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Thirty Steps of the Be-JA Road

Diet and mobility in the Danube Delta region in Late Antiquity: A multi-isotope approach

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ABSTRACT

This study examines diet and mobility in Late Antique populations in the region between the River Danube and the Black Sea coast of Romania using a multi-isotope approach. Analysing human bone and enamel samples from three 4th to 7th c. CE cemetery sites — Histria, Callatis, and Ibida — diet was assessed through bone collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values via the Bayesian linear mixing software FRUITS, while mobility was examined through enamel isotopes ($\delta^{13}\text{C}$, $\delta^{34}\text{S}$, $\delta^{18}\text{O}$, and $^{87/86}\text{Sr}$). The results indicate that, despite significant political and social changes, diets were largely homogeneous and reflected those of other Roman Empire populations, primarily consisting of C_3 plant foods, with cereals, wine, and olive oil as likely staples. Notably, individual diets varied, with most consuming minimal animal products and only a small amount of C_4 plants; however, one individual from Histria obtained a significant portion of their calories from these sources. Interestingly, aquatic resources contributed little despite the proximity of the sites to riverine, estuarine, lagoonal and marine ecosystems. The study also identified two first-generation migrants with distinct ‘non-local’ enamel isotope ratios, suggesting their origins in more northerly regions, potentially associated with the Migration Period movements. More ^{14}C dates are needed to contextualise these findings further.

KEYWORDS

Stable isotope analysis, Danube Delta, Black Sea, Late Antiquity, diet, mobility

Introduction

Between the 4th and 7th c. CE, the Danube Delta region (fig. 1) underwent significant demographic and political changes. Located at the border of the Roman Empire and adjacent to the Black Sea (Latin: *Pontus Euxinus*), it served as a strategic and often contested area. In the 4th c., the Delta was part of the Roman territories, influenced by Roman civilisation and military presence. However, as the Roman Empire began to decline, the region faced invasions from various migrating tribes, including the Goths,

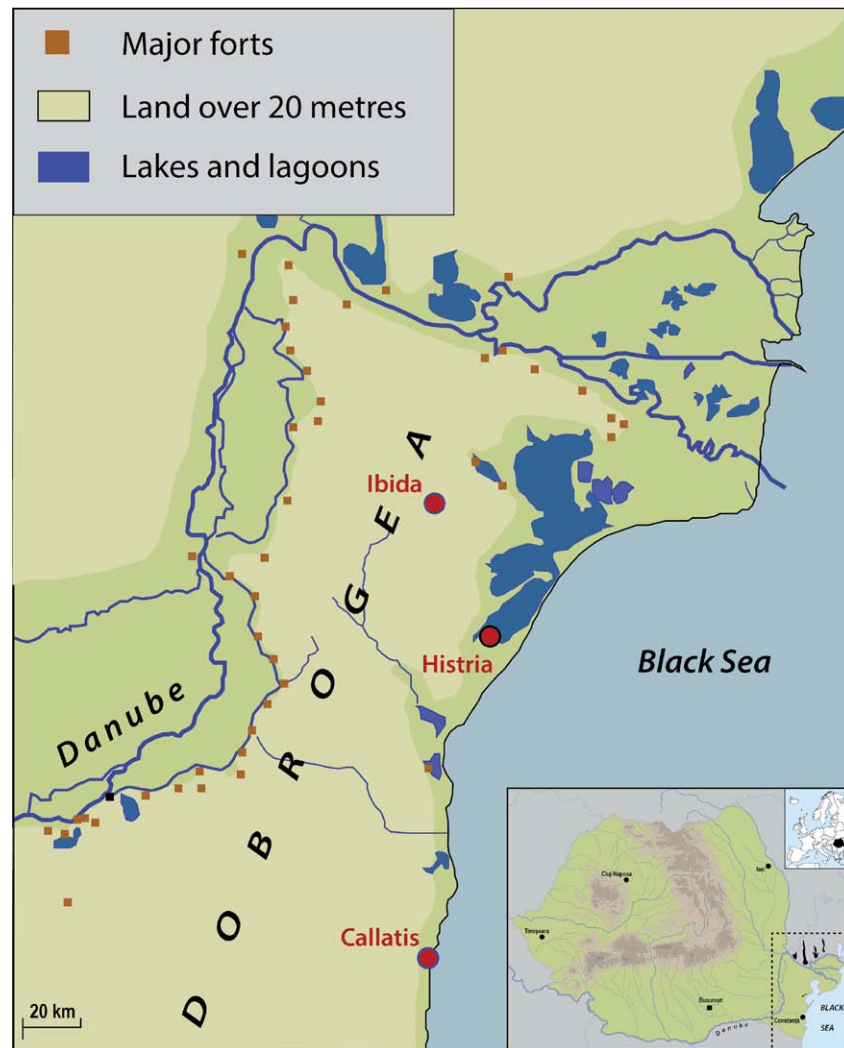


Fig. 1. Locations of the principal sites discussed in the text (author C. Bonsall)

Huns, and later the Avars. These invasions led to periods of instability and shifts in control. By the 7th c., as the Byzantine Empire sought to reclaim and stabilise its borders, the region began to experience the impact of Slavic migrations, which further altered the demographic and cultural landscape of the Delta region.

Changes in belief systems and population movements can be directly studied through stable isotope analysis of human skeletal remains. In this paper, we present the findings of a pilot study that investigates the diets and mobility of a small subsample of Late Roman cemetery populations from the Danube Delta. This study employs multi-tissue/element analysis, examining rib, femur or humerus, and enamel samples, as well as multi-isotope analysis, including collagen $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{34}\text{S}$, and enamel $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, and $^{87}\text{Sr}/^{86}\text{Sr}$.

Historical and Archaeological Evidence for Diet and Mobility in the Late Roman Danube Delta region

The Danube Delta in the Roman period was a fertile and strategically important region, significant for Roman settlement and agriculture.

Documentary sources offer critical insights into the dietary practices of Classical Antiquity, highlighting a reliance on a triad of grains, olives (and oils), and wine. The main cereals consumed were various types of wheat (*Triticum* spp.), while barley (*Hordeum vulgare*) and millets (*Panicum miliaceum* and *Setaria italica*) played a secondary role. Millets, considered to have lower baking quality and nutritional value, were often reserved for times of famine or as animal feed. Meat, including poultry, was a luxury primarily enjoyed by the elite, in accordance with the Roman sacrificial calendar. Fish were more accessible across social classes, although distinctions were made regarding the types deemed appropriate for the different tiers of society. Larger fish such as sea bream, tuna, and eels were reserved for the affluent, whereas those of lower status typically consumed smaller species. Wine, customarily mixed with water, was the main beverage source (Garnsey 1999; Murphy 2016; van Limbergen 2018a).

Documentary accounts of Roman diets often exhibit bias, focusing primarily on elite and luxury foods while neglecting other societal groups (Murphy 2016). Archaeological evidence provides concrete, though incomplete, insights into Roman food sources; animal remains indicate that sheep and goats were significant meat sources in the Eastern Roman Empire (van Limbergen 2018b).

The Delta's wetlands boast one of the world's most diverse fish populations, supporting various aquatic species, including marine, estuarine, and freshwater-adapted fish, as well as anadromous and catadromous species (Bănăduc et al. 2016). However, the coastal configuration of the region has undergone significant changes since the Middle Holocene. At the time of their foundation (7th c. BCE), Greek colony ports, such as Histria, were located on the Black Sea coast (Vespremeanu-Stroe et al. 2013). While the configuration of the Delta region has evolved continuously since then, the result of both natural and anthropogenic processes, deltaic progradation and the development of the wetlands are evident from at least 2000 years ago, which reduced the viability of the former port sites and may also have impacted the importance of fishing in the eastern Black Sea area (Preoteasa et al. 2013; Vespremeanu-Stroe et al. 2017). Roman fishing gear and processing facilities are, however, prevalent in the northern Black Sea region, though fish remains are relatively scarce. Sites like Olbia and Berezan, on the Dnieper–Bug estuary, reveal a better representation of species such as sturgeon, pike, and catfish (Høtje 2005).

During the Roman period, bread wheat, naked barley, and rye were prevalent cereal grains, while evidence suggests millet was also cultivated, particularly along the Danube frontier (Gyulai 2014). Archaeobotanical evidence indicates that millet, specifically broomcorn millet (*Panicum miliaceum* L.), was integrated into the agricultural practices at Aelia Mursa in Croatia (Reed 2024) and the North Pontic citadel of Olbia, Ukraine. The discovery of over 27,000 grains of broomcorn millet at Olbia (Stobbe et al. 2019) highlights its significance, with this crop noted for its adaptability to diverse conditions and a short growing season, proving valuable in areas such as the Danube Delta.

