). Enamel does not usually survive the cremation process (Beach et al., 2008; Schmidt, 2008), which is significant as both inhumation and cremation were practiced within the Roman Empire (Toynbee, 1971), with varying preferences according to regions and time period (Capuzzo et al., 2020; Noy, 2000). Snoeck et al. (2015) demonstrated that calcined bone is resistant to diagenesis, and therefore provides a suitable material for $^{87}Sr/^{86}Sr$ analysis. This allows for the investigation of a part of the Roman population that could previously not be studied. In recent years, $^{87}Sr/^{86}Sr$ analyses on cremated individuals from the period have been undertaken, with recent applications of the method on populations from sites in Italy (Seghi et al., 2024), the Netherlands (Kootker et al., 2022), Lebanon (Kalenderian et al., 2023) and Belgium (Dalle et al., 2022; James et al., 2025). Still, mobility analyses on cremated populations remain relatively rare for the Roman period, and contribute to an incomplete picture of mobility within the borders of the Roman Empire.

Although reconstruction of residential mobility is the primary use of strontium isotopes, it is becoming more and more apparent that mobility is not the sole factor in variations seen in $^{87}Sr/^{86}Sr$ in archaeological assemblages. As the Sr assimilated in skeletal tissues relies on food intake, particular diets and/or land used for agriculture can alter these signals, regardless of the mobility of the populations investigated. Examples for the impact of diet on $^{87}Sr/^{86}Sr$ include Wright, (2005), Fenner and Wright (2014), and Dalle et al. (2022), showing that a high consumption of salt skewed the $^{87}Sr/^{86}Sr$ values of Maya and Roman populations towards the current sea water value of 0.7092 (McArthur et al., 2001). Similarly, the consumption of marine resources was shown to have impacted $^{87}Sr/^{86}Sr$ values of a medieval population in Finland (Lahtinen et al., 2020). Perry et al., (2017) demonstrated that the importation of cereals from the Nile area affected $^{87}Sr/^{86}Sr$ values of Byzantine populations living in Jordan. Buckley et al., (2021) suggested that the import of limestone from sources located between 60 and 150 km away from Teotihuacan could have caused an upward shift in the $^{87}Sr/^{86}Sr$ of the city's population through the traditional process of nixtamalization, consisting of the soaking of dried maize kernels in an alkali solution of lime or wood ash. Differences in land use have been demonstrated to influence $^{87}Sr/^{86}Sr$ in cases from Neolithic Hungary (Depaermentier et al., 2020), Neolithic to Bronze Age Ireland (Snoeck et al., 2020a), Bronze Age Scotland (Schulting et al., 2023), Late Bronze Age Austria (Fritzl et al., 2024) and the early medieval Netherlands (Veselka et al., 2021), and point to the importance of understanding the surrounding environment to adequately interpret the $^{87}Sr/^{86}Sr$ values measured within a given site and on a diachronic basis.

Changes in diet, food sourcing or landscape use are important factors to take into consideration when discussing $^{87}Sr/^{86}Sr$ analyses in the Roman world. The inclusion of a territory within the Roman Empire could bring changes in the material culture, techniques and day-to-day habits of its inhabitants, including cooking and agricultural traditions (Roymans and Derks, 2011). The integration of a territory into the empire also meant greater integration to the empire's trade networks, and potential increases in exports and imports. For changes in dietary practices, the material culture (e.g. Banducci, 2018), archeozoological (e.g. Azaza and Colominas, 2020; Trentacoste et al., 2021) or archaeobotanical (e.g. Bouby et al., 2022; van der Veen et al., 2008) remains can be relied upon for insights into the food consumed on a daily basis, and show phenomena such as a rise in pork consumption or the introduction of new species of plants, fruits and herbs. Stable isotope ratios can provide useful insights as well, and have shown a variety of dietary practices across the whole empire (e.g. Chenery et al., 2010; Craig et al., 2009; García-Moreno et al., 2016; Keenleyside et al., 2009; Killgrove and Tykot, 2013; Lightfoot et al., 2012; Redfern et al., 2010).

Understanding patterns of land-use with $^{87}Sr/^{86}Sr$ requires an understanding of the values encountered around an archaeological site, which can be studied through the construction of an environmental baseline. Several methods exist to construct such a baseline, among which the use of modern plants (Holt et al., 2021) which is one of the most commonly used methods (Bataille et al., 2020; Holt et al., 2021; Janzen et al., 2020; Snoeck et al., 2020b; Wang et al., 2023). A recent map using plants for the construction of a baseline has been created for Belgium (Sengeløv et al., 2025), and will be used in this study for the interpretation of the human data.

2. Archaeological context

The *vicus* of Tienen (Tirlemont in French), was part of the *civitas Tungrorum*, and located on an important road linking Cologne (present-day Germany) to Boulogne-sur-Mer (present-day France), passing by the *civitas'* capital Tongeren (present-day Belgium). Tienen was founded around 10 AD (Verbeelen, 2021) and the construction of the *vicus* was done *ex-nihilo*, as no trace of an immediate previous settlement was encountered at the site (Martens, 2012). Gallo-Roman Tienen's occupation has since been continuous. Tienen was an important center within the *civitas Tungrorum* and was considered the second largest settlement after its capital Tongeren. As a *vicus*, the settlement had administrative functions. However, Tienen is best known for its role as a big center of craft production, with workshops dedicated to ceramics, bronze, iron, glass, textile, and leather production (Martens et al., 2002a; Martens, 2012). The presence of clay sources in the immediate vicinity of the settlement likely motivated the ceramic production, which was the primary industry (Martens, 2012) and can be accounted for the continuity of this craft during all of Tienen's Roman occupation (Borgers et al., 2020). As such, the population of Tienen is thought to have been mainly composed of families involved in the craft and/or trade of these products. There is little evidence of socio-economic variety within the *vicus.* The lack of evidence for a wealthy section of the population (based on material culture) suggests that the craft production was owned and supervised by individuals not living within the settlement (Martens, 2012). Similarly, there is no evidence that the people living in the *vicus* also owned villa estates or farms in the countryside. Such a focus on craft production implies that Tienen inhabitants were not self-sufficient regarding agricultural production, and that the importations of resources from the local area or even beyond were necessary for the subsistence of the settlement's population (Martens, 2012; Méniel et al., 2006; Roymans and Derks, 2011). Consequently, the average inhabitant of Tienen is thought to have benefited from a certain degree of personal wealth. This status allowed inhabitants a decent access to a wide range of imported products and goods (Martens, 2012). This is reflected in the ceramic imports found in Tienen, such as wine amphoras from southern Gaul (Marseille and the Rhône valley), *defrutum* amphorae, olive oil amphorae, or imported pots with products from the Ardennes-Eifel area. In the archaeobotanical charred finds of the associated Grijpenveld cemetery, the presence of non-local products such as grape and olive remains are more proof of connection to this wide trade network and of the imports that came with it (Cooremans, 2008).

On the bases of ceramic typology, both imported and locally produced, Tienen's occupation has been divided in four phases. Theses phases reflect changes and evolutions experienced within the *vicus*, also echoing the cultural and political context of the *civitas* (Martens, 2012).

Phase 1 (AD 1–70), described as a period of "*restructuring landscape and society*" (Martens, 2012), was a period where the key elements of the Gallo-Roman culture came into place, with the potential influence of newcomers familiar with these elements. This adoption of new traits is visible in various ways in Tienen, notably through the production of wheel-thrown pottery, previously not used, and forms differing from the previous Late Iron Age ones. These new shapes, found in the tableware, point to the introduction of new ways of cooking, drinking and eating (Martens, 2012), a phenomenon seen in other parts of the empire (Rodríguez Nóvoa et al., 2023). In the Augustean enclosure of the *vicus*, remains of bread wheat were found and indicate the early introduction of this crop in the area. This mirrors what is seen throughout the *civitas*, with the application of new agrarian techniques such as the Gallic harvesting machine (Roymans and Derks, 2011).

