



OPEN Isotope analyses reveal chronological and bioarchaeological consistency at a tribal community of the Sântana de Mureş-Chernyakhov culture in Transylvania

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By the 4th century CE, the territory of post-Roman Dacia constituted the western frontier of the Sântana de Mureş-Chernyakhov culture's expansion. In this study, we analysed 26 individuals of the culture's eponymous cemetery in the Carpathians at Sântana de Mureş. Radiocarbon modeling implies that the cemetery might have been established a few years after the Roman Empire's retreat and was probably used only for a few decades at most. In the meantime, we could not identify the founding generation or any subsequent large-scale mobility within the community. Irrespective of regions, a harsh lifestyle might have characterized the studied individuals, who were probably affected by chronic and epigenetic diseases, strenuous physical exertion and poor overall health conditions. Inadequate intake of nutrients may also have contributed to a difficult lifestyle because access to terrestrial animal protein was modest while millet consumption uniformly dominated over other cereals. In contrast to the lifestyle of the previous provincial society, this type of diet might have been inherited from the predecessor Wielbark culture and most closely resembles that of other contemporary tribal communities, such as the Sarmatians in the Carpathian Basin.

Keywords Transylvania, Sântana de Mureş-Chernyakhov, Radiocarbon, Stable isotopes, Mobility, Diet reconstruction

Contrary to the importance of the province, Roman control of Dacia was relinquished during Emperor Aurelian's reign in 271 CE^{1,2}. The roads to Transylvania then became open to the tribal alliances living in the eastern part of the empire. During its final decades, the province was already subject to a series of external attacks, but it has been remained unclear if the tribes occupied the abandoned areas immediately or some time had passed after the evacuation of the Roman military units and civilian administration^{3,4}.

It is certain that during the 4th century CE, the eastern half of the Carpathian Basin already constituted the western edge of the extensive Sântana de Mureş-Chernyakhov culture (hereafter referred to as SCC)⁴. According to our current knowledge, the Wielbark culture may have preceded this complex archaeological horizon consisting of two 'sister cultures': the SCC can be linked to the Visigoths of the Tervingi, while the Chernyakhov culture can be linked to the Ostrogoths of the Greuthungi⁵. The ethnic composition of SCC is also known from historical sources and can be described as a tribal association of Germanic, Sarmatian and Thracian groups, led by the Goths⁶. The Gothic origin of the Chernyakhov culture has been proven by DNA analyses as well⁷.

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The Transylvanian region was the culture's last territorial acquisition, ranging across the south-eastern forest-steppe zone of Eurasia, from the lower Danube to the upper Siverskyi Donets Rivers^{8–10}. The SCC, as well as the local Dacian and remaining provincial communities supposedly coexisted within the Carpathians, characterized by several types of possible relationships (e.g., newcomers and native inhabitants or socially superior and inferior groups)^{9,11}. Tribal rule in Transylvania lasted for only a few generations and finally declined near the end of the 4th century CE, coinciding with the end of the SCC. This was partly due to the arrival of the Huns in the Black Sea region (after 375 CE), which completely changed life in the Carpathian Basin¹².

An SCC cemetery in Sântana de Mureș and our motivation

In 1903, a cemetery was discovered during sand mining in the area of Sântana de Mureș (Romania, N 46.576111, E 24.554167; 314 m a.s.l.), in the vicinity of Târgu Mureș (Fig. 1a). István Kovács, an archaeologist from the National Museum of Transylvania, began the excavation less than three days after the discovery, but the central part of the cemetery had already been destroyed by the mining activities (Fig. 1b). A rescue excavation was carried out on the edges of the sand pit, where a total of 80 graves were unearthed and five additional human skulls were found outside the burials^{9,13}. The high number of graves, representing more than a third of all burials of the SCC in Transylvania, makes Sântana de Mureș the largest cemetery among the known necropolises in the region, which are concentrated in the valleys of the Olt, Târnava Mare and Mureș Rivers (Fig. 1a). A more detailed history of the archaeological research related to the cemetery has been previously presented^{9,13}, thus here we offer only a short summary.

Based on the position of the burials, the cemetery may have been oriented in a west-east direction^{9,13}. The majority ($n = 61$) of the excavated graves were oriented in the north-south direction, but some graves ($n = 11$) were found in a west-east position, and one was oriented westward (Fig. 1b). All burials can be typochronologically dated to the general 4th century CE, or to the end of the 4th century CE. Accordingly, the