The Danube became a crucial frontier of the Roman Empire from the 1st c. CE, serving as a natural barrier to the 'barbarians' to the north (Karavas, Hanscam 2023). The Delta region, ideally situated for trade, hosted several important Roman cities, including Histria, a significant trading centre on the Black Sea Coast, Callatis (modern-day Mangalia) and Ibida (modern-day Slava Rusă), a fortified town. The Migration Period (c. 300 to 700 CE) was a time of social upheaval that witnessed major population movements across Europe, as well as significant political and cultural changes in the Delta region. As migratory groups from the north advanced on the Caucasus and the northern Black Sea region in the late 4th c. CE, the militarisation of the Lower Danube escalated. Increasing pressure from Hunnic troops under Attila culminated in invasions in the 5th c. CE, resulting in a decline in Roman urban centres south of the Danube along with a deterioration of local governance structures. This period was characterised by depopulation of these urban centres and breakdown of local administrative frameworks; disruption to trade routes followed. Various tribes, including the Goths and Sarmatians, traversed or settled the region in the 4th and early 5th c. CE (Poulter 2010; Preiser-Kapeller et al. 2020). Other populations, including the Goths, Dacians, Sarmatians, and, later, the Gepids, moved through or temporarily settled the wider

region (Poulter 2010; Kelly 2019; Knight 2022; Karavas, Hanscam 2023). In the 6th c. CE, Justinian I sought to restore control, prompting a temporary revival in urban and ecclesiastical structures (Poulter 2010). However, persistent raids and eventual Slavic and Avar settlement led to the cessation of Byzantine influence by the 7th c. CE.

Stable Isotope Analysis

Stable isotope analysis of human remains is a long-established and widely used method for modelling past diets and inferring mobility in archaeological populations.

Principles

Investigating diet through stable isotope analysis is based on the principle ‘we are what we eat’, i.e., the isotopic composition of human tissues reflects and can be used to model dietary intake. Two proxies, the stable isotope ratios of carbon ($\delta^{13}\text{C}$, $^{13}\text{C}/^{12}\text{C}$) and nitrogen ($\delta^{15}\text{N}$, $^{15}\text{N}/^{14}\text{N}$), are commonly used to model diets in archaeological populations (e.g., Bonsall et al. 1997; Fetner 2025). Sulphur stable isotope ($\delta^{34}\text{S}$, $^{34}\text{S}/^{32}\text{S}$) ratios are increasingly deployed as a third dietary proxy (e.g., Nehlich 2015; Bonsall et al. 2015).

Plants assimilate CO_2 during photosynthesis. Plant $\delta^{13}\text{C}$ values depend on both the environmental carbon source and the photosynthetic fixation pathway. There are three photosynthetic pathways – C_3 , C_4 , and crassulacean acid metabolism – however, food species that utilise the CAM pathway, such as pineapple and agave, were not available in Europe until the 16th c. CE (Carvalho 2020; Holtum 2023). Most plants use the three-carbon or C_3 photosynthetic pathway (Calvin-Benson cycle). A small proportion (c. 3%) of land plants, mostly tropical and sub-tropical species, use the four-carbon or C_4 pathway (Hatch-Slack cycle) (Hatch, Slack 1970). C_3 plants incorporate a greater proportion of the lighter isotope, ^{12}C , into tissues than C_4 plants and, therefore, generally have lower $\delta^{13}\text{C}$ values than C_4 plants (Maberly et al. 1992). The mean $\delta^{13}\text{C}$ value of C_3 plants is -26.5‰, while that of C_4 plants is -7.5‰ (Tykot 2004). This difference in isotope ratios passes through food chains to consumer tissues, and it is therefore possible to distinguish the proportions of foods that an individual has consumed from the C_3 vs C_4 food webs. Most temperate region grasses and cereal crops, such as wheat and barley, as well as most fruits and vegetables, are C_3 plants, while some tropical grasses and a small number of cereals, such as maize, millet and sorghum, are C_4 plants.

There are two primary sources of carbon for plants. Terrestrial plants obtain carbon by fixing atmospheric CO_2 , while marine plants mainly acquire carbon from dissolved inorganic carbon in seawater. However, they can also utilise the atmospheric CO_2 present in surface waters. Many marine plants use the C_3 photosynthetic pathway to fix carbon. They primarily fix carbon from oceanic carbonate, which is relatively enriched in ^{13}C (+7‰) compared to atmospheric CO_2 . This distinction allows terrestrial and marine C_3 food sources to be differentiated. Consumption of terrestrial C_3 foods can, therefore, be distinguished from marine C_3 foods. Freshwater plants may obtain carbon from various sources, including atmospheric CO_2 , dissolved inorganic carbon from bedrock and soils, as well as organic carbon from decomposing materials (Katzenberg, Waters-Rist 2018).

The $\delta^{13}\text{C}$ values of some food groups overlap, for example, marine foods and C_4 plants (both relatively ^{13}C -enriched compared to C_3 foods), as well as terrestrial C_3 and freshwater fish and shellfish. Co-analysis of other dietary proxies, $\delta^{15}\text{N}$ and $\delta^{34}\text{S}$, can improve discrimination when modelling food sources.

The $\delta^{15}\text{N}$ values of plants vary, reflecting differences in environmental nitrogen sources (von Wirén et al. 1997). Nitrogen incorporated into plants can come from atmospheric N_2 (which has a $\delta^{15}\text{N}$ of 0‰), as well as soil nitrogen (which has variable $\delta^{15}\text{N}$). Further variation in $\delta^{15}\text{N}$ is introduced with

each step (or trophic level) of the food chain – the consequence of metabolic fractionation, or isotopic discrimination, which generally leads to ^{15}N enrichment in consumer tissues relative to diet (Minagawa, Wada 1984). Clinical studies have shown that metabolic fractionation in humans results in a c. 6‰ offset between human bone collagen and whole diet $\delta^{15}\text{N}$ (O’Connell et al. 2012). Within a single biome, plants exhibit lower $\delta^{15}\text{N}$ values than herbivores, which in turn have lower values than carnivores (DeNiro, Epstein 1981; Katzenberg, Waters-Rist 2018), i.e., individuals consuming mainly plant foods will have lower $\delta^{15}\text{N}$ values than those who include animal food sources in their diets. Freshwater and marine food chains typically have more trophic levels than those of terrestrial environments, resulting in relatively high $\delta^{15}\text{N}$ values in species at the top of aquatic food webs (Schoeninger, DeNiro 1984; Schoeninger, Reitsemá 2023). Human consumers of marine or freshwater resources, therefore, generally have elevated $\delta^{15}\text{N}$ values in comparison to those relying entirely on terrestrial resources (Bonsall et al. 2009).

Like $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, sulphur stable isotope ratios ($\delta^{34}\text{S}$) in human tissues reflect those of the consumed foods (Richards et al. 2003; Nehlich 2015). Metabolic fractionation of $\delta^{34}\text{S}$ is negligible, and thus, human bone collagen values are directly comparable to food sources. Theoretically, therefore, collagen $\delta^{34}\text{S}$ more precisely reflects dietary intake than other proxies (Bonsall et al. 2015; Krajcarz et al. 2019). In contrast to other commonly analysed diet proxies, sulphur in food sources largely derives from bedrock. Geological $\delta^{34}\text{S}$ values are geospatially variable, dependent on bedrock type. $\delta^{34}\text{S}$ can, therefore, serve as both a proxy for diet and a marker of mobility (e.g., Privat et al. 2007; Richards 2023). $\delta^{34}\text{S}$ can be a valuable indicator of the contribution of aquatic resources to diet (Connolly et al. 2004; Nehlich et al. 2011). Terrestrial plants exhibit a wide range of $\delta^{34}\text{S}$ values, spanning at least -22‰ to $+22\text{‰}$, with the majority falling between -7‰ and $+8\text{‰}$ (Peterson, Fry 1987; Krouse 1989; Thode 1991; Nehlich 2015).

In contrast, marine food $\delta^{34}\text{S}$ values range from c. $+15\text{‰}$ to $+20\text{‰}$, reflecting the oceanic $\delta^{34}\text{S}$ value of $+21\text{‰}$ (Thode 1991). In coastal areas, the $\delta^{34}\text{S}$ values of terrestrial biomes may be influenced by a ‘sea spray effect’, the transfer of oceanic sulphate to nearshore regions, resulting in ^{34}S -enriched values of terrestrial resources (Nielsen 1974). For example, an individual with a terrestrial diet who lived in a coastal area affected by sea spray would have bone collagen carbon and nitrogen isotope ratios consistent with the consumption of terrestrial foods and sulphur isotope ratios in the marine range. In contrast, a coastal dweller with a marine diet will typically have carbon, nitrogen and sulphur isotope ratios in marine ranges. Sulphur isotope values may thus provide multifaceted biographical information about an individual, including diet, residence and lifetime mobility.