Phase 2 (AD 70–140) of occupation of Tienen has been defined as a period witnessing the "*creation of a new culture*", expressing new lifestyles and regional identities (Martens, 2012). The circulation of people, goods and ideas was facilitated through the construction of the road network and bridges, and as a consequence, a larger range of imported and locally produced foodstuff became more available and were found within the *vicus*. The ceramic assemblage also shows the introduction of new forms and types, pointing to changes in the preparation of food. The landscape of the *civitas* was more intensively used than in the preceding phases (Bakels, 2009; Pigière, 2017; Roymans and Derks, 2011). The construction of the *horreum* in Tienen testifies of significant influx of grain from the villas, and the cattle bones found within the *vicus* point to an intensification of agriculture in the region, with products reaching the *vicus*. The craft production of Tienen intensified and diversified as well during Phase 2, with glass and textiles being produced within the *vicus*.

During Phase 3 (AD 140–200), life in Tienen is described as a "*flourishing culture and society*", echoing the relative stability known within the empire during that period (Martens, 2012). The imported ceramics, as well as the imported luxury items of bronze and glass, show a certain level of prosperity in the *vicus*. Contacts with surrounding and far areas developed even more and allowed Tienen's population access to a larger and wider availability of foodstuff. Imported products such as olive oil and *garum* became more widely available for consumption (Martens, 2012). As in Phase 2, the increase in cattle bones found within the *vicus* indicate an intensification of agriculture within the region.

In the fourth and last phase of occupation of Gallo-Roman Tienen (AD 200–300), the population became a "*regionally oriented community*". This was a response to the instability resulting of the weakening of the Germanic *limes* due to the civil wars, and to the incursion of populations from the other bank of the Rhine (Potter, 2014). This unstable context did not allow for the safe transportation and exchange of goods or people, and the imports therefore diminished. As a result, the subsistence system becomes much more self-reliant, and changes in the husbandry system or land-use are seen through the animal assemblage. However, the geopolitical context of the period did not entirely disturb Tienen's craft activities. The production of iron and bronze objects continued and so did the ceramic production, only restricted in the variety of forms produced (Martens, 2012).

Through all phases of Tienen's occupation, the Grijpenveld cemetery, connected to the periphery of the *vicus* and located on the south-western part of the settlement, was in use. The creation and definition of the cemetery, in its location outside of the delimitation of the *vicus* and expansion, was concomitant with the foundation of the *vicus* in the Augustan period. As of today, it is the only known cemetery associated with the *vicus* of Tienen. Following its complete excavation between 1997 and 2003, over 1400 funerary contexts were recovered. Despite many of the graves being found in a deteriorated state, this makes the Grijpenveld cemetery one of the largest excavated Gallo-Roman cemeteries in the Low Countries (Belgium, the Netherlands, and Luxembourg). The size of the cemetery would suggest that Grijpenveld was the main cemetery of the *vicus*.

The overwhelming majority of burials were cremation deposits, with only 19 inhumations encountered. Cremation was then the major funerary treatment for the inhabitants of the *vicus*, a trend observed in Belgium during Roman times (Capuzzo et al., 2020). However, cremation deposits found within the Grijpenveld cemetery are not uniform and show variations. The majority of the cremation deposits are composed of secondary deposits, being Brandgrubengrab (BRG), Brandschüttungsgrab (BSG), Bonepackgrave (BN) and Urngrave (U), according to the terminology of De Mulder (1994). This typology reflects differences relying on the presence/absence of a container, and the presence/absence of pyre debris. BRGs are the preferred funerary treatment during all phases. Primary deposits were also found, always in the form of busta, where the pyre was built above a pit, and the resulting burial deposit contains both pyre debris and cremated remains (Van Doorselaer, 1963).

Within the cemetery, there is no indication that some higher or lower class individuals were buried. This reflects what has been established for the *vicus* itself, that there is no indication that a significant lower class should be present, nor a higher one. Out of the over 1400 graves encountered in the cemetery, about a third could be attributed to a specific phase (n = 27, 281, 200 and 55 for each phase respectively), on the basis of the associated grave goods that could accompany the deposits. Proportions for each type of deposit varied slightly through phases. For cremations, *busta* always represent the least common type of cremation practice, oscillating between 1 and 4 per phase. For all phases, BRGs are the preferred funerary treatment. Variations in the proportion of each type of funerary deposit can be seen in Fig. 1.

During Phase 2 of the occupation, a small cluster of graves appeared to the southwest of the Grijpenveld cemetery, and remained in use through phases 2–4. This cluster of graves, reaching about 100 deposits, was termed the "small cemetery", in opposition to the main cemetery, located about 150 m away. No difference between the small and main cemetery were detected regarding funerary characteristics (type of deposit or frequency, nature and number of grave goods). It is possible that this small cemetery belonged to a villa in the vicinity of the *vicus*, but it remains unclear why a fraction of the population was buried separately (Martens, 2012).

The Avendoren tumulus, located next to the main road connecting the *vicus* to Boulogne, on the northwest of the settlement, was erected during phase 3. Through comparison of the funerary goods of other tumuli, and the presence of coins, the tumulus is dated to the end of the 2nd century CE (Massart et al., 2015; Mertens, 1952). The funerary chamber was planked with wood, and within it was found a lead urn, containing cremated remains. Numerous funerary goods accompanied the urn, ceramics and objects of bronze, silver, gold, glass and bone were found within the chamber. The nature of the funerary building and of the funerary deposits associated with the grave point to the remarkable status of the deceased, and of its link to the Tienen community (Massart et al., 2015; Mertens, 1952).

Through the integrated use of archaeological data and Sr isotope and concentration analyses, this paper suggests new insights into the lives of the communities that occupied this part of the Roman Empire, and provides new lines of evidence regarding the dietary habits, the food sourcing and the mobility of the Tienen community.

3. Materials and methods

3.1. Sample selection

Osteological assessment and documentation of the Grijpenveld cemetery was done for 859 deposits, but due to the fragmentary nature of the skeletal material, determining sex and age at death of most individuals was not possible. Still, no juveniles were recorded. For this study, 146 cremation deposits from the Grijpenveld cemetery were selected for $^{87}Sr/^{86}Sr$ and [Sr] analyses. Selection of the contexts was first done randomly, before being adjusted in order to reach 10–15 individuals per sub-category of the parameters investigated (phases, type