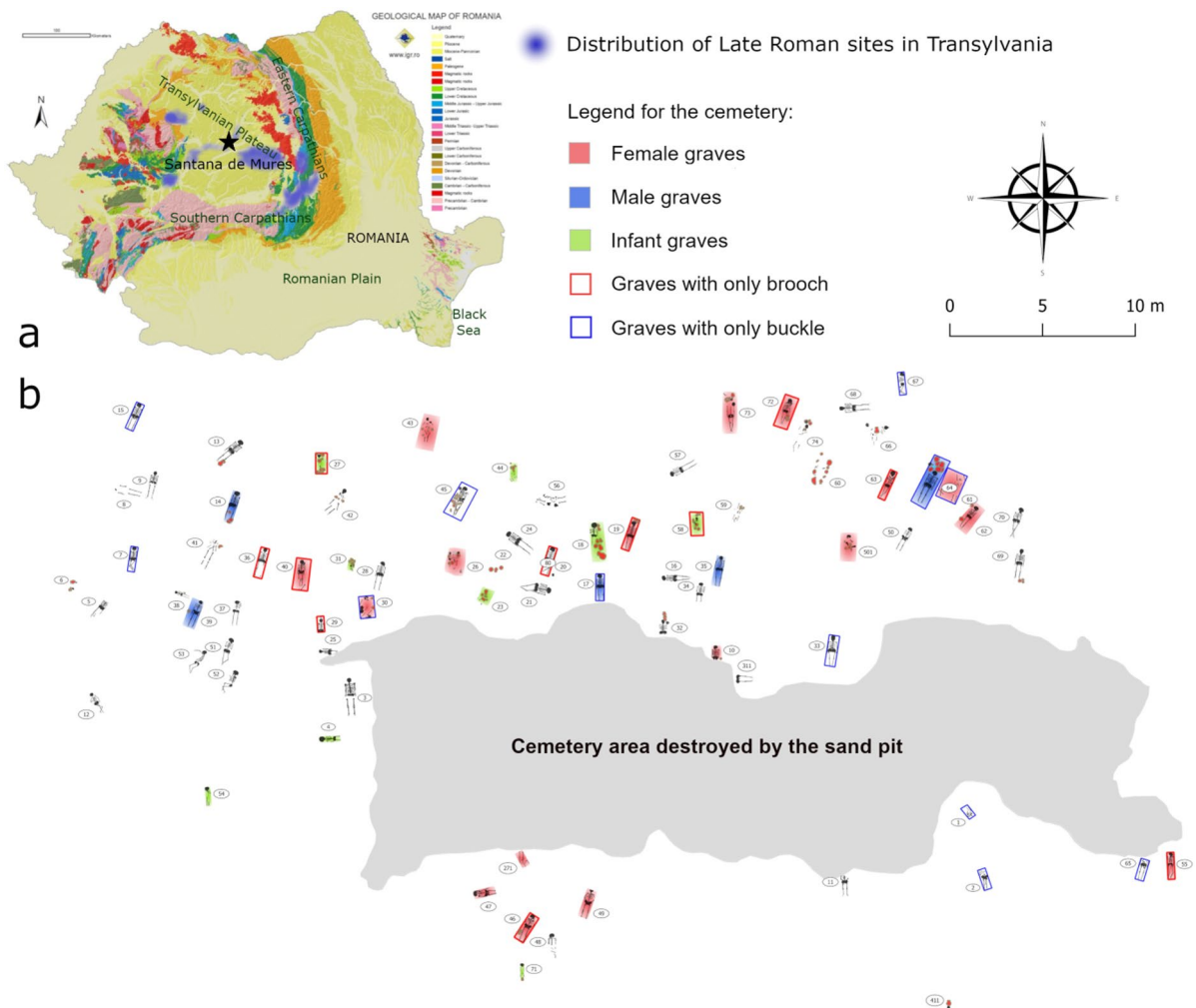


Fig. 1. **a** Top-down view geological map of Transylvania with the distribution of Late Roman sites. Sântana de Mureș is marked by a black star. **b** Map of the cemetery at Sântana de Mureș. The geological map was free of charge downloaded from the website of the Geological Institute of Romania, https://geoportal.igr.ro/galerie_geo, the cemetery map was created by Zsolt Körösfői using the QGIS 3.38 software.

graves with a W-E orientation have been assumed to be slightly later than those with a more traditional N-S orientation, but confirmation of this assumption is difficult due to the small number of related finds. Only two W-E orientated graves contained artifacts, but the fragment of a double-plate brooch indeed dates grave M56 to the late period of the cemetery. The presence of combs, double brooches (iron and bronze), single buckles (iron, bronze and silver) or possibly more buckles may correspond to the sex of the decedent (Fig. 2d–g)⁹.

Following the excavation, the skeletal remains of 29 out of the 80 total graves were stored in the Museum of Cluj-Napoca, Romania. In our study, we sampled all human and animal skeletal material to complement the existing archaeological observations⁹ with new bioarchaeological results. We aimed to estimate the starting time and the possible chronology of this unique cemetery, in accordance with peopling and abandonment of the site. Stable strontium isotope analysis ($^{87}\text{Sr}/^{86}\text{Sr}$) was applied to reveal the immigrant founding generation of the community and other mobility tendencies. Finally, stable carbon and nitrogen isotope analyses (data expressed in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, respectively) were undertaken to help us in clarification of any sociocultural continuity after the retreat of the Roman Empire, or any relationship with the predecessor cultures in the north or other contemporaneous tribal groups across Europe.

Bioarchaeological approach

Although scientific investigations (physical anthropological examinations, genetic studies and isotopic analyses) have remarkably helped to provide a more accurate and detailed understanding of the human population dynamics, mobility tendencies and the overall health and lifestyles of past individuals over the world, Eastern Europe has remained under-represented^{14–18}. Anthropological analyses allow the determination of biological sex, age at death, skeletal morphologies and paleopathologies of individuals in different populations^{19,20}. Using the $^{87}\text{Sr}/^{86}\text{Sr}$ result of dental enamel, scientists can possibly determine the birthplace and mobility tendencies of studied humans and animals^{21,22}. Bioavailable strontium (BASr) enters the skeletal parts through absorption



Fig. 2. Examples of the general (M16) and late phase (M40) burials from the cemetery of Sântana de Mureș. **a** Sacralisation is a congenital skeletal irregularity, which was found in the elderly female from grave M19. **b, c** Red-walled clay vessels, **d** oval buckles and **e** bone combs characterise the general phase, while **f** brooches with inverted feet, **g** buckles with a thickening frame, **h** conical glasses and the **i** faceted red vessels are typical of the late phase. Grave photos, object photos and object drawings were made by András Lehóczki (1903, National History Museum of Transylvania), Péter Lapedus (2023) and Albert Manz (1911, National History Museum of Transylvania), respectively.

from food and drinks, so to determine spatial movements, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio from the enamel fraction is compared to a baseline built up using local soil, plant and faunal samples²³. However, the interpretation of $^{87}\text{Sr}/^{86}\text{Sr}$ values must be done with caution, as they come with a major geographic limitation. The same rock type (e.g., basalt) in different locations has similar or identical $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, thereby making it impossible to determine an individual's geographic origin using strontium isotope ratios alone. Additionally, previous studies have shown that bone is much more susceptible to diagenesis, which can affect its stable isotopic composition. As such, dental enamel is preferred as the source for strontium isotope analysis^{24,25}. Stable carbon and nitrogen isotope analyses of skeletal apatite and collagen are used to determine the relative consumption of C_3 and C_4 plants, as well as animal protein by the studied individuals^{26–29}. For example, cereals, like wheat, barley and rye, and most others are C_3 plants and have lower $\delta^{13}\text{C}$ values (mean around -27‰) compared to C_4 plants, which include millet and maize (mean around -13‰)^{30,31}. The $\delta^{15}\text{N}$ values of terrestrial consumers typically range between 7‰ and 10‰ , whereas higher consumption of plants results in lower values and more animal protein in the diet leads to higher values. Aquatic animal protein sources are more enriched in ^{15}N , which usually causes the consumer's $\delta^{15}\text{N}$ value to exceed 10‰ ³².