Traditionally, the investigation of provenance and mobility has relied on the analysis of strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) and/or oxygen ($\delta^{18}\text{O}$, $^{18}\text{O}/^{16}\text{O}$) isotope ratios (e.g., Price et al. 1994; White et al. 1998; Pederzani, Britton 2019; Allen et al. 2020). $^{87}\text{Sr}/^{86}\text{Sr}$ was widely regarded as the gold standard for provenance studies (e.g., Price et al. 1994). Increasingly, however, multi-isotope likelihood modelling is seen as the most effective approach for residence studies. A prerequisite for reliable probabilistic provenance assignment (Bataille et al. 2021) is the availability of high-resolution comparative isoscape data (Holt et al. 2021). Such data may become available for the Danube Delta region through major data initiatives such as IsoMemo (<https://isomemo.gea.mpg.de/>).

Strontium isotope ratios vary geospatially, reflecting variations in the $^{87}\text{Sr}/^{86}\text{Sr}$ of bedrocks (Bentley 2006; Bataille et al. 2020). The isotope ratios of bioavailable strontium directly reflect geological values, i.e., there is little metabolic fractionation of $^{87}\text{Sr}/^{86}\text{Sr}$ isotopes (Lewis et al. 2017). Strontium derived from food and drinking water is incorporated into human bioapatite in small quantities, replacing calcium. Both calcium and strontium are alkali earth metals with similar chemical properties (Bentley 2006).

Drinking water $\delta^{18}\text{O}$ co-varies with vertical and horizontal distances from oceanic sources of precipitation – i.e., there is spatial variation in drinking water $\delta^{18}\text{O}$ values (Pederzani, Britton 2019). Hu-

man bioapatite oxygen derives largely from drinking water. Thus, enamel phosphate and carbonate $\delta^{18}\text{O}$ vary geographically, are dependent on drinking water sources, and may, therefore, be used as a proxy for mobility (Evans et al. 2006).

Selection of human tissues for modelling diet and provenance/mobility

Bone collagen and tooth apatite may be analysed to gain insights into the diets of archaeological individuals. Traditionally, the analysis of enamel carbonate for dietary studies has been undertaken to supplement bone collagen data (Tieszen, Fagre 1993) or in cases where collagen has not been preserved (e.g., Lee-Thorp 2000).

Bone collagen is commonly used in archaeological dietary studies due to its unique chemical structure and the way it is synthesised. It primarily consists of Type 1 collagen (>90% of the organic bone matrix) and provides data for two dietary proxies, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ (Naomi et al. 2021). Bone collagen carbon is primarily, though not exclusively, derived from dietary protein, accounting for c. 74% of collagen. The remaining 26% comes from carbohydrates and lipids (Fernandes et al. 2012).

In contrast, bioapatite, a calcium phosphate with small quantities of substituted carbonate (Elliot 1997), serves as a record of one dietary proxy, $\delta^{13}\text{C}$. Bioapatite carbon may be drawn from all three macronutrients used for energy: protein, lipids and carbohydrates (Krueger, Sullivan 1984; Hedges 2003; Richards 2015). Traditionally, bone collagen data have been seen as easier to interpret, as they provide two diet proxies from a tissue mainly derived from one macronutrient. In contrast, enamel carbonate yields a single diet proxy that reflects a complex mix of dietary macronutrients (Wright, Schwarcz 1999, 1161). However, valid concerns have been raised about the limitations of diet reconstructions based only on bone collagen stable isotope ratios, which are biased toward protein sources. Notably, this approach may overlook low-protein but high-calorie foods, such as sugars, fats and certain cereals (Ambrose, Norr 1993; Richards 2015).

Advances in diet modelling (through both discriminant function analysis and Bayesian mixing modelling) and improved understanding of macronutrient routing have facilitated analysis of multiple consumer tissues and food source isotopic data, thereby enhancing the accuracy of dietary models (Cheung, Szpak 2021).

Apatite $\delta^{13}\text{C}$ reflects that of blood bicarbonate, which is derived from cellular metabolism, particularly the oxidation of carbohydrates, fats, and proteins, and thus acts as a proxy for whole diet $\delta^{13}\text{C}$ (Lee-Thorp et al. 1989; Hedges 2003; Fernandes et al. 2012). The size of the observed offset in feed studies between consumer $\delta^{13}\text{C}_{\text{en}}$ and $\delta^{13}\text{C}_{\text{whole diet}}$ is variable, ranging from c. 11.5‰ to greater than 14‰ (Zhu, Sealy 2019). A $\delta^{13}\text{C}_{\text{bioapatite-diet}}$ offset of $-10.1 \pm 0.2\text{‰}$ was modelled from experimental animal data and can be applied to calculate whole diet from bioapatite $\delta^{13}\text{C}$ (Fernandes et al. 2012). However, while both bone and tooth enamel are bioapatites, they differ in composition and structural organisation, reflecting their distinct functions. The offset between enamel apatite $\delta^{13}\text{C}_{\text{en}}$ and whole diet may be larger than that between bone apatite and whole diet. $\Delta^{13}\text{C}_{\text{bone-enamel}}$ spacing has been reported to be in the order of c. 0–2‰ (see Zhu, Sealy 2019). Therefore, the whole diet $\Delta^{13}\text{C}$ offset of 10.1‰ in enamel should be interpreted cautiously.

While models of diet from multiple tissue isotope data can be highly accurate, a cautious approach to interpreting the results is taken here. Bone collagen is an active tissue that remodels throughout life and, as such, records time-averaged dietary intake for a circumscribed period before death. However, some elements and some portions of individual elements are more metabolically active than others – the timespan represented varies by skeletal element. Trabecular bone, for example, has a larger surface area, is more metabolically active, and has a faster rate of turnover than cortical bone. Ribs, which comprise significant proportions of trabecular bone and are under high mechanical load, are widely assumed to have a relatively rapid turnover of one to five years before death (Hedges et al. 2007; Ubelaker, Parra

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Site	Burial ID	Sex	Age (yrs)	Element	$\delta^{13}\text{C}_{\text{en}}$	$\delta^{18}\text{O}_{\text{CSMOW}}$	$\delta^{18}\text{O}_{\text{PO4}}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\delta^{13}\text{C}_{\text{co}}$	$\delta^{15}\text{N}$	$\delta^{34}\text{S}$	%C	%N	%S	C:N	C:S	N:S
Callatis	M10	M	20	M2	-12.1	26.0	17.2	0.70987									
				Fe					-19.3	9.1	2.9	44.5	15.9	0.23	3.3	500	149
				R					-19.1	9.5	8.5	21.1	7.8	0.16	3.1	349	111
Callatis	M19	F	55	M2	-10.3	24.6	15.7	0.70979									
				Fe					-18.2	9.8	10.3	33.9	12.5	0.17	3.2	530	168
				R					-18.2	9.8	12.3	23.7	8.8	0.19	3.1	328	104
Callatis	M20	F	40	M2	-10.8	24.9	16.1	0.71000									
				Fe					-19.0	10.0	10.3	16.6	6.2	0.13	3.2	333	106
				R					-19.0	9.8	10.4	42.6	15.4	0.20	3.2	561	168
Callatis	M53	M	22	M2	-12.6	24.9	16.1	0.71189									
				Fe					-19.4	10.2	8.3	26.2	9.7	0.16	3.2	427	135
				R					-19.1	11.1	8.4	26.1	9.6	0.12	3.2	581	183
Callatis	M99	F	20	M2	-12.1	23.5	14.6	0.70979									
				Fe					-18.5	10.3	11.5	40.5	14.7	0.20	3.2	537	168
				R					-18.6	10.4	11.0	35.8	13.0	0.20	3.2	478	149
Histria	M5		9	M2	-11.4	25.6	16.7	0.70929									
				Fe					-17.3	10.7	7.4	42.5	15.2	0.19	3.3	579	174
				R					-17.7	10.8	8.3	41.4	14.7	0.22	3.3	505	151
Histria	M15	M	45	M2	-5.8	25.2	16.3	0.70985									
				Fe					-15.4	11.3	3.5	40.9	14.5	0.16	3.3	658	194
				R					-16.1	11.5	5.4	42.7	15.2	0.19	3.3	599	178
Histria	M21	F	22	M2	-10.4	25.5	16.6	0.71025									
	M32	M	38	M2	-11.0	25.1	16.2										
				H					-19.0	10.5	7.9	44.7	14.3	0.22	3.6	541	146
				R					-18.4	10.8	9.2	42.6	14.9	0.17	3.3	678	197
Histria	M57	F	50	M2	-7.9	25.7	16.9	0.70968									