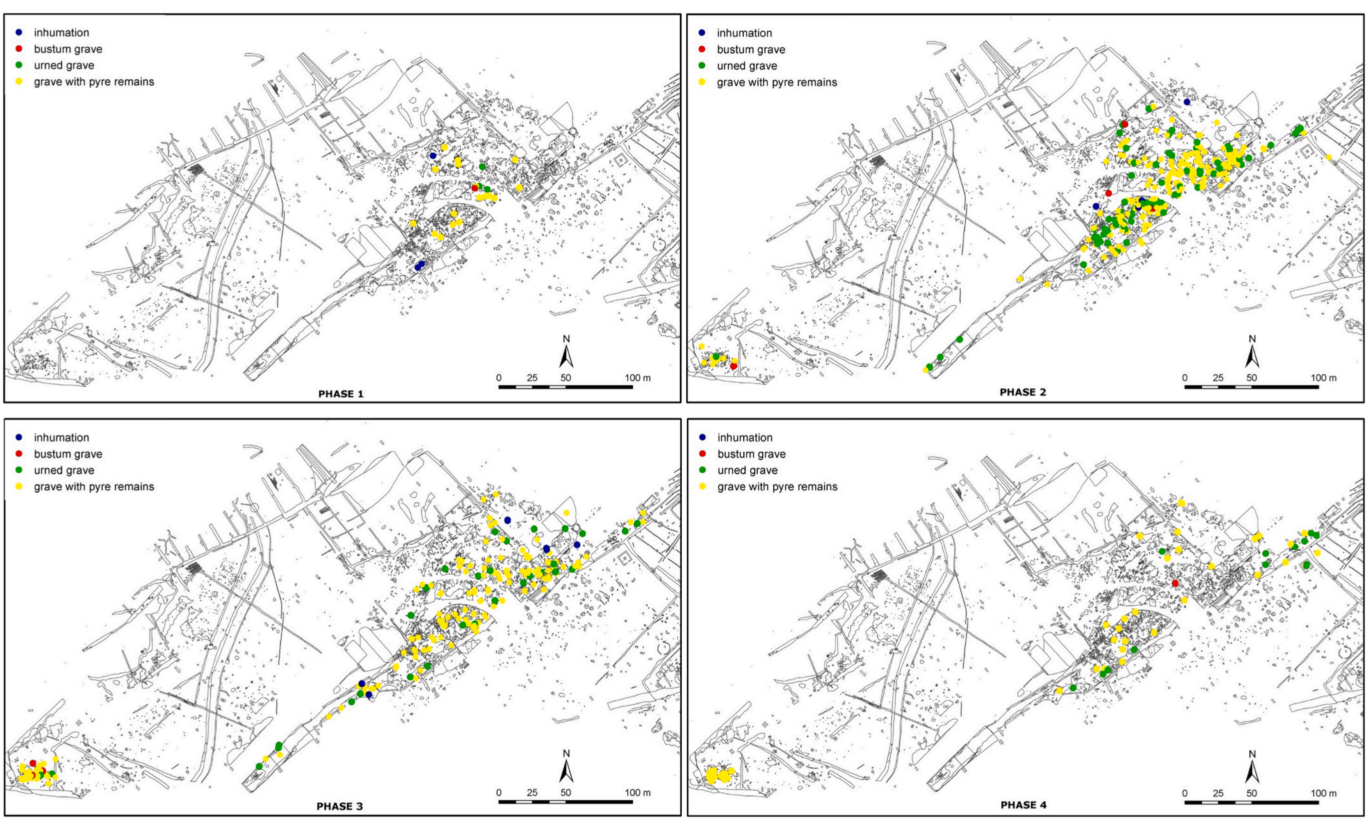

Fig. 1. Type of funerary deposit per phase within the main and the small cemeteries of Grijpenveld, maps adapted from Martens (2012).

of deposit, or location within the cemetery). The low number of deposits of a certain category existing within the cemetery (i.e. bustum), the state of preservation of the deposit, or the degree of calcination of the available bones were elements that prevented reaching that number for each category. Chronological attribution of the deposits to one phase was done on the basis of the associated grave material. Only a third of the deposits encountered within the cemetery presented such material, therefore not all selected deposits could be attributed to a specific phase. An overview of the selected samples per subcategory is provided in Table 1.

Following selection of the deposits, one sample was taken per deposit, ensuring that every result obtained after analysis is one of a single individual (see Sabaux et al., 2024). All samples were cortical bone from long bone diaphyses. Bones, unlike teeth, constantly remodel through life, with turnover rates varying from one skeletal part to another (see Frère et al., 2025 for a synthesis on turnover rates within the body). For long bone diaphyses, this can process can represent up to 20 years before death (Hedges et al., 2007; Manolagas, 2000). The elemental signal extracted from these parts therefore represents a mixture of elemental inputs of that time period. The use of such samples mean that mobility signals might be hindered: any individual reaching the *vicus* a few years before death could have had its signature altered by the local one, despite not initially coming from that place.

Only fully calcined bones (subjected to temperatures above 600–700 °C and appearing fully white as a result) were sampled, to ensure that the Sr obtained from these samples represents the *in vivo* ratio (Snoeck et al., 2015).

Similar criteria were applied to the selection of samples from the Avendoren tumulus, for which the osteological assessment established the presence of at least 3 individuals, due to the presence of 3 left pars petrosa. Two diaphysis and one rib were selected in this context.

Permission to analyse the individuals presented in this study was granted by the regional heritage depot at Tienen (managed by IOED PORTIVA).

3.2. *Sample preparation and analysis*

All steps of the analysis were undertaken at the Archaeology, Environmental Changes & Geo-Chemistry (AMGC) Research Unit of the Vrije Universiteit Brussel (VUB). Calcined bone fragments were cleaned, both mechanically and chemically, according to the protocol presented in Snoeck et al. 2015. After careful drilling of the outer surface with an ethanol-cleaned diamond tipped burr, samples were first rinsed three times with Milli-Q water, then pre-treated in approximately 10 mL of 1 M acetic acid in an ultrasonic bath for 10 min, and thoroughly rinsed with multiple Milli-Q ultrasonicated baths. They were left to dry in a 50 °C oven and manually powdered with an agate mortar and pestle. Per cremated bone, 15 mg of powder was weighed and digested in Teflon vials with 1 mL of 14 M HNO_3 acid, and left to dry on a 100 °C hotplate. Samples underwent strontium extraction following Gerritzen et al. (2024), using column chemistry and an ion exchange resin (Sr-Spec, Triskem).

Samples were measured using a Nu Plasma 3 multicollection inductively coupled plasma – mass spectrometer [ICP-MS] (PD017 from Nu Instruments, Wrexham, UK). Repeated measurements of the NBS987 and SRM1400 standards yielded $^{87}Sr/^{86}Sr = 0.710248 \pm 0.000025$ (2SD; n = 24) and an average value of 0.713113 ± 0.000031 (2SD; n = 59) respectively. This is consistent with the mean value for NBS987 of 0.710252 ± 13 (2SD for 88 analyses) obtained by Thermal Ionization Mass Spectrometry (TIMS) (Weis et al., 2006), the value of 0.713120 ± 0.000033 (2SD; n = 6; Lazzerini et al., 2021), and the long term average of AMGC (Gerritzen et al., 2024). A sample-standard bracketing (SSB) method with the recommended value of $^{87}Sr/^{86}Sr = 0.710248$ for NBS987 was used to normalize all sample measurements. Procedural blanks were considered negligeable (total Sr (V) of max 0.02 versus 7–10 V for analyses, equivalent to roughly 0.2 %). The $^{87}Sr/^{86}Sr$ is reported with a 2SE for each sample (absolute error of the individual sample analysis-internal error).

Sr and Ca concentrations were measured, in low and medium resolution mode respectively, using a Nu Instruments ATTOM ES high-resolution ICP-MS, using indium (In) as an internal standard and external calibration versus various matrix-matched certified reference materials (National Institute of Standards and Technology [NIST] standard reference material [SRM] SRM 1400, NIST SRM 1486, and NIST SRM 1515). The strontium data were then normalised to 40 wt% Ca to account for the varying loss of organic matter and carbonate during cremation (Boonants et al., 2025; Dalle et al., 2022). All [Sr] mentioned in the text and Supplementary data refer to Sr concentrations normalised to 40 wt% Ca. The accuracy of the procedure was evaluated by the analysis of an internal bioapatite standard (CBA). Based on repeated digestion and measurement of these reference materials, the analytical precision of the procedure is estimated to be better than 5 % relative standard deviation (1SD, n = 10).

3.3. *Statistics*

The normality of the distribution of the results was tested using a Shapiro-Wilk test. To detect variations between the study parameters, subgroup comparisons of mean strontium isotope and concentration values were analysed by period (Phase 1, 2, 3 and 4) using a Kruskal-Wallis test and a Dunn's post hoc test. Subgroup comparisons per type of deposit (BRG, BSG, BN, Urn, and *Bustum*) were carried using a Kruskal-Wallis test. Subgroup comparison for localisation in the cemetery (main vs. small cemetery) was carried using a Mann-Whitney *U* test. All statistical tests were run using the software PAST (version 4.03). Significance was set at $p < 0.05$.