Results
Anthropological analyses

The biological sex distribution of the preserved human individuals ($n = 26$) was dominated by females (38%) compared to males (27%) in the excavated part of the cemetery (Table 1). Unfortunately, the artificial selection of skeletons to be preserved in the museum might have induced an apparent shift in the distribution of biological sex but our findings were also supported by the archaeological observations of the sex-related grave goods. The number of infants is low (12%), while the sex of 23% of the skeletons was unidentifiable (Supplementary Table 1). The individuals ranged from medium to tall in height, with females and males measuring 1.53–1.60 m and 1.65–1.73 m, respectively. The craniometrical analyses of M30 and a disturbed skull (II. 8166) showed a dolichocranic skull type³³. The paleopathological analyses did not reveal any evidence of violence, but several markers indicating disease were documented (Supplementary Table 1)³⁴. Periodontal disease was the most common, in a total of seven cases (35%). Dental malformation (impacted mandibular canine, grave M50) was documented in one case³⁵. Diseases related to lifestyle, such as osteoarthritis (in two cases, graves M17 and M53), were typical for both sexes. In the case of a male from grave M39, the strong muscle adhesions on the skeleton suggest intense physical work. There are also several signs of chronic diseases, which are indicated by cribra cranii (disturbed skull, II.8166), cribra orbitalia (M31, M55, M50/51), enamel hypoplasia (disturbed skull, II.8169) and abnormal blood vessel impressions (ABVI, disturbed skull, II.8169). In one case (M19, elderly female), traces of sacralisation were observed (Fig. 2a). Epigenetic features of skulls and postcranial skeletons are also common (34%) in the cemetery³⁶. The following paleopathogenic cases and epigenetic traits could also be observed: metabolic disorders (19%), non-specific diseases (8%) and stress markers (4%).

AMS¹⁴C dating and Bayesian modeling

Two (graves M41 and M59) out of 28 samples did not yield appropriate collagen³¹, thus, these samples were not considered in our evaluation. The distributions of the calibrated and modelled ages are shown in Fig. 3a. Regarding only the calibrated radiocarbon results, the starting date of the earliest grave from the general phase is 230 CE, while the ending date for the latest grave is 362 CE (95.4% probability). The same features for the late phase of the cemetery are 247 and 410 CE, respectively. This implies a total usage period of 180 yrs for the excavated cemetery, which was shortened by applying ¹⁴C-based chronological modeling. According to the historical sources of Eutropius³⁷, the Romans relinquished the province of Dacia around 271 CE, so this calendar date was added as a *terminus post quem* (TPQ) date to the model (Supplementary Text1). With this TPQ, the model places the starting date of the cemetery into the more probable range of 275–326 CE (2σ probability, Fig. 3b). Considering the relative chronology of grave goods characterizing the two phases, the start of the late phase is modelled to occur between 319 and 346 CE (2σ probability, Fig. 3c), while its end is placed before or at 383 CE (Fig. 3d), which coincides with the arrival of the Huns around 375 CE¹¹. Based on the starting date of the general phase and the ending date of the late phase, the cemetery's period of use may cover 18–94 years (2σ probability), but considering only 1σ , a smaller range of 30–68 years can also be possible (Fig. 3e). The agreement factor of the model (A_{model}) is 198, which means that the raw results fit very well into the model and there are no significant outliers among the data.

Sex/age	Number	Percent (%)	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)	$^{87}\text{Sr}/^{86}\text{Sr}$
Female	10	38	-15.7 ± 0.6	9.7 ± 1.0	0.709826 ± 0.000366
Male	7	27	-15.4 ± 0.6	10.4 ± 0.9	0.709568 ± 0.000270
Unidentified	6	23	-15.9 ± 0.7	10.1 ± 0.2	0.709520 ± 0.000290
Infant	3	12	-12.5 ± 2.3	11.5 ± 0.6	0.709598 ± 0.000115

Table 1. Summary of the anthropological and stable isotope results of the individuals involved in the bioarchaeological analyses.

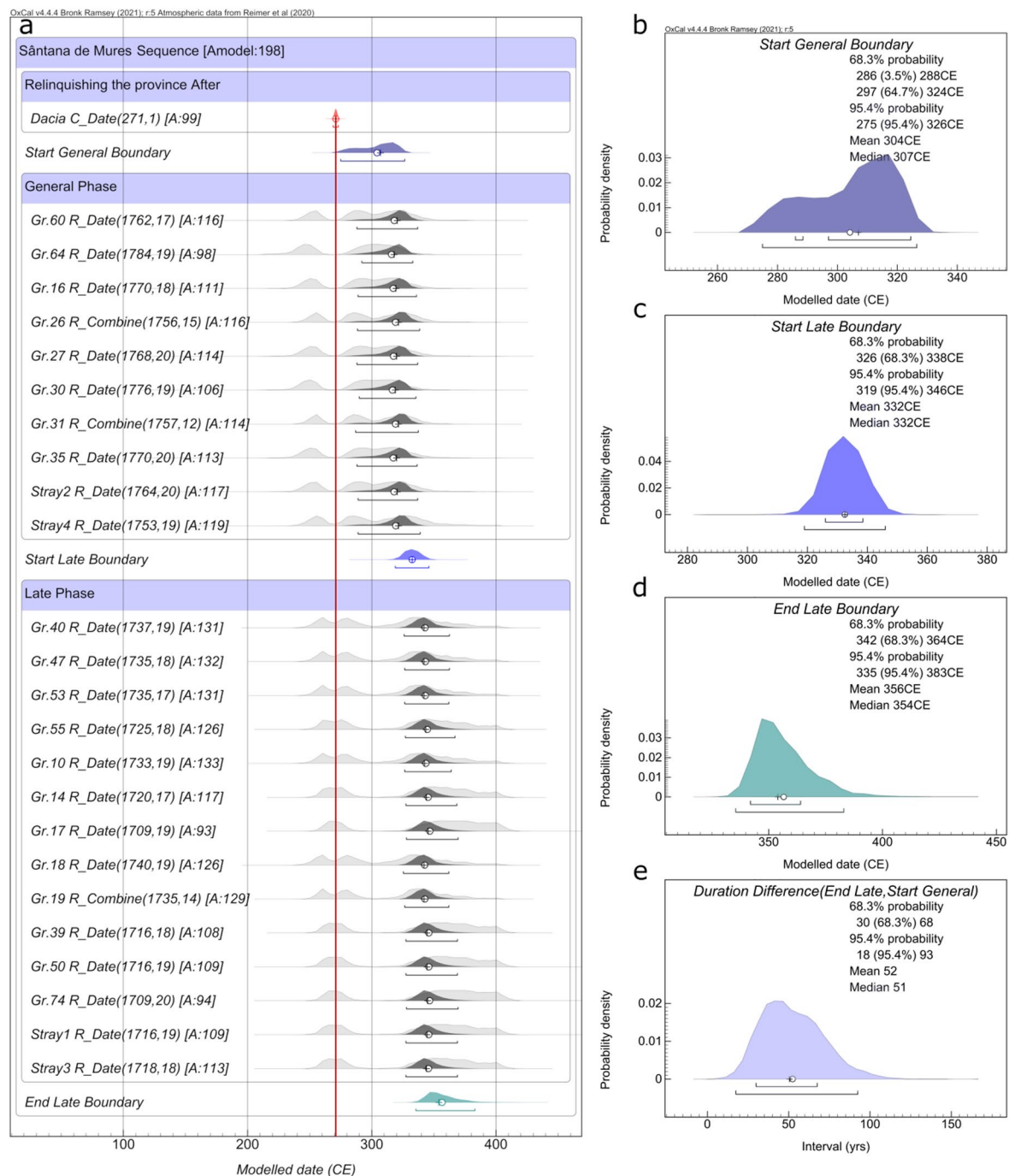


Fig. 3. **a** Distributions of the calibrated and modelled ages. For a better view, the date of 271 CE is marked with a vertical red line and the distributions of the **b** General Start, **c** Late Start, **d** End and **e** Duration constraints are also shown. Crest and circle symbols represent the median and mean values of the density functions, respectively.