Site	Burial ID	Sex	Age (yrs)	Element	$\delta^{13}\text{C}_{\text{en}}$	$\delta^{18}\text{O}_{\text{CSMOW}}$	$\delta^{18}\text{O}_{\text{PO4}}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\delta^{13}\text{C}_{\text{co}}$	$\delta^{15}\text{N}$	$\delta^{34}\text{S}$	%C	%N	%S	C:N	C:S	N:S
Ibida	M21	F	30–35	M2	-9.5	25.7	16.9	0.70913									
				Fe					-19.3	9.6	5.7	44.2	15.9	0.19	3.2	622	183
				R					-19.1	10.6	6.8	41.2	15.0	0.19	3.2	578	170
Ibida	M37	F	20–22	M2	-7.0	24.8	15.9	0.71050									
				Fe					-18.3	9.9	6.6	34.1	12.6	0.14	3.1	641	203
				R					-18.0	9.8	6.6	40.9	14.8	0.17	3.2	651	196
Ibida	M38	M	35–45	M2	-10.9	25.8	17.0	0.71257									
				Fe					-18.5	10.5	5.0	40.8	14.8	0.17	3.2	641	192
				R					-19.6	9.6	6.8	21.2	7.9	0.10	3.2	561	178
Ibida	M72			M2	-12.5	26.1	17.3										
				Fe					-19.6	11.4	6.5	42.7	15.4	0.20	3.2	590	173
				R					-19.3	11.6	6.3	40.1	14.6	0.15	3.2	680	204
Ibida	M127	M	38–45	M2	-11.1	24.2	15.3	0.70913									
				H					-19.2	11.0	8.0	43.1	15.6	0.18	3.2	639	190
				R					-19.0	10.5	7.6	43.1	15.6	0.19	3.2	607	181

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Table 1. Demographic information and stable isotope data for the study populations. The *Histria* individuals sampled were interred in the extramural basilica. Skeletal element abbreviations: Fe – femur, H – humerus, R – rib, and M2 – 2nd molar. Bone collagen – $\delta^{13}\text{C}_{\text{co}}$, tooth enamel – $\delta^{13}\text{C}_{\text{en}}$ (authors C. Pickard, C. Bonsall)

2011). Collagen in cortical bone has widely been reported to remodel more slowly than trabecular bone, and its stable isotope values are thought to represent a weighted ‘lifetime’ average of foods consumed, largely, if not wholly, reflecting diet during periods of rapid bone growth (e.g., adolescence) (Libby et al. 1964; Hedges et al. 2007; Matsubayashi, Tayasu 2019). However, individual variations exist: cortical bone collagen turnover rates may be more rapid in individuals with high-protein diets, and rib collagen may turn over more slowly or unpredictably than once supposed (Quinn 2024; cf. Hedges et al. 2007).

In contrast to bone collagen, enamel is formed during tooth development, specifically in childhood or adolescence, and does not undergo remodelling thereafter (Humphrey et al. 2008). Typically, human enamel extracted for the measurement of $\delta^{13}\text{C}_{\text{apa}}$ comprises a ‘bulk’ sample taken from the crown cusp to the cemento-enamel junction (e.g., Ventresca Miller et al. 2018). As enamel development is a three-stage process (Robinson et al. 1995), the $\delta^{13}\text{C}_{\text{apa}}$ value of such a sample reflects time-averaged whole diet throughout enamel development. The two tissues, tooth enamel bioapatite and bone collagen, reflect different life stages and time spans and, as such, are not equivalent proxies (Zhu, Sealy 2019). Tooth enamel is generally used for both $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ analyses as it is more resistant to diagenetic degradation and arguably less susceptible to elemental exchange with the deposition environment than bone apatite (Slovak, Paytan 2011). Enamel $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ values provide a record of childhood residence and, potentially, mobility, which can be explored in a single individual by sampling teeth that form at different ages (e.g., Hrnčír, Laffoon 2019) and comparing tooth isotopic data with ‘local’ Sr values (where there are differences, non-local provenance is inferred (e.g., Evans et al. 2006)), or through probabilistic provenance assignment (e.g., Laffoon et al. 2017; Bataille et al. 2021).

Materials and Methods

Samples of bone collagen and tooth enamel were taken from 15 individuals, five from each of the three cemetery sites, Callatis, Histria and Ibida (Table 1). The majority of these individuals have been assigned to the 4th c. CE based on grave inclusions or stratigraphy, supported by a single ^{14}C determination that is consistent with this temporal framework (see Table 1 for details). The analyses focused on adults, with sex and age determinations available for 13 of the sampled individuals – six males and seven females. The ages ranged from child to mature adult. Approximately 1 gram of cortical bone from either the femur or humerus, plus a sample of rib trabecular bone, was taken from each of the 14 individuals, with one individual represented solely by cranial bones. The collagen $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{34}\text{S}$ ratios were analysed, with methods described in the Supplementary Information section 1. Additionally, slices of dental enamel were extracted from the second permanent molar of each individual for $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and $^{87}\text{Sr}/^{86}\text{Sr}$ measurements, with pretreatment and mass spectrometric methods outlined in Supplementary Information section 2.

The individual diets of the Danube Delta region individuals were analysed using the Bayesian mixing model FRUITS (version 3.0 Beta) (Fernandes et al. 2014). This assessment utilised isotopic proxies ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) for four primary food groups derived from historical texts and archaeological data: C_3 cereals and oils, C_4 cereals, terrestrial animal meat and products, and fish. Isotope values from both rib and femur/humerus samples were employed in the modelling. Model parameters and results are detailed in Table S1, with contributions reported as mean percentages and a 68% credible interval (2 σ).

Since the stable isotope ratios of food sources vary spatially and temporally, the accuracy of dietary models is improved by using isotope data from food sources that are both contemporaneous and geologically close to the study population. In the absence of relevant animal and plant remains from the Delta region cemetery sites, isotope data were sourced from nearby sites dating to the Late Roman period (Table S2). We used modern food data only when archaeological equivalents were unavailable (e.g. olive oil), as the *Suess effect*, caused by the burning of fossil fuels since the Industrial Revolution,

has lowered the carbon isotope ratio in modern terrestrial food webs (Keeling 1979; Graven et al. 2020). To account for this effect, we adjusted modern terrestrial samples using Dombrosky's (2019) equation, with the corrected values presented in Table S2.

Stable carbon and nitrogen isotope analyses of C_4 plants (i.e., millet grains) from the Danube Delta and related Roman and Byzantine contexts are scarce. Filipović et al. (2020) documented AMS $\delta^{13}C$ values for 19 archaeological broomcorn millet grains from Eastern Europe, resulting in a mean $\delta^{13}C$ value of -10.3‰; however, $\delta^{15}N$ values were not reported. The lack of published $\delta^{15}N$ values for millet in this region and timeframe led to the use of mean $\delta^{15}N$ values for C_3 plants in FRUITS models, although this approach raises concerns regarding its accuracy:

- a) The millet may not have been grown in the same area as the other crops consumed, and may, therefore, have had nitrogen sources with distinct $\delta^{15}N$ values.
- b) If the C_3 and C_4 cereals were grown in the same region, variations in crop management may have influenced their nitrogen values, with studies indicating that agricultural practices, like manuring, can lead to higher $\delta^{15}N$ (e.g., Bogaard et al. 2007; 2013; Christensen et al. 2022; Dong et al. 2022).
- c) Significant differences in $\delta^{15}N$ can occur between coexisting C_3 and C_4 plants, attributed to their sensitivity to water availability and differing interactions with nitrogen and soil microbes (e.g., Handley et al. 1999; Luo et al. 2018; Dong et al. 2022; cf. Lightfoot et al. 2020).

The isotope data for aquatic food sources in the Danube Delta and Black Sea region include analyses of muscle tissue from modern specimens, which cannot be directly compared to archaeological samples analysed for bone collagen. The offsets used to calculate the muscle protein values of these archaeological samples were $\Delta^{13}C_{\text{muscle-collagen}} = -1\text{‰}$ and $\Delta^{15}N_{\text{muscle-collagen}} = +1.5\text{‰}$ (Soncin et al. 2021). The Suess effect on oceanic organism $\delta^{13}C$ values varies based on ventilation and habitat depth. For the modern aquatic food sources listed in Table S2, a conservative Suess effect value of +0.8‰ (Eide et al. 2017) was applied to their $\delta^{13}C$ values.

Results and Discussion

Collagen quality was assessed based on standard criteria, i.e., percentage weight yield of collagen; %C $\geq$ 13%, %N $\geq$ 5% and of 0.15% $\geq$ %S $\leq$ 0.35%; and atomic ratios of C:N = 2.9–3.6, C:S = 600 $\pm$ 300 and N:S = 200 $\pm$ 100 (DeNiro 1985; Ambrose 1990; van Klinken 1999; Nehlich, Richards 2009; Brock et al. 2010). We excluded samples that did not meet the specified quality criteria from both analysis and interpretation.