3.4. *Baseline values*

To produce the BASr baseline for Tienen surroundings, $^{87}Sr/^{86}Sr$ values from plants from 21 sites within 30 km from the cemetery were selected (Sengeløv et al., 2025), among which 8 sites were specifically sampled for the measurement of values in the catchment area around Tienen (Fig. 2). The environment around Tienen is not geologically uniform (Fig. 2), and can roughly be divided in three areas. In the southwest, the outcropping lithologies are dominated by Lutetian and Priabonian sand and clay, whereas the southeast is dominated by Thanetian clay, siltstone and impure carbonate sediment. The area north of Tienen is dominated by Tortonian sand and sandstone and Rupelian clay. Sampling on the site itself was not possible due to the urbanised landscape of modern-day Tienen. Strontium data obtained from modern plant samples in Tienen's surroundings show $^{87}Sr/^{86}Sr$ ranging from

Table 1
Summary of the samples selected for analysis.

Chronology	Phase 1	Phase 2	Phase 3	Phase 4	Undetermined	Total
Number of samples	10	46	34	15	41	146
Type of deposit	BRG	BSG	BN	Urn	Bustum	Total
Number of samples	87	11	24	19	5	146
Location	Main cemetery	Small cemetery				Total
Number of samples	128	18				146

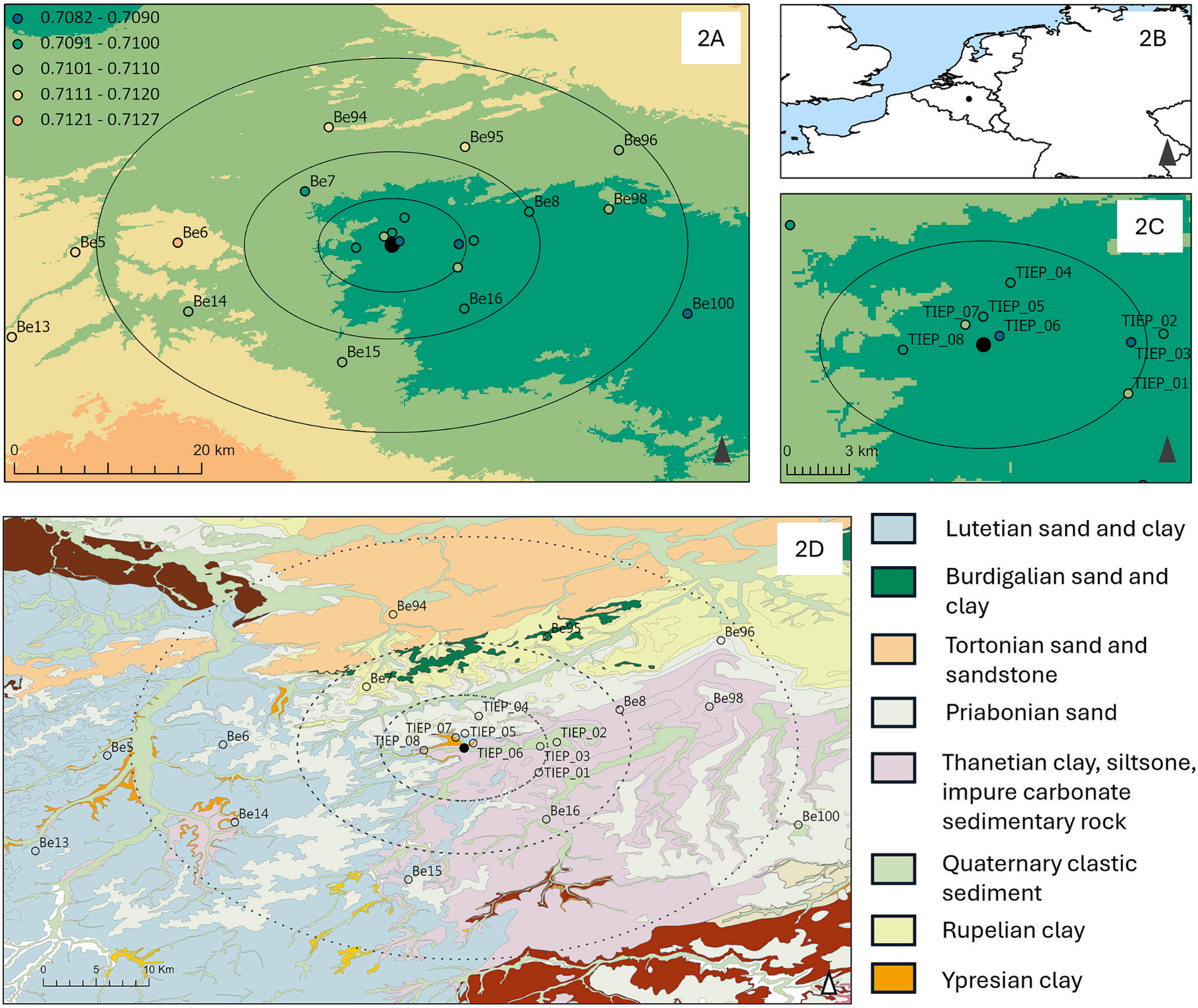

Fig. 2. 2A) BASr values for Tienen surroundings and associated $^{87}Sr/^{86}Sr$ values for the sampling points, extracted from Sengeløv et al. 2025. The value represented for each sampling point is the median of the values extracted from the grass, shrub and tree sample of each sampling site. Ellipses represent a 5, 10 and 20 km radius around Tienen. 2B) Location of Tienen. 2C) is a zoom-in of 2A, the ellipse represents a 5 km radius. 2D) Age and lithology of Tienen surroundings. Ellipses represent the same distances as in 2A (Modern political administrative boundaries from GeoBoundaries, Runfola et al., 2020).

0.7097 to 0.7135, with the highest values observed for sample Be13T, a tree sample on Lutetian sand and clay located 27 km southwest of the site. Lowest values were observed for sample TIEP_01G, a grass sample on Thanetian clay and siltstone at 5 km from the site to the southeast (Sengeløv et al., 2025).

Within this 30 km range, three sub ranges with a radius of 5, 10 and 20 km were determined. These ranges, adapted from studies from Cavazzuti et al., 2019, Schulting et al., 2023, and Snoeck et al., 2016, allow to nuance the dichotomous notion of local and non-local individuals, and to look at mobility on different scales.

Following Cavazzuti et al., 2019, the 5 km radius area is defined as the immediate site catchment area, and the 20 km as the immediate hinterland accessible within a day of travel by foot. The 10 km radius area represents therefore an intermediate value of closeness to the site. The range of $^{87}Sr/^{86}Sr$ values for 5 km and 10 km are the same, $^{87}Sr/^{86}Sr = 0.7081–0.7102$, and for the 20 km radius a range of 0.7081–0.7120 is seen.

4. Results

Strontium isotope ratios in cremated remains in Tienen range from 0.7088 (sample 00337) to 0.7117 (sample 00277), with a mean of 0.7100 (±0.004). Overall, the population distribution of the $^{87}Sr/^{86}Sr$ was deemed not normal by a Shapiro-Wilk test ($W = 0.95$, $p < 0.001$). Differences in $^{87}Sr/^{86}Sr$ values between chronological phases were detected with a Kruskal-Wallis test ($p < 0.001$). A Dunn's post hoc test detected no significant difference between phases 2 and 3 ($z = 0.807$, $p = 0.420$), but a difference was noted between phases 1 and 2 ($z = 2.437$, $p = 0.015$), between phases 3 and 4 ($z = 2.625$, $p = 0.009$), and between phases 1 and 4 ($z = 4.488$, $p < 0.001$). Simply put, phase 2 and 3 are relatively similar in their median value, but phase 1 and 4 are notably different, both within themselves and compared with the immediately preceding or following phase. Differences according to the type of burial or the location within the cemetery were not detected (respectively: Kruskal-Wallis, $\chi^2 = 5.041$, df = 4, $p = 0.283$; Mann Whitney U test, $z = 0.43155$, $p = 0.66607$). Distribution of the results depending on the location within the cemetery can be found in Supplementary 1.