Strontium isotope values

Although bone is not recommended for Sr analysis, we did not have the opportunity to choose tooth enamel samples from each grave, so bone samples were also included in our study, along with dental samples. Price et al. (2002) highlighted the need for comparative faunal baselines to evaluate the integrity of bone-derived isotopic signatures and recommended caution when interpreting porous skeletal elements³⁸, thus, we took the results of enamel samples as threshold of an accepting range for bones.

After thorough physical and chemical processing, the human and animal skeletal samples yielded an average $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.709668 ± 0.000326 and 0.709736 ± 0.000226 , respectively (Fig. 4). The results of the human bones fit well into the range assigned by the human teeth. Based on biological sex determination, the

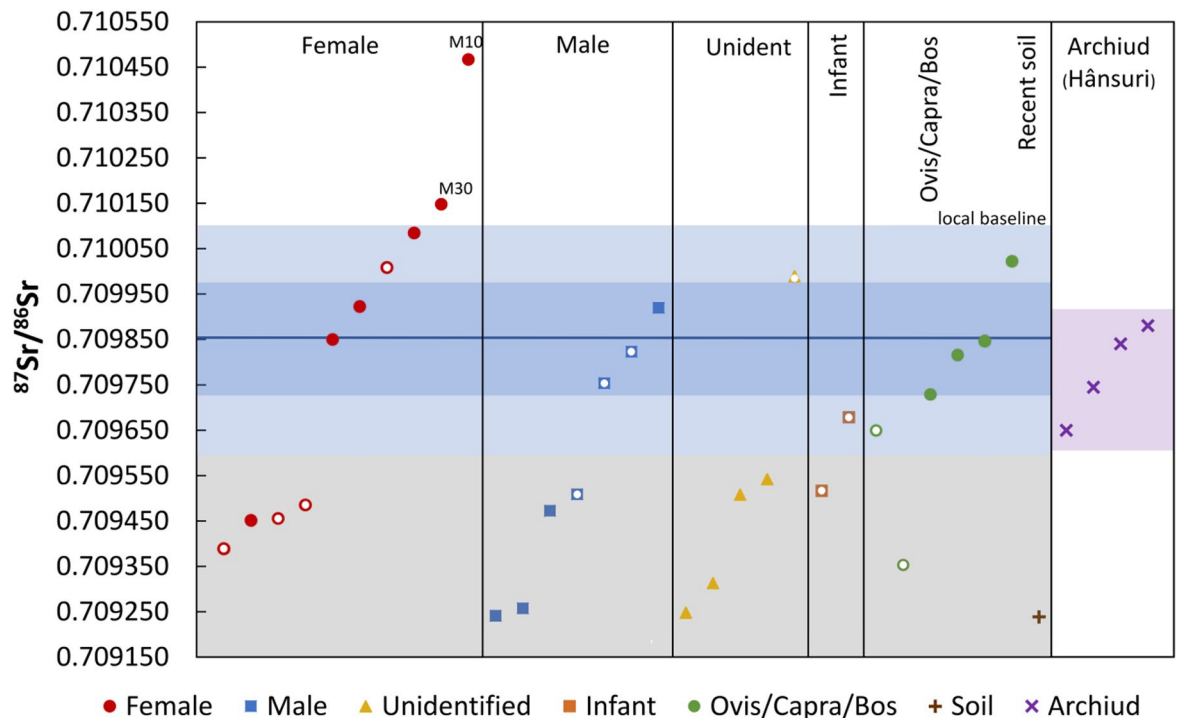


Fig. 4. Strontium isotope compositions of bone (marked by white dot in the symbol) and tooth enamel samples from the Sântana de Mureș cemetery. The dark and light blue areas represent the 1 and 2 σ possibility ranges of the average values calculated for the animal teeth, respectively. The grey area expands the local BASr isotope range with the strontium isotope ratio of a modern soil sample. Individuals from the Archiud (Hânsuri) cemetery in Transylvania, Romania are also depicted.

averages obtained for female ($n=10$), male ($n=7$), unidentifiable adult ($n=5$) and children ($n=2$) remains are 0.709826 ± 0.000366 , 0.709568 ± 0.000270 , 0.709598 ± 0.000115 and 0.709520 ± 0.000290 , respectively (Table 1). The values of the sheep/goat (*Ovis/Capra*) enamels and the cattle (*Bos taurus*) femur are congruent, but the value of 0.709353 for the sheep/goat calcaneus bone is significantly different. Hence, only the enamel from the sheep/goat teeth were at first considered to represent the typical BASr signal for the site, as their ages at death were estimated to be 1–2 years old or younger. Later, the local baseline was extended with a modern soil sample ($^{87}\text{Sr}/^{86}\text{Sr}=0.709238 \pm 0.000104$) collected at a depth of 10 cm at the excavation site, although some isotopic differences due to recent residential disturbance of the upper soil layer are conceivable. This extended baseline provided the final 2 σ $^{87}\text{Sr}/^{86}\text{Sr}$ range of all local samples to be broadened, spanning from 0.709135 to 0.710099. Considering the 2 σ probability range of the primary baseline, we found 16 samples that failed to correspond to the criterion of local individuals. Considering the recent soil sample as well, only the dental $^{87}\text{Sr}/^{86}\text{Sr}$ values of two females (M10 and M30) were outside of the local range.