Each of the bone collagen samples had wt%C and wt%N, and atomic C:N consistent with modern, and therefore well-preserved, collagen (Table 1; DeNiro 1985; Ambrose 1990; van Klinken 1999; Richards et al. 2001). Three bone collagen samples (Callatis M20 [femur], Callatis M53 [rib] and Ibida M37 [femur]) had wt%S of <0.15% but had C:S and N:S ratios within the range of modern collagen. For each individual, a second sample from a different skeletal element had well-preserved collagen with quality indicators in acceptable ranges, and the $\delta^{34}S$ values of those samples are used in the discussion below.

Diet

Bone collagen $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values, along with summary statistics, are presented in Figure 2 and Table 1. Unless otherwise stated, the discussion below details diet modelled from rib values.

Estimates of dietary contributions indicate that C_3 cereals, wines, and oils were the primary caloric sources for the individuals studied (Table 2), with C_3 plant-derived foods comprising 61 $\pm$ 13% (Histria M15) to 84 $\pm$ 12% (Ibida M38) of their diets. In contrast, C_4 cereals and terrestrial animal products served

Diet and mobility in the Danube Delta region in Late Antiquity: A multi-isotope approach

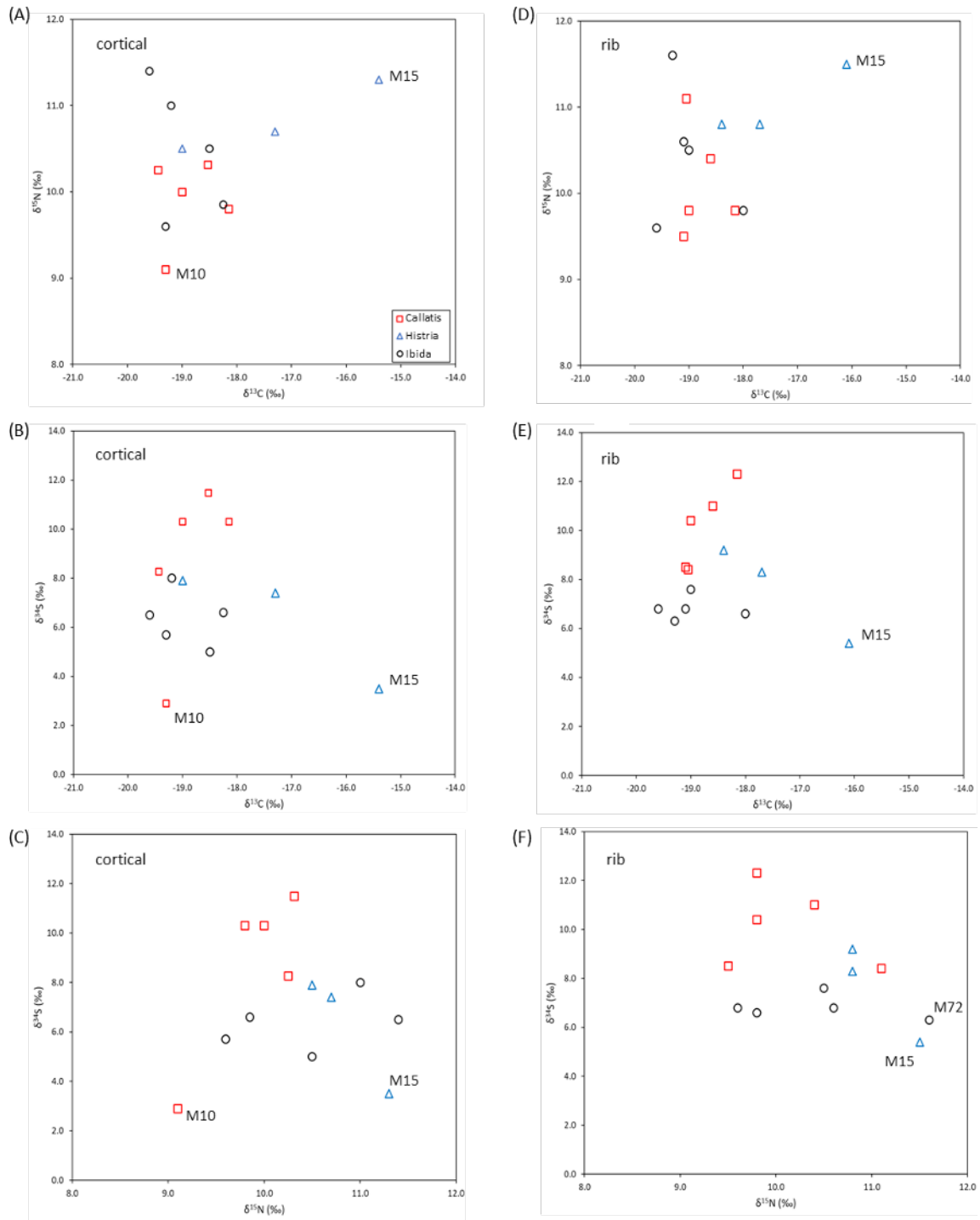


Fig. 2. Scatterplots of cortical (A, B and C) and rib (D, E and F) collagen $\delta^{13}\text{C}$ vs $\delta^{15}\text{N}$, $\delta^{13}\text{C}$ vs $\delta^{34}\text{S}$ and $\delta^{15}\text{N}$ vs $\delta^{34}\text{S}$ values (author C. Pickard)

as secondary energy sources for some. The dietary patterns observed in the Danube Delta individuals reflect those of the broader Roman Empire, as drawn from archaeobotanical and stable isotope evidence (e.g., Craig et al. 2009; Propstmeier et al. 2016; García-Moreno et al. 2022).

In the Danube Delta population sampled, the dietary contribution of C_4 cereals was generally minimal, with mean contributions for all but one individual ranging from $5 \pm 5\%$ (Ibida M38) to $10 \pm 8\%$ (Ibida M37 and Histria M5). Notably, individual M15 from Histria exhibited a higher consumption of C_4

Site	Burial	Bone	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	C_3 plants				C_4 plants				Terrestrial				Aquatic			
					Mean Estimate	CI (68%)	CI (95%)		Mean Estimate	CI (68%)	CI (95%)		Mean Estimate	CI (68%)	CI (95%)		Mean Estimate	CI (68%)	CI (95%)	
Callatis	M10	Femur	-19.3	9.1	85±11	75-95	57-98		6±5	1-10	0-19		8±9	1-18	0-34		1±1	0-1	0-3	
		Rib	-19.1	9.5	82±12	67-93	53-97		7±6	1-12	0-22		11±10	1-23	0-35		1±1	0-2	0-4	
Callatis	M19	Femur	-18.2	9.8	77±12	63-90	52-95		9±7	2-15	0-27		13±10	3-25	0-35		1±1	0-2	0-4	
		Rib	-18.2	9.8	77±12	63-90	52-95		9±7	2-15	0-27		13±10	3-25	0-35		1±1	0-2	0-4	
Callatis	M20	Femur	-19.0	10.0	79±12	64-92	54-97		7±6	1-12	0-22		13±11	2-26	0-36		1±1	0-2	0-4	
		Rib	-19.0	9.8	80±13	65-93	53-97		7±6	1-12	0-22		12±11	2-25	0-36		1±1	0-2	0-4	
Callatis	M53	Femur	-19.4	10.2	81±12	67-93	56-97		6±5	1-11	0-19		12±11	2-25	0-36		1±1	0-2	0-4	
		Rib	-19.1	11.1	76±13	61-90	51-96		6±6	1-12	0-22		16±11	4-29	0-38		2±2	0-3	0-6	
Callatis	M99	Femur	-18.5	10.3	76±13	61-90	51-95		8±7	2-14	0-25		15±11	3-27	0-36		2±1	0-3	0-5	
		Rib	-18.6	10.4	77±13	62-90	52-96		7±6	1-13	0-23		14±11	3-27	0-36		2±1	0-3	0-5	
Histria	M5	Femur	-17.3	10.7	69±13	56-83	45-92		13±9	3-22	1-35		16±10	5-27	1-35		2±2	0-4	0-7	
		Rib	-17.7	10.8	71±12	58-85	48-92		10±8	2-18	0-31		16±10	2-18	1-31		2±2	0-4	0-7	
Histria	M15	Femur	-15.4	11.3	57±12	45-70	36-81		26±13	13-39	3-51		13±8	5-21	1-30		3±3	1-6	0-9	
		Rib	-16.1	11.5	61±13	49-74	37-86		20±12	6-33	1-46		15±8	6-24	1-32		4±3	1-6	0-10	
Histria	M32	Humerus	-19.0	10.5	77±13	62-91	52-96		7±6	1-12	0-23		15±11	3-28	0-37		1±1	0-3	0-5	
		Rib	-18.4	10.8	74±12	60-88	51-95		8±6	2-14	0-24		16±11	4-29	1-37		2±2	4-29	1-37	
Ibida	M21	Femur	-19.3	9.6	84±11	71-94	57-97		6±5	1-10	0-19		10±10	1-22	0-36		1±1	0-2	0-3	
		Rib	-19.1	10.6	78±13	63-91	53-96		6±6	1-11	0-22		14±11	3-27	0-37		2±1	0-3	0-5	
Ibida	M37	Femur	-18.3	9.9	77±13	62-90	51-95		8±7	2-15	0-26		14±11	3-27	0-36		1±1	0-2	0-4	
		Rib	-18.0	9.8	74±13	59-89	48-95		10±8	2-18	0-30		15±11	3-27	0-36		1±1	0-2	0-5	
Ibida	M38	Femur	-18.5	10.5	75±13	61-89	52-95		7±7	1-14	0-24		15±11	4-28	1-37		2±1	0-3	0-6	
		Rib	-19.6	9.6	84±12	71-95	56-98		5±5	1-10	0-19		10±10	1-21	0-36		1±1	0-2	0-3	
Ibida	M72	Femur	-19.6	11.4	78±13	62-91	54-96		5±5	1-10	0-19		15±11	3-29	0-37		2±2	0-3	0-6	
		Rib	-19.3	11.6	75±13	61-90	52-95		6±5	1-11	0-19		17±11	4-29	0-38		2±2	1-4	0-7	
Ibida	M127	Humerus	-19.2	11.0	77±13	62-91	53-96		6±6	1-11	0-20		15±11	3-29	0-37		2±2	0-3	0-6	
		Rib	-19.0	10.5	77±13	62-91	52-96		7±6	1-12	0-23		15±11	3-28	0-37		1±1	0-3	0-5	