Samples from the individual found in the Avendoren tumulus provided results ranging from 0.7097 (rib) to 0.7098 (diaphysis). The existence of 3 left pars petrosa within the deposit calls for caution when interpreting the results of these samples, as they could belong to three different individuals. However, as the range displayed is very narrow, a mean of both values for diaphyses (0.7098) is used for discussion of the results, and as a way to ensure comparison with results from the Grijpenveld cemetery.

Strontium concentrations ([Sr]) in cremated remains from Grijpenveld cemetery range from 83 to 293 ppm (Fig. 3). Population distribution was deemed not normal by a Shapiro-Wilk test ($W = 0.87$, $p < 0.001$). Differences between the criteria selected for our analysis were evaluated. For chronological phases and type of deposit, a Kruskal-Wallis test was applied. No significant difference was detected between any of the phases ($\chi^2 = 1.738$, df = 3, $p = 0.628$) or between any of the type of deposits ($\chi^2 = 6.217$, df = 4, $p = 0.183$). For location within the cemetery, a Mann-Whitney test was applied. No significant difference was detected between the values of the small and the main cemetery ($z = 0.59532$, $p = 0.55163$).

5. Discussion

5.1. Roman Belgium

As [Sr] showed no statistical difference due to chronology, location within the cemetery, or the type of deposit, the results from all samples are taken altogether to discuss Tienen's population. A comparison with existing data for Bronze, Iron Age, and Roman Belgium (Dalle et al., 2022; Sabaux et al., 2021) shows that Tienen's values plot with Roman values, meaning that [Sr] are relatively high (Fig. 3). A Kruskal Wallis followed by a Dunn's post-hoc test was applied on the different populations represented in Fig. 3 (see Supplementary for results). This test determined that Tienen's population is similar to values encountered within Roman Blicquy only, that are overall lower than those seen in Tienen. Roman populations from Fize-le-Marsal and Destelbergen are statistically different from Tienen's population and present higher values for [Sr]. Such differences in [Sr] between Roman populations has been highlighted in the United Kingdom, with values ranging between 34 and 255 ppm (Evans et al., 2012). Differences in [Sr] values between Tienen and sites like Fize-le-Marsal or Destelbergen could tentatively be explained by a difference in bioavailable [Sr] contents in the diet. [Sr] are not uniform in space and present variations according to regions or underlying geology, which can be reflected in the [Sr] of consumed plants (Frank et al., 2022; Montgomery, 2010). In the absence of published data for bioavailable [Sr] in Belgium, and without data for Metal Ages populations in the region of Tienen, it is not yet possible to explain the discrepancy between Roman values. However, Tienen's population is statistically different from all of Belgian Metal Ages populations by its higher [Sr]. In that context, Tienen's values can be assimilated to the general roman values encountered in Belgium (see Supplementary Information, S1). For Roman Belgium, such high concentrations have been associated with an increased consumption of salt compared to the Metal Ages (Dalle et al., 2022; James et al., 2025). Salt was produced and consumed prior to the integration of the area to the Roman Empire, but the production had a significant boom in the Flavian period (69–96 AD) and the late 2nd – early 3rd century in the neighboring *civitas Menapiorum* (Dekoninck, 2023). This increase in production likely was a response to an increasing demand for salt, used to preserve food, and used in the preparation of specific foodstuffs, like *garum*, a fermented fish sauce made with a brine. These phenomena occur alongside changes in the way people cooked and ate after their integration in the empire (e.g. Lightfoot et al., 2012; Redfern et al., 2010). In Tienen, changes can be seen in the ceramic assemblage, that testifies through the phases of the adoption of more Roman cuisine and diverse ways of preparing food (Martens, 2012), a phenomenon observed in other regions of the empire such as the northwestern Iberian peninsula (Rodríguez Nóvoa et al., 2023).

In Roman Belgium, increasing salt consumption have also been accompanied by shrinking $^{87}Sr/^{86}Sr$ ranges, moving towards the value of modern seawater, and by extension marine salt, of 0.7092 (Dalle et al., 2022; James et al., 2025). As $^{87}Sr/^{86}Sr$ values showed no differences according to location within the cemetery or type of deposit, but only between chronological phases, results are here discussed differing by their phase only. The shift of $^{87}Sr/^{86}Sr$ values towards the one of the seawater is seen in Tienen, with a gradual decrease of $^{87}Sr/^{86}Sr$ according to phases, becoming progressively closer to 0.7092 (Fig. 4). This trend is simultaneous with a rise in salt-related remains seen in the archaeological record of Tienen. From Phase 1, salt seem to be present in significant quantities, as the presence of numerous shards of salt containers in a Late Augustan enclosure of the site has been interpreted as redistribution of salt in a feasting context (Martens, 2015; Martens et al., 2002b). During Phase 2, *garum* is introduced in the *vicus*, which is seen through the presence of the amphora type Dressel 7/11, a typical transport amphora for fish sauce coming from the Mediterranean (Martens, 2012). During Phase 3, *garum* becomes even more available, and remains of fish sauce produced in northern Gaul have been found within the settlement (Van Neer et al., 2005), testifying to its wide use on a daily basis (Van Neer et al., 2010). However, this pattern of higher

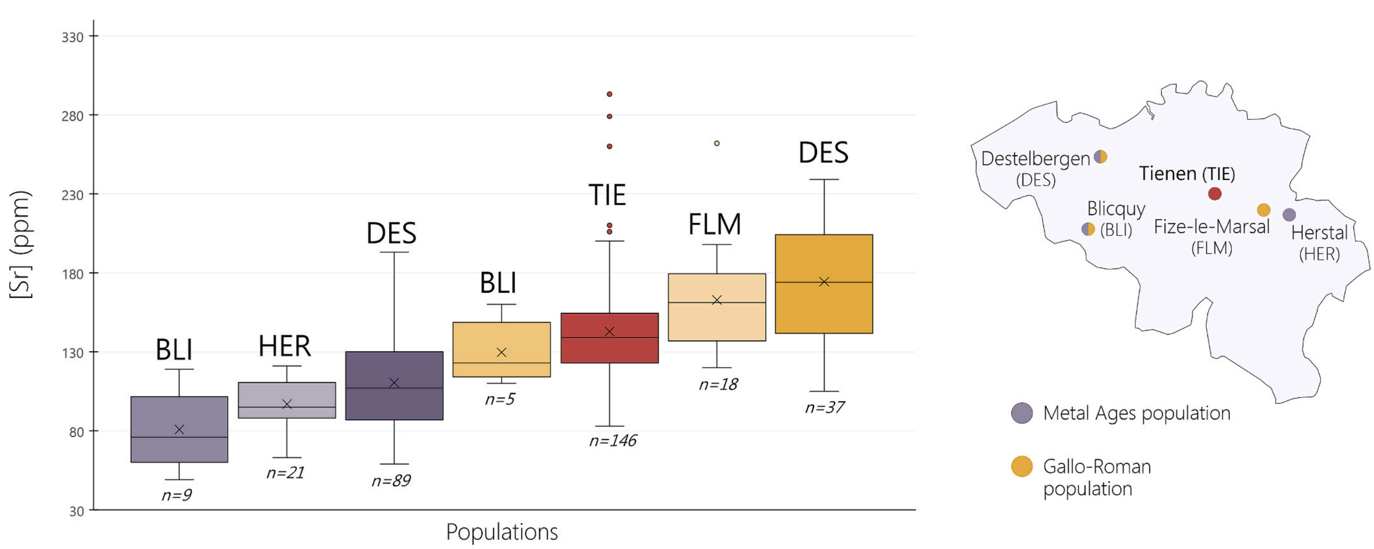

Fig. 3. [Sr] for Metal Ages and Roman populations in Belgium (comparison data from Dalle et al. 2022).