Stable carbon and nitrogen isotope values

The mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values obtained for the available animal (sheep/goat and cattle) teeth and bones were -21.0 ± 0.6 and 7.3 ± 1.3 ‰, respectively. Their number is low, but due to the direct relationship with the cemetery, they were used as a basis for comparison to study the diet of humans. The single $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of the individuals are depicted in Fig. 5a and b, respectively. The mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for the humans were -15.3 ± 1.2 ‰ and 10.1 ± 1.0 ‰, respectively. The mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values and their 1 σ standard deviations for the females were -15.7 ± 0.6 ‰ and 9.7 ± 1.0 ‰, respectively, while those for the males were -15.4 ± 0.6 ‰ and 10.4 ± 0.9 ‰, respectively (Table 1). The mean stable carbon and nitrogen isotope values for the two children and the individuals of unidentified sex were -12.5 ± 2.3 ‰ and 11.5 ± 0.6 ‰, as well as -15.9 ± 0.7 ‰ and 10.1 ± 0.2 ‰, respectively. The mean carbon isotope values for males and females (normally distributed) are essentially indistinguishable using a statistical two-sample t-test ($t = -1.0551$; $p = 0.3101$). The means of the nitrogen isotope values are not significantly different either (two-sample t-test, $t = -1.5916$; $p = 0.1350$). However, when the most distinct nitrogen isotope results are excluded from the female (stray find, 12.0‰) and male datasets (grave M64, 8.8‰), a significant difference between the nitrogen isotopic means becomes clear (two-sample t-test, $t = -4.1527$; $p = 0.0023$). For the children, both the carbon and the nitrogen isotope values are different from the adult's means and no statistical analyses were conducted due to the low number of child samples. Comparing all $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isotopic values to the Sr or ^{14}C results, no significant correlation or trend could be revealed.

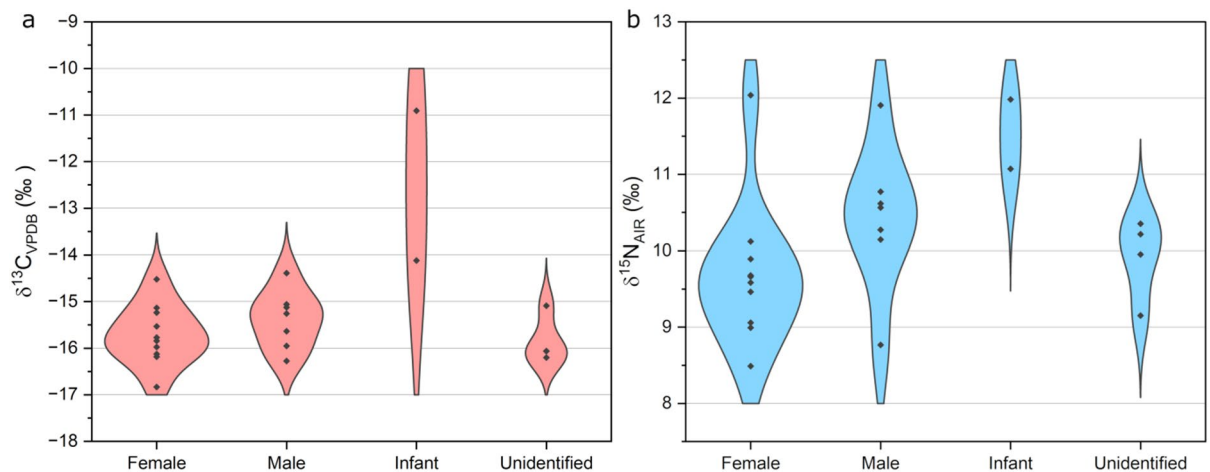


Fig. 5. Violin plots of the stable **a** carbon and **b** nitrogen isotope results of the skeletal remains from Sântana de Mureș.

Discussion

Chronological refinement

Only a comprehensive study of the central part of the cemetery, which was destroyed by sand mining, and the unexcavated north-eastern part could have helped to offer the approximate dates of the establishment and abandonment of the entire cemetery. This, however, is no longer possible. Nevertheless, the archaeological finds unequivocally suggest the presence of a post-provincial tribal association at the site. Grave goods characteristic for the early period of the SCC are absent in Sântana de Mureș. The double-plate brooches and plate buckles with a thickening frame, which were frequently found in the cemetery, are the main finds from the culture's late period. This period is also represented by the faceted and red-walled clay vessels, as well as by the conical glass jars (Fig. 2f–i), which observations were considered while refining the radiocarbon model. The rest of the finds in the cemetery, including the many varieties of hump-backed bone combs; the large number of brooches with inverted feet and the simple round and oval buckles, can generally be dated to the 4th century CE (Fig. 2b–e)⁹. The general phase is archaeologically represented by graves M16, M26, M27, M30, M31 and M64, whereas the later phase involves graves M40, M47, M53 and M55. Serial analysis revealed that graves M14, M39 and M74 should be classified as general phase based on their ^{14}C ages, but the finds suggest that they more likely belong to the later phase. Considering only the calibrated ^{14}C ranges, the establishment of the cemetery can be placed at the latter half of the 3rd century. However, the modelling suggests a possible commencement as late as the very beginning of the 4th century. The average range of the calibrated ^{14}C ages is around 100 years. Based on typochronological observations, the cemetery may have been used for a maximum of three or four generations⁹. This is a short period of time, and the ^{14}C modeling is able to further condense this range to a mere 70 years, resulting in an overlap between the two analyses. Grave M16 (W–E orientation) was radiocarbon dated to the end of the 3rd century CE, in accordance with the archaeological conclusion, whereas grave M47 (W–E orientation) was dated to the beginning of the 4th century CE. This indicates that burials without grave goods or of a W–E orientation were not necessarily later than the others, but that they may have belonged to the earliest burials of the excavated part of the cemetery⁹. Consequently, on the one hand, the ^{14}C age results and modeling confirm the typo-chronological dating of the cemetery, but on the other hand, they seemingly exclude the expected chronological discrepancy between the N–S and W–E orientation burials.

Possibility of migration

Based on the values of enamel samples, the results from the human skeletal remains are situated in the 2σ possibility range of the extended local baseline. The two exceptions are the two females aged approximately 40 years old from graves M10 (dated to the late phase) and M30 (general phase). The moderate difference between their strontium isotope data and that of the local range suggests that movement of about some tens of kilometres may have occurred, such as from the more radiogenic parts of the Carpathian Mountains. This is supported by the fact that, based on analyses performed on recent environmental materials for the nearby Rodna, Rarau, and Calimani Mountains in the Eastern Carpathians, as well as for the Romanian Plain and the Danube River Valley in Southern Romania, the BASr signal varies in a range from 0.70842 to 0.72667^{39,40}. The lower values are in accordance with the values of the Sântana de Mureș cemetery. The closest archaeological analogue to the $^{87}\text{Sr}/^{86}\text{Sr}$ signal from the Transylvanian Plateau was measured for four human individuals at the Archiud (Hânsuri) cemetery (4th–7th centuries CE), which is situated ~ 25 km north of Sântana de Mureș. These values ranged from 0.70959 to 0.71016⁴¹, coinciding accurately with the strontium isotope results of our individuals. When interpreting the migratory tendencies of individuals by strontium isotopes, it is important to consider that recent and archaeological isotope values can represent multiple regions or large areas, even within Europe, if the geological and environmental conditions are consistent⁴². For example, isotope ratios similar to ours have been recorded for other Roman Age sites in present-day Eastern Hungary⁴³, Western Poland⁴⁴, Southern Ukraine⁴⁵