Table 2. FRUITTS estimates of food source contributions. For model parameters, see Table S2 in the Supplementary Information (author C. Pickard)

Diet and mobility in the Danube Delta region in Late Antiquity: A multi-isotope approach

Site	Burial	$\delta^{13}\text{C}_{\text{en}}$	$\delta^{13}\text{C}_{\text{whole diet}}$
Callatis	M10	-12.1	-22.2
	M19	-10.3	-20.4
	M20	-10.8	-20.9
	M53	-12.6	-22.7
	M99	-12.1	-22.2
Histria	M5	-11.4	-21.5
	M15	-5.8	-15.9
	M21	-10.4	-20.5
	M32	-11.0	-21.1
	M57	-7.9	-18.0
Ibida	M21	-9.5	-19.6
	M37	-7.0	-17.1
	M38	-10.9	-21.0
	M72	-12.5	-22.6
	M127	-11.1	-21.2

Table 3. Estimated childhood whole diet $\delta^{13}\text{C}$ (author C. Pickard)

Sample ID	Locality	$^{87}\text{Sr}/^{86}\text{Sr}$
BONS-01	Mangalia	0.71054
BONS-02	Histria	0.70938
BONS-03a	west of Mangalia	0.70862
BONS-04	Histria	0.70919
BONS-05	Ibida (Slava Rusă)	0.70959
BONS-06	Ibida (Slava Rusă)	0.70936

Table 4. $^{87}\text{Sr}/^{86}\text{Sr}$ values of modern plants collected from the vicinity of the three sites. Mean $^{87}\text{Sr}/^{86}\text{Sr}$ value = 0.70945; standard deviation = 0.00063 (Authors: C. Pickard, C. Bonsall)

resources, likely millet, contributing as much as $20 \pm 12\%$ of their caloric intake. Although demographic information is lacking for individual Histria M15, evidence indicates that millet consumption in the North Pontic regions and along the Lower Danube dates back to at least the mid-2nd millennium BCE (Dal Corso et al. 2022). While C_4 cereals were minor in the diets of most Graeco-Roman communities, some individuals exhibit significant consumption levels (e.g., Killgrove, Tykot 2013), with those from Olbia showing high $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values indicative of reliance on C_4 resources (Privat 2004). Historically perceived as an inferior grain, millet consumption may correlate with lower socioeconomic status (Spurr 1983; van Limbergen 2018b), suggesting that the diet of individual Histria M15 could reflect social standing or indicate origins from regions where millet was more prominent.

The contribution of meat and dairy to diets was relatively uniform: the lowest mean estimate is $10 \pm 10\%$ (Ibida M38: 1–21%), and the highest $17 \pm 11\%$ (Ibida M72: 4–29%) (Table 2). Across the Roman Empire, variations in wealth strongly influenced meat consumption (Garnsey 1999), with lower-income households typically accessing poorer-quality meat, eggs and cheese (Dalby 2009; van Limbergen 2018b). However, stable isotope data do not provide insights into the specific sources of animal protein, including the quality of meat consumed or the relative proportions of meat to dairy.

Aquatic resources appear to have had a limited impact on the diets of individuals, contrasting with expectations based on the geographic setting and historical accounts emphasising the prevalence of *garum/liquamen* in Roman cuisine (Grainger 2018). Research indicates that proximity to major water

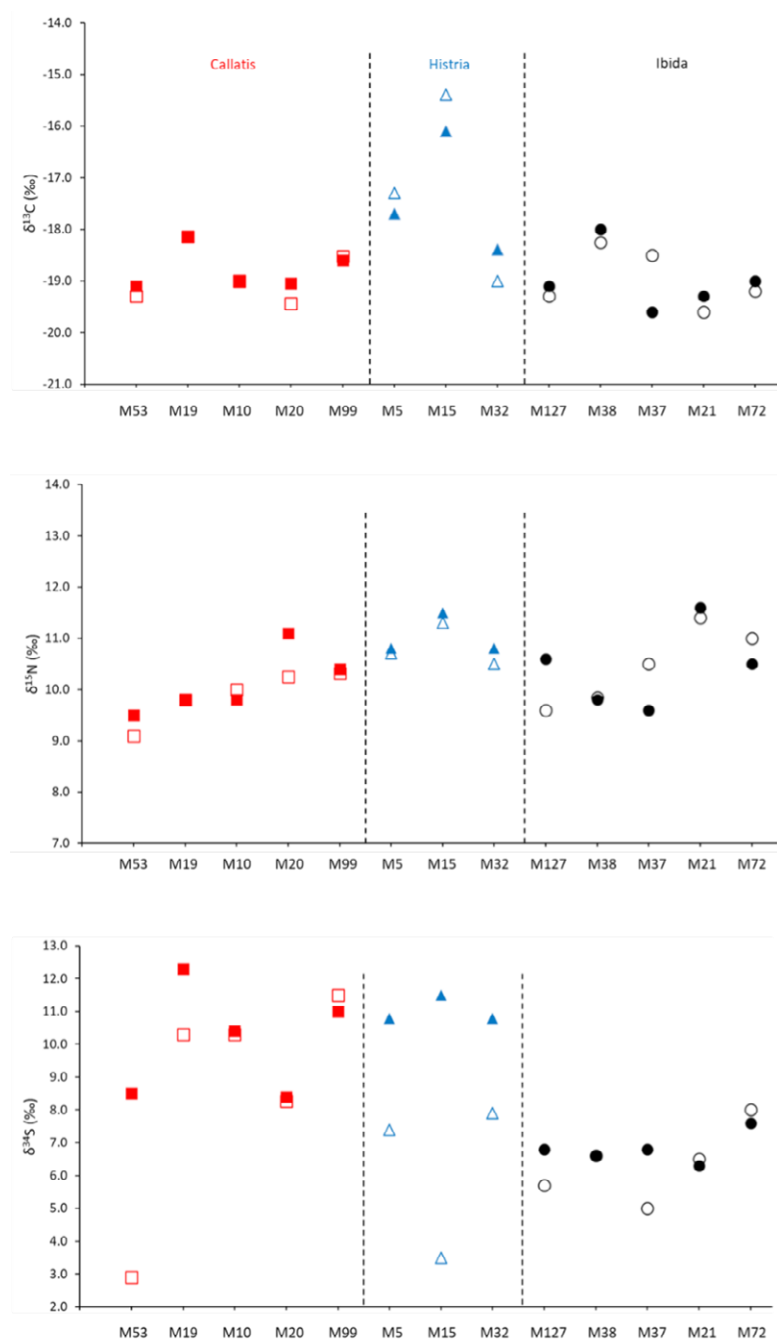


Fig. 3. Comparison of cortical/cranial bone vs rib collagen δ¹³C, δ¹⁵N, and δ³⁴S values by individual (author C. Pickard)

bodies does not correspond with higher consumption of aquatic foods during this time (e.g., Fuller et al. 2010; Moles 2012; Alaica et al. 2019; Defant et al. 2025). Further, while archaeological evidence of fish processing is abundant in the northern Black Sea region, it is scarce along the western Black Sea coast (Højte 2005).