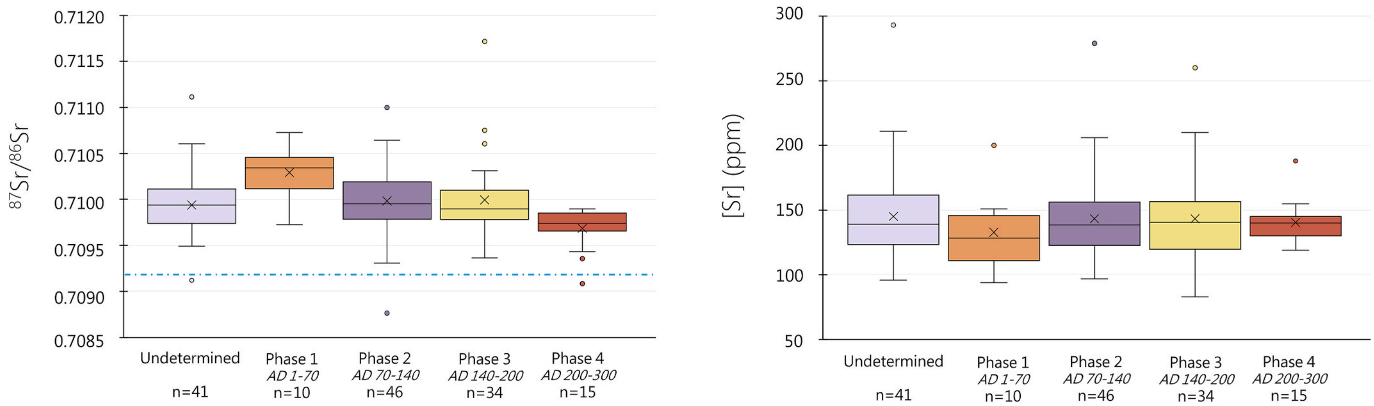

Fig. 4. ^{87}Sr/^{86}Sr and [Sr] values in Tienen according to phases. The dotted blue line represents the seawater value of 0.7092.

salt accessibility and potential consumption is not applicable to Phase 4. Despite a significant drop in ^{87}Sr/^{86}Sr values, there is no proof of a high salt consumption in Tienen during Phase 4. *Garum* seems to have been consumed during this phase, but the zooarchaeological remains associated with the fish sauce have been found in the ritual context of the Mithraeum only (Lentacker et al., 2004), and cannot be taken as an indication of a consumption by the inhabitants of the *vicus* on a regular basis (Martens, 2012). Phase 4 therefore challenges the idea that salt is the *sole* factor behind the pattern seen in the chronological phases at Tienen. Overlapping values between the environmental baseline and the marine value also adds difficulty to the strict identification of salt consumption. Besides, if an increased consumption of salt is to be taken as the major driver behind the chronological trend observed in ^{87}Sr/^{86}Sr values, a rise in [Sr] should also be expected. While visible, the slight increase in [Sr] from Phase 1 to 3, followed by a slight drop in Phase 4, is not statistically significant (Fig. 4). The impact of salt consumption on ^{87}Sr/^{86}Sr values in Tienen is therefore nuanced and cannot be taken as the unique factor responsible for the diachronic changes observed in ^{87}Sr/^{86}Sr values.

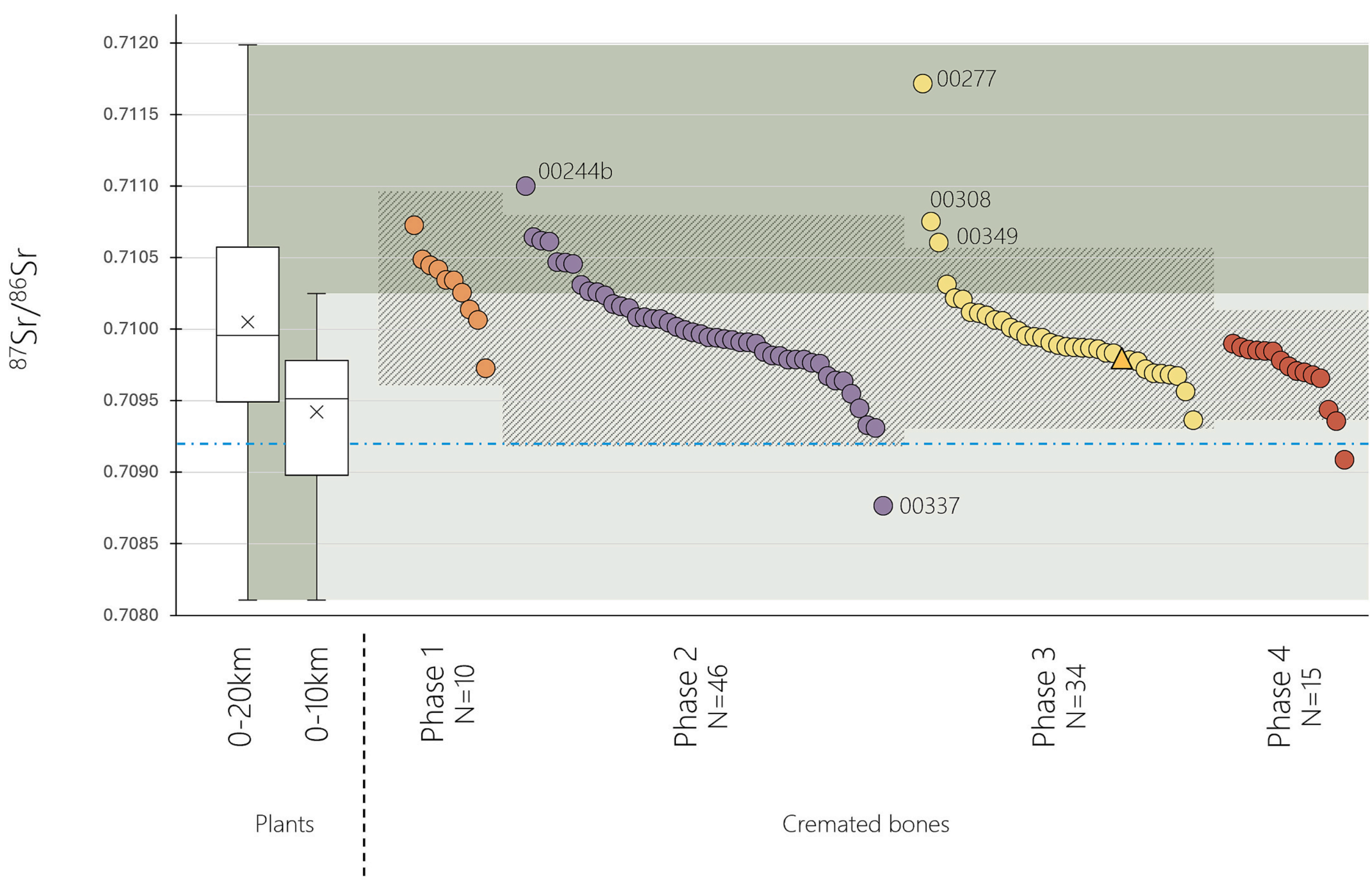

Fig. 5. Chronological variations of ^{87}Sr/^{86}Sr in human samples against the baseline values. The grey line shaded areas represent Tukey's IQR range for each phase. Human values falling outside of this range can be defined as outliers. Boxplots and the background green shading represent the ^{87}Sr/^{86}Sr range of all the plants measured within the radius defined. Circles stand for individuals from the Grijpenveld cemetery, the triangle represents the average value of the samples from the Avendoren tumulus (see Methods). The blue dotted line represents the seawater value of 0.7092. Values for the 0–10 and 0–20 km ranges were obtained with the ^{87}Sr/^{86}Sr results of each plant sample sampled within these radii.