or Great Britain⁴⁶. Due to this effect, even the immigrant individuals may seem to be locals as has been shown for the Wielbark culture (Malbork-Wielbark site, northern Poland), which played a remarkable role in the sociocultural evolution of the Sântana de Mureş-Chernyakhov and other Gothic cultures⁴⁷. Some Thuringian sites in Central Germany also provide good examples, where the Langobards was thought to migrated through Central Germany⁴⁸. Based on the conclusions of this study, some grave goods, especially the brooches, can be good indications of interregional relationships among communities, but they do not necessarily reflect the birthplace of an individual. In our case, neither the archaeological remains nor the radiocarbon measurements can help to identify the founding generation due to notable overlap of the dates. It is possible that oxygen isotope analyses from dental enamel could provide more precise geographical information, enabling the determination of the provenance, as the human and faunal $\delta^{18}\text{O}$ values can be compared with the drinking water $\delta^{18}\text{O}$ values from Romania⁴⁹. All these circumstances make difficult to clearly identify the exact geographical origin of the individuals in Sântana de Mureş. The strontium isotope results, at the current level of our knowledge, suggest no large-scale migration during this short period and seemingly all studied person were local to the Mureş region, including the individuals aged over sixty years old (grave M19 and a disturbed skull).

Lifestyle of the community

In accordance with the ‘minimal migratory theory’, the anthropological analyses also did not reveal any skeletal evidence of violence. It can therefore be assumed that the daily life of the community was relatively peaceful, without remarkable battles. On the other hand, the large number of pathological signs on the skeletons indicates a poor general state of health. Traces of severe muscle contractures (more robust muscle attachment on the skeleton) are related to lifestyle and are indicative of intense physical work. Overall, the high incidence of periodontal and chronic diseases implies intense physical exertion and inadequate nutrition. For example, *cribra cranii* and *cribra orbitalia*, which have frequently been associated with chronic acquired anaemia in the literature⁵⁰, were detected on the skeletons of five females.

Although archaeological observations of the high number of faunal bones at other SCC sites in Transylvania suggest a society reliant upon animal husbandry^{51,52}, the isotopic results at Sântana de Mureş partly skew the picture of meat consuming. In general, the mean $\delta^{13}\text{C}$ value of the community is higher than that of the local C_3 vegetation, which was widespread in Central Europe at the time⁵³. Meanwhile, the mean $\delta^{15}\text{N}$ value is in the lower to middle range of the values characteristic for humans (Fig. 5b). We can exclude a significant consumption of aquatic foods due to the lower $\delta^{15}\text{N}$ values, and the higher $\delta^{13}\text{C}$ values may be explained by millet (*Panicum miliaceum*) consumption⁵⁴. Exclusively C_4 plant consumption results in $\delta^{13}\text{C}$ values above -12‰ , thus, the average diet of this community can be characterized by a mixed consumption of C_3 and C_4 species⁵⁵. Nevertheless, considering the mean $\delta^{13}\text{C}$ value of around -15‰ , the prevalence of millet is undeniable. Due to the low likelihood of aquatic protein consumption, the nitrogen isotope results also suggest the dietary dominance of terrestrial animal protein sources. Additionally, the mean $\delta^{15}\text{N}$ values obtained for the sheep/goat and cattle bones and teeth are relatively close to the lowest female $\delta^{15}\text{N}$ values. The nitrogen isotope value of adult small ruminants can be higher in certain cases, probably due to pasturing practices that involve grazing animals on ^{15}N -enriched or manured pastures⁵⁶. Other ruminant species may also produce relatively high nitrogen isotope values, which has been demonstrated for cattle in the tribal Pannonian Basin⁵⁷. We suppose that the higher $\delta^{15}\text{N}$ value of sheep/goat teeth derives from physiological effects, while the lower values of the bones do not imply remarkable manuring activity of the soil, rather utilizing of plants grown on natural pastures. Zooarchaeological analyses at other SCC excavation sites in Transylvania have revealed that most of the animal skeletal remains belonged to species such as cattle, pigs (*Sus sp.*), sheep or goats^{51,52}. Thus, we suggest that mean $\delta^{15}\text{N}$ values of these species at Sântana de Mureş would be located similarly close to the human $\delta^{15}\text{N}$ range, representing a moderate contribution of animal protein to human diet.

Considering the ^{14}C and Sr results, we could not determine any temporal or spatial differences related to the carbon and nitrogen isotope values, consequently the community shows a picture of uniform diet. In general, no significant difference was shown between the mean $\delta^{13}\text{C}$ values of males and females. Males, however, possessed a significantly higher average $\delta^{15}\text{N}$ value than females, excluding the $\delta^{15}\text{N}$ result of one male (grave M64) and one female (disturbed skull) individual. If both sexes subsisted on the same food sources, this difference indicates that males consumed more animal protein than females, who may have eaten more plant-based foods. As such, the isotopic results support the anthropological observations, suggesting greater meat consumption by males, probably to fuel intense physical exertion, and a more monotonous, plant-dominated diet for females. The bones of individuals in grave M27 (0-1-yr-old child) and M31 (1-2-yr-old child) also showed relatively high $\delta^{15}\text{N}$ value, which could be a consequence of breast-feeding or animal milk consumption⁵⁸. The nitrogen isotope value of nursing children is higher than their mother's value, which corresponds to the trophic level of an exclusive consumer of animal protein, at the top of the food chain⁵⁹. Additionally, the $\delta^{13}\text{C}$ value of the child from grave M31 is much higher compared to that of the other studied individuals. This child, intentionally or by necessity, may already have been in the phase of being weaned, as indicated by the lower nitrogen isotope value as well. The most plausible explanation for the higher $\delta^{13}\text{C}$ value comes from a study in north-eastern China (5th to 2nd centuries BCE), in which the similarly high $\delta^{13}\text{C}$ value of a child was explained by the effect of heavy millet consumption during the weaning period, possibly in the form of porridge⁶⁰.