In the northern Black Sea region, there was extensive fish processing for export, notably saltfish and *garum/liquamen* (Højte 2005; Bekker-Neilsen 2023), with the latter being a low-calorie filtered fish sauce made from small fish species such as sand-smelt, red mullet, anchovy, and sardine (van Limbergen 2018b). Isotopic analysis of *garum* from Pompeii indicated δ¹³C and δ¹⁵N values of -12.2‰ and +4.9‰, respectively (Pate et al. 2016), which overlap with those of C₄ plant sources, complicating dietary assessments. Additionally, the isotopic values of aquatic organisms in low-salinity environments, such as

the Danube Delta, tend to be lower than those in high-salinity habitats, adding further complexity to dietary modelling in these regions (Andrews et al. 2023).

The difference in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values between cortical and trabecular tissue in an individual is typically minimal (fig. 3), often within the range of laboratory measurement error. Such data imply that diet remained broadly consistent from adolescence (represented by collagen extracted from femoral cortical bone) until a few years before death (represented by the rib). However, alternative interpretations propose that the rib and femoral tissues may reflect similar dietary intake periods (e.g., Quinn 2024). Individual M38 from Ibida has a femur $\delta^{13}\text{C}$ value $>1\text{‰}$ higher than that of their rib. FRUITS models suggest that this reflects a shift in the relative proportions of C_3 and C_4 plant foods in diet, with a greater contribution from C_3 plants reflected in the rib stable isotope values. However, physiological stresses, such as pregnancy, lactation, starvation, and growth spurts, can affect metabolic isotope discrimination (e.g., Olsen et al. 2014; D’Ortenzio et al. 2015; Craig-Aitkens et al. 2018). The effects of such stressors on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values can mimic dietary changes, potentially leading to misinterpretation. In this case, it seems likely that the time spans reflected by the rib and the femoral isotope values are distinct.

Enamel $\delta^{13}\text{C}$ values can provide information about childhood diet. The enamel of the M2 tooth begins to develop from c. 2.5 years and deposition is completed c. 6.5 years (AlQahtani et al. 2010). Therefore, the $\delta^{13}\text{C}_{\text{en}}$ value is likely not impacted by a nursing signal and will typically reflect post-weaning, early childhood dietary intake. The mean $\delta^{13}\text{C}_{\text{en}}$ and standard deviations of the three sites are distinct: Callatis $\bar{x} = -11.6 \pm 1.0\text{‰}$, Histria $\bar{x} = -9.4 \pm 3.1\text{‰}$, and Ibida $\bar{x} = -10.2 \pm 2.0\text{‰}$. However, the differences in mean $\delta^{13}\text{C}_{\text{en}}$ between the sites are not statistically significant (Kruskal–Wallis, $p=0.29$), likely reflecting the large intra-site variation in individual values, as well as small sample sizes.

To explore childhood diets, Fernandes et al.’s (2012) enamel apatite to whole diet $\delta^{13}\text{C}$ offset of -10.1‰ was applied to the Danube Delta $\delta^{13}\text{C}_{\text{en}}$ values (Table 3). Two individuals, M15 from Histria and M37 from Ibida, have $\delta^{13}\text{C}_{\text{en}}$ values that suggest a significant intake of C_4 food sources in childhood. The enamel and rib/femur collagen $\delta^{13}\text{C}$ values of individual Histria M15 suggest that C_4 food sources were important sources of calories in both childhood and adulthood. By contrast, the childhood diet of M37 likely included a higher proportion of C_4 resources than the adult diet. Crowder et al. (2019) observed increased reliance on C_4 resources during adolescence in a 4th to 7th c. CE ‘barbarian’ population from Archiud in north-central Romania. This was attributed to the need for greater caloric intake during periods of growth or stress. Notably, this Gepid group had a much greater dependence on C_4 plants than the Late Roman Danube Delta individuals (see Table S1 in Crowder et al. 2019).

Changes in food consumption over time can reflect an influx of populations with distinct cultural values or culinary preferences or point to disruptions to food supplies due to social disorder. The combined $\delta^{13}\text{C}_{\text{en}}$, $\delta^{13}\text{C}_{\text{femur}}$, and $\delta^{13}\text{C}_{\text{rib}}$ values of individual M37 from Ibida, a young adult female estimated to be around 20–22 years old at death, suggest a significant dietary shift during late childhood/early adolescence. The femoral and rib collagen $\delta^{13}\text{C}$ values indicate a predominantly C_3 plant-based diet [$74 \pm 13\text{‰}$; range 59–89%], which is distinct from the childhood $\delta^{13}\text{C}_{\text{en}}$ value, reflecting a diet based on C_4 resources. The reasons for this change remain speculative, potentially linked to migration, diet alterations during weaning, or variations in social status or health.

Although bone apatite-collagen $\delta^{13}\text{C}$ spacing can further elucidate the contribution of low-protein sources to diet (e.g., Ambrose, Krigbaum 2003; Harrison, Katzenberg 2003), bone apatite $\delta^{13}\text{C}$ values are not currently available for the study populations.

Rib collagen $\delta^{34}\text{S}$ values across the three sites range from 5.4‰ to 12.3‰, indicating consumption of terrestrial, bioavailable $\delta^{34}\text{S}$ (e.g., Peterson, Fry 1987; Nehlich 2015). Femoral collagen $\delta^{34}\text{S}$ values are slightly lower, ranging from 2.9‰ to 11.5‰, though the differences between rib and femur/humerus $\delta^{34}\text{S}$ values are not statistically significant (Mann-Whitney, $p>0.05$). While the mean rib vs femur/humerus $\delta^{34}\text{S}$ values of all of the individuals analysed are distinct (rib $\bar{x} = 8.3\text{‰}$ and femur/hu-

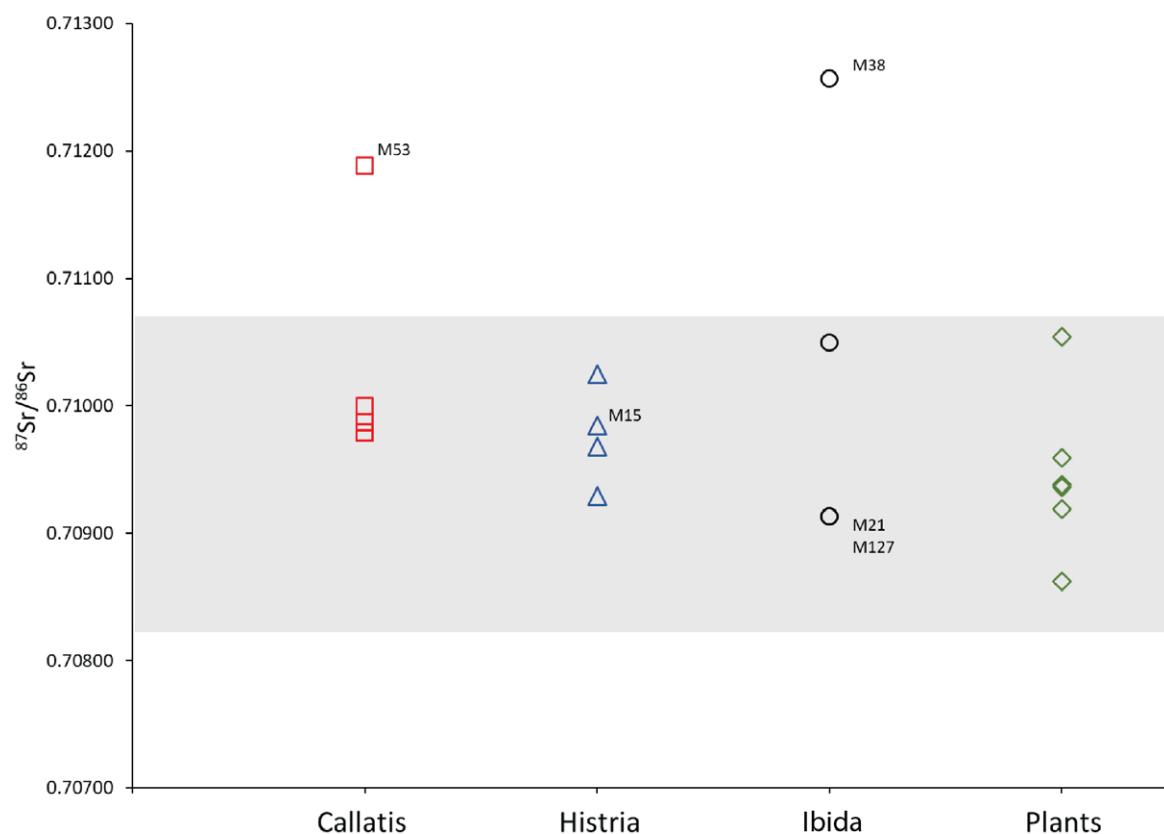


Fig. 4. M2 enamel $^{87}\text{Sr}/^{86}\text{Sr}$ values. The 'local' bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ range (shown in grey) was determined from the plant mean value $\pm 2\sigma$ range (author C. Pickard)