5.2. Mobility and food sourcing

Examining the archaeological remains alongside the cultural characteristics observed and described for each phase can help understand the diachronic pattern observed in the $^{87}Sr/^{86}Sr$ data. During the three centuries of occupation of Tienen, it is not unlikely that land exploitation of the region or area of food importation changed. Considering the geological variety and partition of Tienen's hinterland, a varying reliance on some areas through cultivation, trade, and imports could shift the $^{87}Sr/^{86}Sr$ results observed in the different phases. In these conditions, and with the potential skewing impact of the consumption of salt highlighted by the overall high [Sr] within Tienen's population, a statistical assessment allows to differentiate individuals whose diet, in their origin, would differ enough from the majority of the population to be statistically distinct, rather than relying solely on a strict comparison of the human values to a local range. To that end, Tukey's IQR method, put forward by Lightfoot and O'Connell (2016), was elected, which uses 1.5 IQR to asses for outliers within a population. This method is less sensitive to outlier values to determine a range that can be defined as a norm. Tukey's IQR ranges can be seen for all phases in Fig. 5. This method is conservative, meaning that the number of outliers determined here is probably an underestimation to the reality. Additionally, since strontium isotopes do not display a continuous distribution in the environment, an underestimation of the identification of outliers through statistical assessment is probable as well. Results are examined per phase.

During Phase 1 (AD 1–70), despite the lowest and highest values exhibiting slightly different values from the remaining individuals, Tukey's IQR does not highlight any outliers that would imply mobility. However, within the IQR range (0.7096 – 0.7110), approximately half of the measured individuals overlap with values from the 0 to 10 km (Figs. 5 and 6) and approximately half of the measured individuals overlap with values from the 0 to 20 km baseline. This could either indicate that inhabitants from the first phase of occupation of Tienen subsisted on food grown within 20 km from the *vicus*, or that first generations of inhabitants of the *vicus* had new settlers coming from both the immediate site catchment and the immediate hinterland of the site. The pattern observed here is more likely due to the latter, involving mobility of individuals. Based on the archaeological record, Phase 1 is thought to have seen an influx of newcomers. New cooking wares, the adoption of a new cuisine, the high quality of the wheel-thrown ceramic produced within the *vicus*, and the presence of incense burners in funerary contexts are all Gallo-Roman traits and customs. They are rapidly displayed in the first phase of occupation of the site, which could be explained by the arrival of people already familiar with these elements (Martens, 2012). Additionally, this phase saw the arrival and settlement of new groups of population within the region (Raepsaet, 2013; Roymans et al., 2020). The pattern observed for Phase 1 is therefore likely due to the dynamics of the installation of a new *vicus*, attracting inhabitants from a rather wide territory.

As Phase 2 (AD 70–140) and 3 (AD 140–200) display the same broad cultural traits, with an intensification during Phase 3, and because the $^{87}Sr/^{86}Sr$ results displayed no statistical difference between these phases, these are discussed together here. As in Phase 1, the IQR ranges of both phases (0.7092–0.7108 and 0.7093–0.7106) overlap with values from the 0–10 km and the 0–20 km baseline range. However, unlike Phase 1, these ranges are unequally distributed, and most samples plot within the 0–10 km range: 36 out of 46 individuals, and 30 out of 34 individuals match with the 0–10 km range for phases 2 and 3 respectively. Archaeological remains from phase 2 and 3 in Tienen displayed signs of an intensification of agricultural activitiesin the region, with the products of the crops reaching the *vicus*. This intensification, seen in the age at death and morphology of the cattle remains found within the *civitas* and the *vicus* (Martens, 2012; Pigière, 2017), could mean reliance on a wider area and zones that were not exploited before through the establishment of villas, but also an intensification of agrarian work on territories that were already exploited, to obtain a better yield. Considering the geological variety of Tienen's hinterland (Fig. 2D), and the $^{87}Sr/^{86}Sr$ results of these geological formations (Fig. 2A), the results of phases 2 and 3 could also point to a larger reliance on products grown

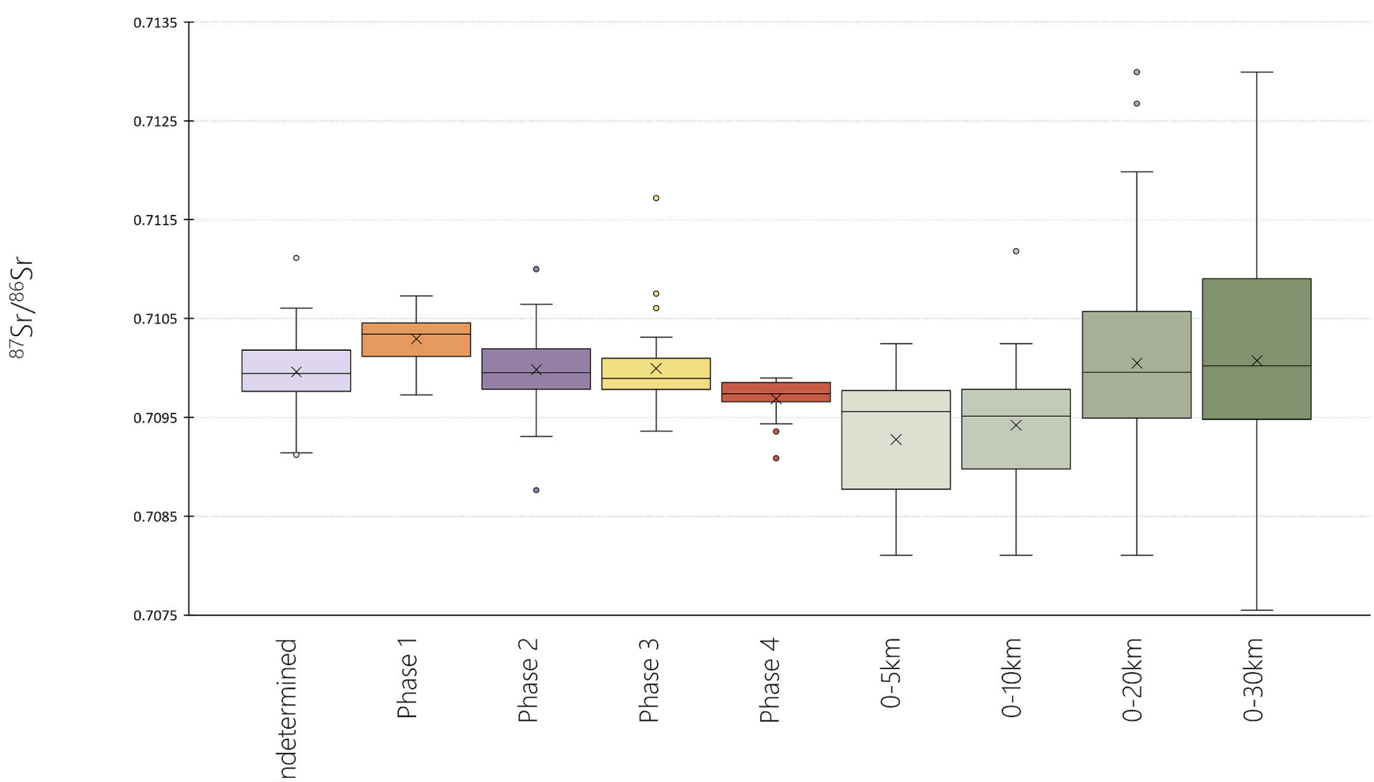

Fig. 6. $^{87}Sr/^{86}Sr$ values for human samples according to phases, and plant samples according to the distance from the site.

on lithologies with lower $^{87}Sr/^{86}Sr$ for agricultural purposes, such as the Thanetian, Quaternary, Rupelian, Ypresian lithologies, mostly found in the southeast of Tienen (Fig. 2). It is however difficult to establish if this larger reliance is due to new importation circuits, a better agricultural yield on these zones or a new exploitation of these areas compared to the preceding phase. Regardless, these results point to a rather consistent trade circuit between the hinterland and the *vicus* for phases 2 and 3, as $^{87}Sr/^{86}Sr$ patterns did not evolve greatly between these two phases.