Dietary analogues across Europe

So far, mainly archaeological observations have been used to infer the lifestyle of the SCC population living on the Transylvanian Plateau, so it was important to place our isotopic results into a European context (Fig. 6). Despite the limited number of published isotope data, the Wielbark culture in Northern Europe may have actually had a sociocultural relationship with the SCC. Based on the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ data of the individuals in the 2nd century Wielbark cemetery of Rogowo in Poland, this culture also used millet and its consumption might

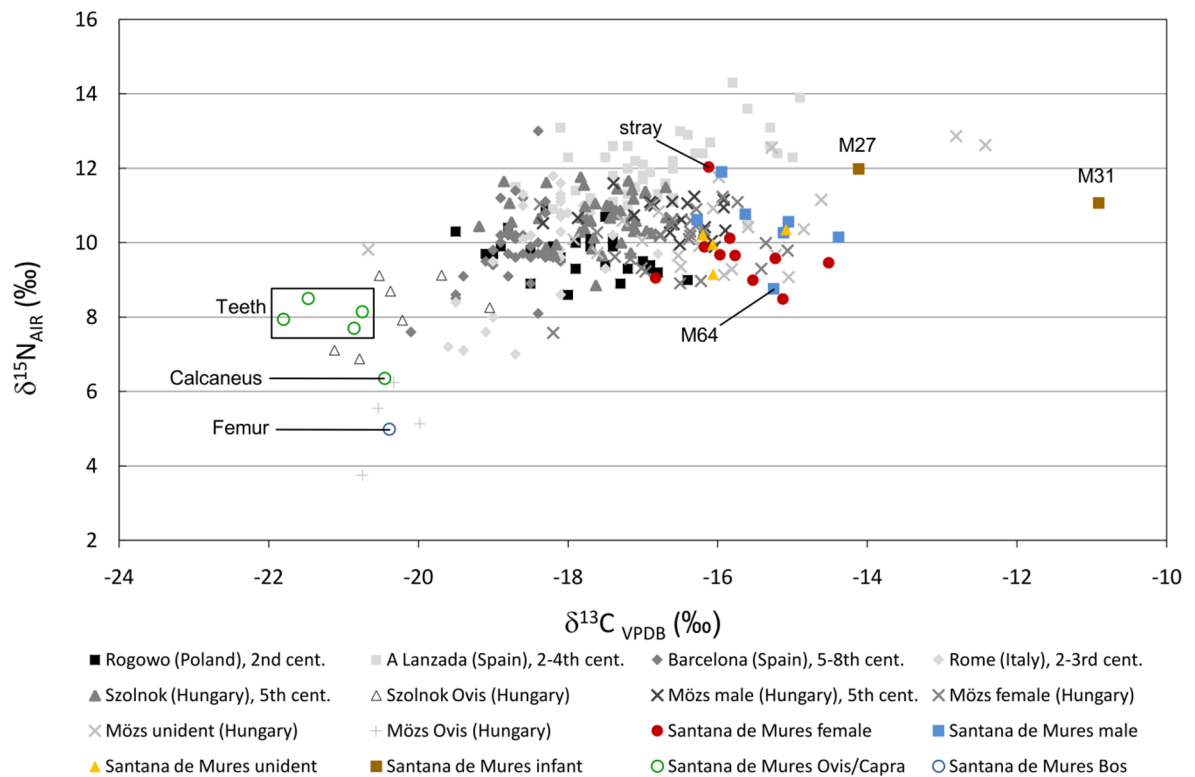


Fig. 6. Comparison of the stable carbon and nitrogen isotope results from Sântana de Mureș, Transylvania with data from other contemporaneous European sites as a wider context.

have been remarkable. In addition, sex-based differences in stable isotope ratios suggest that diets of women included more millet, and possibly less animal protein (meat or dairy) than diets of men, in the same way as in the Sântana de Mureș⁶¹. Related to other communities contemporaneous with the SCC, Murphy (2016) collected the available stable isotopic data across the Roman Empire. She reported that based on the increasing cases of recovered common and Italian millet (*Setaria italica*) from Roman sites, its role in agrarian societies has been underestimated⁶². According to ancient written sources, archaeobotanical evidence and stable isotope studies, peoples of the outer regions of the Roman Empire (e.g., A Lanzada in Spain) cultivated and relied upon millet more extensively than the society in central Rome, where it was consumed only in times of need or by the poorer classes^{63–65}.

Looking eastward, the territory of present-day Hungary (Pannonian Basin) was socially divided into two halves by the Danube River at that time. To the west, the territory of Pannonia belonged to the Empire, whereas the eastern territories were ruled first by the Sarmatians and later by various Germanic tribal groups. Archaeobotanical analyses of plant macro-remains have shown that wheat (*Triticum sp.*), barley (*Hordeum vulgare L.*) and rye (*Secale cereal L.*) were cultivated and consumed in the Pannonian half (Cserdi-Horgas-dűlő, Hungary)⁶⁶. In contrast, similar analyses revealed that millet, barley and einkorn wheat (*Triticum monococcum L.*) were the main cultivated species in the Sarmatian territories (e.g. Apc-Farkas-major, Hatvan-Baj-puszt, Heves County, Hungary)⁶⁷. Additionally, the written sources of Pliny state that Sarmatian tribes preferred to consume millet porridges (e.g., millet mixed with horse blood or milk)⁶⁸. Following the retreat of the Roman Empire in the 5th century CE, different ethnic groups entered Pannonia from the eastern areas of the Empire, where the tribes may have had a cultural characteristic very similar to that of the SCC in Sântana de Mureș. For example, a mixed population in Szolnok and other settlements (Keszthely-Fenekpuszta; Hács-Béndekpuszta; Győr; Mözs, Hungary) on the Great Hungarian Plain did not show significant differences in protein consumption between the provincial and tribal areas⁵⁷. Additional isotopic investigations have been carried out at the Mözs-Icsei-dűlő site in present-day southern Hungary, and the ranges of the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values overlap with that at the Sântana de Mureș site⁶⁹. The authors suggested that by that time, Roman and tribal customs had already mixed in this area, making the detection of dietary dominance impossible, although they managed to reveal more non-local individuals, using Sr analysis. Nevertheless, the relatively higher carbon isotope range suggests a significant consumption of millet.

Concluding the dietary results of these complex studies suggests that tribal groups preferred to cultivate millet and consumed it in many different ways. Outside the empire, its distribution rather followed cultural patterns than geographical or climatic constraints⁶¹. Thus, the increase in its proportion in the diet at the Sântana de Mureș site may imply sociocultural continuity with their Wielbark predecessors migrating southward. In contrast, inhabitants of the provinces of the empire cultivated mainly wheat, barley and rye instead of millet. We can only theorise that the significant millet consumption observed in Sântana de Mureș is directly related

to the demographic changes between the provincial and tribal groups in Transylvania. Nevertheless, we know cases in which these tribal groups changed their dietary customs in the opposite direction during the upcoming westward migration into new regions of Europe. For example, Visigoth groups in the 5th and 7th centuries CE at the sites of Sant Pere de Terrassa, Barcelona and Valencia (present-day Spain) seemingly entirely gave up utilization of millet (Fig. 6). We can see that their average $\delta^{13}\text{C}$ value is lower than the mean at Sântana de Mureş, not exceeding -18‰ ^{70,71}. As such, a marked consumption of millet can be excluded at these Visigoth sites.

Conclusions

In our study, the skeletal remains of 26 humans and 5 animals from the Sântana de Mureş-Chernyakhov culture in Sântana de Mureş, Romania were analysed archaeologically, anthropologically and for stable isotopes. The site is a good representation of the transitional period following the retreat of the Roman Empire from the region whilst tribal groups ruled the Transylvanian Plateau. Contrary to the absence of the earliest phase of the culture, radiocarbon modeling of the excavated part implies that the cemetery might have been established years after the abandonment of the province around 271 CE, and that it was used only for a few decades at most. We did not manage to identify the founding generation because the studied individuals appear to have lived their entire lives in the immediate area but this could be influenced by the shortages of the Sr technique. The minor differences in the results may be due to the more radiogenic rocks of the nearby mountainous areas. This non-migratory lifestyle might not have been easy either because the studied individuals undertook substantial physical stress and suffered from poor overall health, as evidenced by signs of chronic and epigenetic diseases. This observation was supported by the stable carbon and nitrogen isotope results, which indicated moderate animal protein consumption and potential nutritional deficiency. The data also suggest a heavier reliance upon C_4 plants, like millet, compared to C_3 plants. This was surprising, as the archaeological sources implied that the individuals practiced a lifestyle dominated by animal husbandry. There was only a minimal difference between the diet of males and females, and millet, probably as porridge, might have significantly contributed to the diet of one of the studied children. Contrary to the long presence of provincial society in the region, the dietary stable isotope results at Sântana de Mureş share only minimal similarities with that of the central regions of the Roman Empire, suggesting significant sociocultural changes after the retreat. This community rather preserved its lifestyle inherited from the predecessor Wielbark culture, which seemingly resemble more to that of the contemporaneous Sarmatian and other tribal groups in the Carpathian Basin.

Materials and methods

Anthropological analyses

During the morphological analysis, human skeletal material from 26 burials was identified and examined. The analyses were hindered by the poor and incomplete condition of the skeletons, as well as by issues relating to storage. In most cases, the biological sex and age at death of the studied individuals could be determined. Height of the studied individuals could also be calculated in several cases⁷². Craniometrical analyses were successful in only two cases, of which one has a definite provenance (grave M30), whereas the other is a stray (disturbed) find. The osteological analyses facilitated the study of the dietary differences of the individuals based on biological sex and age.

Isotope analytical procedures for chronology and diet

To carry out our studies, appropriate and rigorous laboratory pre-treatment and measurement methods were applied and pursued. The corrected results were processed using modeling and statistical methods to produce age and isotope distribution figures.

Twenty-six burials were used in the anthropological studies, but the skeletal remains of only 24 burials were included in the isotopic research. In total, the human samples comprised 12 teeth and 11 bones, whereas faunal samples were composed of 4 sheep/goat teeth and 1 bone, in addition, a cattle bone. The sample processing and analyses occurred at the INTERCT laboratory of the HUN-REN Institute for Nuclear Research (ATOMKI) in Debrecen, Hungary^{73,74}. Because ^{14}C dating and the subsequent stable carbon and nitrogen isotope measurements were performed on the organic component (collagen) of the skeletal material, gelatine resulting from a series of physical and chemical treatments was split into smaller aliquots. Briefly, a small skeletal fragment (~700 mg) from each grave was crushed, and an acid-base-acid (ABA) chemical treatment was used to remove carbonaceous contaminants. After filtration and freeze-drying, a small amount of gelatine (~5 mg) was split for dating, and, following combustion in a sealed glass tube, the resulting gas was purified and graphitized.

The AMS measurement of the samples was normalized to the NIST oxalic acid (oxalic acid standard, SRM-4990 C), while the background of the measurements was determined using graphitized fossil CO_2 . The average blank value was subtracted from each ^{14}C date. In parallel with the actual samples from Sântana de Mureş, laboratory background and standard bone samples were prepared and measured, and all unknown-age results were corrected for these, as well^{73,75}. The final radiocarbon age results were calibrated using the IntCal20 calibration curve and the online program OxCal, and they were used later to model the chronological characteristics of the site^{76,77}. To refine the age of graves M1, M26 and M31, the radiocarbon dates of the human and animal samples were combined using the Combine function of OxCal.

Stable carbon and nitrogen isotope measurements for dietary analysis were performed from the other half of the extracted gelatin. In triplicate runs, approximately 0.3 mg of the gelatine was weighted in an ultrapure aluminium capsule, and after combustion in an elemental analyser (ThermoScientific™, EA IsoLinkCNSOH), the stable carbon and nitrogen isotope ratios were measured by an on-line coupled ThermoFinnigan Delta Plus XP mass spectrometer. The obtained $^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$ isotope ratio results were calibrated with laboratory sulphanilamide, as well as with international IAEA N1 and UREA standard materials. The $^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$

isotope ratio results are reported as $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, respectively. The uncertainty of the carbon and nitrogen isotope data was $\pm 0.1\text{‰}$ and $\pm 0.2\text{‰}$, respectively⁷⁸.

Stable isotope analytical procedures for mobility

The $^{87}\text{Sr}/^{86}\text{Sr}$ absolute isotope ratios were also measured at the HUN-REN ATOMKI, Debrecen, Hungary, in the laboratory of the Isotope Climatology and Environmental Research Centre (ICER). Bone and dental enamel samples were first chemically cleaned to remove surface contaminants. Local background samples (soil), blank and standard solutions (NBS987 SrCO_3) were prepared alongside the skeletal samples to verify the blank and accuracy of the chemical procedure. Twenty mg of enamel and 50 mg of bone were weighed into PFA beakers. After completed mineralisation occurred, the samples were loaded into pre-cleaned Sr spec columns to separate the Sr from the other matrix elements. All sample preparation occurred in a Class 1000 clean room. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were measured using a Neptune Plus MC-ICPMS (Thermo Scientific), equipped with an Aridus-3 (CETAC) desolvating system^{21,22}. The results were corrected for instrumental mass discrimination and normalized to the accepted value of 0.710248 for NIST SRM 987⁷⁹. The overall uncertainty was 0.000016.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

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Declarations

Competing interests

The authors declare no competing interests.

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