Phase 4 (AD 200–300) has been described as a "regionally oriented community" (Martens, 2012), as a response to the general instability that characterised the *civitas* during the 3rd century. The weakening of the *limes* and the incursion of populations from the other side of the Rhine affected the security of the roads, and disrupted the trade network (Brulet, 2008). As a result, patterns of trade and products reaching Tienen changed, with imports from far away territories, such as Southern and Central Gaul, decreasing. Trade with closer regions, such as the Rhone or Meuse Valley, was also equally affected (Martens, 2012). Instead, ties are reinforced with local communities of the *civitas*, which can be seen through a stronger presence of Tienen wares in these settlements. As the trade network changed, subsistence strategies also adapted to the instability seen in the region. In the Belgian and Dutch loess region, which Tienen is part of, there is a drop in cattle remains, which has been linked to less reliance on cattle for agricultural purposes, as agriculture becomes less intensive (Pigière and Goffette, 2019). By the end of the 3rd century, the number of villas and rural settlements found within the *civitas* is significantly reduced, a phenomenon starting already by the late 2nd century in Northern Gaul (Van Thienen, 2020). Pollen records also show that woodland and forest areas are becoming more important between the 3rd and the 7th c., as a result of less intensive agricultural practices (Kooistra et al., 2004). In Tienen, changes in subsistence strategies are seen through a drop of the proportion of cattle and pigs, but a rise in the proportion of sheep remains, which would imply a change in the husbandry systems and the exploitation of the hinterland. This is accompanied by a significant increase in the proportion of chicken, that could be easily be kept within households. This has been interpreted as a change in land-use, and as a more centered and self-sufficient economy for the inhabitants of the *vicus* of Tienen (Martens, 2012). In light of these elements, the narrower Tukey's IQR range observed for Phase 4 (0.7094–0.7101, Fig. 5) is likely indicative of a narrower range of exploitation of the territory and of the provenance of food. Similarly, all individuals analysed for Phase 4 plot within the 10 km range defined by the baseline (identical to the 5 km range), and underline the more locally centered nature of the community. It is then very likely that the difference seen between Phase 3 and 4 can majorly be attributed to a change in food sourcing through the newly established trade networks, but also land-use from the surrounding communities. However, it should also be noted that Phase 4 presents a lower variability than the preceding phases, and that the outliers present less radiogenic values than the individuals from phases 1 to 3, with values exclusively found within the 0–10 km range. This suggests some changes in mobility patterns during phase 4, a phenomenon occurring again at a more restrained scale, likely due to the instability that characterized the region during this time.

5.3. Mobility in Roman Belgium

Generally speaking, outliers are relatively rare in the *vicus,* as only 7 out of the 147 individuals studied can be considered an outlier following Tukey's IQR range for their respective phases. A comparison with contemporary *vici* shows that the number of outliers in Tienen is proportionally common to what is seen elsewhere in the wider region. The same Tukey's IQR method applied to Tienen's population was applied to strontium data from Destelbergen and Fize-le-Marsal (Dalle et al., 2022), showing respectively 2 outliers out of 37 individuals, and 1 out of 18. All of Tienen's outliers, regardless of the chronological phase or of the possible motivation behind their movement, plot within the $^{87}Sr/^{86}Sr$ range defined within a 20 km radius from Tienen. The mobility seen in Tienen could therefore be one of a regional scale, as seen for example in Vagnari in Italy (Emery et al., 2018).

As the use of Tukey's IQR is admitted to be a rather conservative method to detect outliers, and therefore potential mobility, it is likely that the results presented in this paper generally underestimate the mobility witnessed in Tienen in its Roman history. Similarly, the use of bone diaphyses for this study likely provided an underestimated picture of the mobility occurring in the *vicus*, since mobility of that sort would only be detected for individuals coming to the settlement shortly before their death, leaving no time for their signal to be altered by the food consumed within the *vicus*. It is however notable that the higher number of outliers are still found within Phases 2 and 3, when the craft production of Tienen was well established, and increased in variety and volume. Mobility with the aim to find work has been demonstrated in several cases throughout the empire (Eckardt et al., 2010; de Ligt and Tacoma, 2016; Woolf, 2016). As Stark et al. (2022) suggested for the Jacques Brel necropolis in Saintes, which also acted as a craft production center, mobility to Tienen could have been motivated by work opportunities, especially since the production flourished during those two phases. In both phases 2 and 3, the lowest and highest $^{87}Sr/^{86}Sr$ values in Tienen are found (samples 00337 and 00277 respectively), and three additional individuals (00244b, 00308 and 00349) also plot outside of the Tukey's IQR ranges defined for each of these phases. Individual 00277 is especially noteworthy, as this individual presents the highest $^{87}Sr/^{86}Sr$ value measured in the Grijpenveld cemetery, but also has among the highest [Sr] (260 ppm) of the population. $^{87}Sr/^{86}Sr$ outliers for these phases do not display remarkable traits in their funerary context, which is in accordance with the description of the Grijpenveld cemetery as a cemetery for a rather homogenous segment of the population, neither particularly rich or poor. Conversely, the individual recovered from the Avendoren Tumulus shows no remarkable variation from the population found within the Grijpenveld cemetery during Phase 3, both for $^{87}Sr/^{86}Sr$ and [Sr] values (Fig. 5). While the exact identity or occupation of the deceased is unknown, it is notable that this person does not seem to have consumed a diet differing from the more common population of Tienen. The values retrieved from that person seem to show that neither the origin of the food or its nature differed, despite a status warranting a significantly different burial setting.

6. Conclusions

The $^{87}Sr/^{86}Sr$ and [Sr] data measured here investigated the mobility, food-sourcing patterns and dietary habits of a Gallo-Roman population in Belgium. Salt consumption was visible through ¯elevated [Sr] values for all phases. However, the chronological pattern observed in $^{87}Sr/^{86}Sr$ data can not entirely be attributed to the consumption of salt, as changes in food-sourcing or land-use could have also skewed $^{87}Sr/^{86}Sr$ values towards lower ones, such as those values encountered to the southeast of Tienen. This is especially visible in Phase 4, where no sign of salt consumption was detected in the archaeological record, despite $^{87}Sr/^{86}Sr$ values going towards 0.7092. Mobility was demonstrated as rather low through a statistical assessment per phase, with more outliers detected for Phases 2 and 3. This corresponds to periods of greater craft production for the *vicus*, and could point to mobility motivated by work. While the importation of food and the consumption of salt calls for cautious interpretation of mobility, this study demonstrates that by combining the use of a thorough $^{87}Sr/^{86}Sr$ baseline and a statistical assessment of the population, insights into mobility as well as food sourcing, land-use and diet can be made. Cremation was a frequent funerary practice throughout the Roman Empire, and traditional stable isotopic analyses are not possible on cremated remains, this study highlights how strontium analysis can be an important avenue for the understanding of Roman populations.

CRediT authorship contribution statement

Emma M. Legrand: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marleen Martens:** Writing – review & editing, Writing – original draft, Validation, Resources, Formal analysis, Data curation, Conceptualization. **Christina Cheung:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Barbara Veselka:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Tom Debruyne:** Resources, Data curation. **Guy De Mulder:** Writing – review & editing, Resources, Data curation, Conceptualization. **Steven Goderis:** Writing – review & editing, Methodology, Funding acquisition. **Sarah Dalle:** Writing – review & editing, Data curation. **Christophe Snoeck:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Hannah F. James:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Methodology, Data curation, Conceptualization.

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.2025.105371.

Data availability

All $^{87}Sr/^{86}Sr$ and [Sr] data are available as a dataset (Legrand et al., 2025) on the IsoArcH database (https://isoarch.eu/) under a CC- BY 4.0 license following the FAIR and CARE principles (Plomp et al., 2022; Salesse et al., 2018). Dataset can be accessed here: https://doi.org/10.48530/isoarch.2025.014

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