merus $\bar{x} = 7.2\text{‰}$, respectively), this is only slightly higher than measurement error. The mean $\delta^{34}\text{S}$ and standard deviation values of the three sites are Callatis $\bar{x} = 8.7 \pm 3.4\text{‰}$, Histria $\bar{x} = 6.3 \pm 2.4\text{‰}$, and Ibida $\bar{x} = 6.4 \pm 1.0\text{‰}$. Callatis, the most southerly of the three sites and located the farthest from the Danube, has the highest mean $\delta^{34}\text{S}$ value. Nehlich (2015) proposed that the sea spray effect (i.e., the aerosol deposition of marine sulphur, which has $\delta^{34}\text{S}$ of c. 21‰, on terrestrial ecozones) would result in $\delta^{34}\text{S}$ values of at least 14‰ in coastal populations irrespective of dietary constituents. However, the $\delta^{34}\text{S}$ value of the Black Sea may be influenced by the freshwater catchment. Andrews et al. (2023) proposed that relatively low $\delta^{34}\text{S}$ values would be expected, primarily due to the contribution of microbial sulphides in a low-oxygen environment. They demonstrated that tuna from the eastern Black Sea region had lower $\delta^{34}\text{S}$ values than those typical of marine fish from the Mediterranean. Notably, there is little trace of a conventional sea spray effect in the $\delta^{34}\text{S}$ values of archaeological coastal populations, nor in modern sheep's wool from the Black Sea region (e.g., Hedges et al. 2005; Irvine, Erdal 2020).

Mobility/Migration

We explored the provenance of the individuals from Callatis, Histria, and Ibida through the analysis of $\delta^{18}\text{O}$, $^{87}\text{Sr}/^{86}\text{Sr}$ (fig. 4) and $\delta^{34}\text{S}$ values. This analysis is set against the backdrop of regional instability and upheaval during the Migration Period, which provides essential context for interpreting the data.

The $\delta^{18}\text{O}_{\text{PO}_4}$ values of the Danube Delta populations sampled ranged from 14.6‰ to 17.3‰, with mean values of $15.9 \pm 0.9\text{‰}$ for Callatis, $16.6 \pm 0.3\text{‰}$ for Histria, and $16.4 \pm 0.8\text{‰}$ for Ibida. While the range of values varies, the differences across these sites are statistically insignificant (Kruskal–Wallis, $p > 0.05$). $\delta^{18}\text{O}_{\text{PO}_4}$ can differentiate between long-term residents and non-residents, but such analyses

typically require a broader context of investigation into mobility. The small range of $\delta^{18}\text{O}_{\text{PO}_4}$ values (2.7‰) within the sampled group is relatively low compared to typical archaeological populations, which often exhibit variations of at least 3‰. The values observed in the Danube Delta fall within the ‘post-infant-dentition’ range found in Bulgarian archaeological populations (13.9‰ to 17.8‰) (Lightfoot, O’Connell 2016). Such $\delta^{18}\text{O}_{\text{PO}_4}$ values are prevalent across Europe, complicating the identification of outliers or migrants based solely on $\delta^{18}\text{O}_{\text{PO}_4}$ measurements.

Analyses of modern plant samples from near the three sites revealed local $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.70819 to 0.71070 (Table 4), comparable to those determined for both Epipalaeolithic to Neolithic people of the Iron Gates region (0.7085 to 0.7100) and the Chalcolithic people of Gumelnița in the Danube Delta (with ‘local’ values from 0.7083 to 0.7103) (Borić, Price 2013; Tafani et al. 2025). Most individuals examined exhibited dental enamel $^{87}\text{Sr}/^{86}\text{Sr}$ values within this local range, suggesting long-term residency. However, two males, Callatis M53 and Ibida M38, displayed values outside the local range (0.71189 and 0.71257), suggesting residential mobility from geologically distinct areas. However, pinpointing their exact origins is complicated due to the complex geology of Southeast Europe and limited strontium isotope mapping. Human and faunal remains exhibiting similar $^{87}\text{Sr}/^{86}\text{Sr}$ values have been found in various regions, including Russia, the eastern Baltic, southern Scandinavia and Kazakhstan (e.g., Haverkort et al. 2008; Gerling 2015; Petersone-Gordina et al. 2022; Piličiauskas et al. 2022), yet the $\delta^{18}\text{O}_{\text{PO}_4}$ values of M53 and M38 do not align with those of known Kazakhstani populations (Hamre, Daux 2016; cf. Ventresca Miller et al. 2017).

Thus, individuals M38 and M53 may have migrated to the Danube Delta from northern regions during the Gothic incursions in the 3rd and 4th c. CE. However, establishing their origins through $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic analysis involves a process of exclusion. While this method can definitively indicate where individuals did not grow up, pinpointing their precise origins is challenging due to insufficient mapping of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ isoscapes in the Danube Delta region. Furthermore, residential mobility during tooth development periods can complicate the signals obtained, as they may reflect a mixture of geological $^{87}\text{Sr}/^{86}\text{Sr}$ signatures from various locations.

The $\delta^{34}\text{S}$ values of the femur and rib from the individual Callatis M10 are distinct (2.9‰ and 8.5‰, respectively). The femur’s $\delta^{34}\text{S}$ value is the lowest among all samples from the three Danube Delta sites and falls outside the mean $\pm 2\sigma$ range (3.1–13.3‰). This divergence in $\delta^{34}\text{S}$ values suggests a potential dietary or residential change, indicating that collagen from rib and femur may reflect different life stages. However, measurement uncertainty ($\pm 0.6\text{‰}$) could extend the $\delta^{34}\text{S}$ mean range of the sample population, and other isotopic measurements ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and $^{87}\text{Sr}/^{86}\text{Sr}$) do not support a change in diet or mobility.

Conclusions

C_3 plant foods, likely including both cereals and oils, made the most significant contribution to dietary calories at all three Late Roman period sites studied. C_4 cereals, meat and dairy products were important secondary food sources for some individuals in terms of calories. Aquatic resources made a minor contribution at most. However, the consumption of fish sauce may be indistinguishable from C_4 cereals. In at least two individuals, their diets differed between childhood and adulthood. Analysis of serial, incremental dentine samples from these individuals and others at the three sites would provide a clearer picture of childhood diet and culturally informed nursing, weaning, and culinary practices in the Late Roman Danube Delta region.

There were three main limitations to this multi-isotope pilot study of diet and mobility in archaeological populations from the Danube Delta:

The small sample size. Only five individuals from each of the three sites (Callatis, Histria and

Ibida) were sampled for $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and $\delta^{34}\text{S}$ analysis.

Limited food source data, particularly the lack of $\delta^{34}\text{S}$ values. Reconstruction of diet from stable isotope values is more robust where the stable isotope signatures of potential foods are known. However, archaeological remains of foods are seldom recovered from cemeteries of the Late Roman period, and none were available for this study.

The absence of ^{14}C dates for the majority of the human remains. This limits the interpretation of the stable isotope data and our ability to provide explanations for individual dietary differences.

Future research on Danube Delta populations should include analysis of the preservation quality of bone apatite in conjunction with measurements of the bone apatite $\delta^{13}\text{C}$ in suitably preserved samples. Conducting stable isotope analysis on serial, incrementally sampled dentine has the potential to deepen our understanding of dietary trends and physiological stress experienced during childhood. Furthermore, aDNA analysis of a broad subset of individuals from these cemetery populations would yield critical insights into the ancestry and population dynamics of these Migration Period communities.

Postscript

Since the manuscript was finalised, the authors have had sight of a draft of a paper submitted to another journal, which includes some new ^{14}C dates from Slava Rusă (Ibida). These dates may indicate a broader time range for the Ibida burials, but this does not materially affect our conclusions.

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Diet and mobility in the Danube Delta region in Late Antiquity: A multi-isotope approach

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Diet and mobility in the Danube Delta region in Late Antiquity: A multi-isotope approach

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Diet and mobility in the Danube Delta region in Late Antiquity: A multi-isotope approach

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Danube Delta – Supplementary Information

Sample Pre-Treatment and Isotope Measurement

Pre-treatment and Collagen Extraction

- Collagen extraction was performed in the Wet Chemistry Laboratory at the School of History, Classics and Archaeology, University of Edinburgh, using a modified Longin (1971) method. Pre-treatment consisted of sample cleaning by removal of the outer 2 mm of the bone surface, ultra-sonication in milli-Q™ purified water (carbon content < 3ppb), demineralisation in 1 N HCl for a minimum of 24 hours, and gelatinisation in 0.03 N HCl at 80°C for ~16 hours; the resulting solution was lyophilised.
- $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and $\delta^{34}\text{S}$ mass spectrometric measurements of bone collagen were undertaken at the SUERC Radiocarbon Laboratory facility, East Kilbride, UK. Measurements were corrected for linearity and instrumental drift, and reported as per mil (‰) relative to the international standards V-PDB, AIR and V-CDT, respectively. 1σ repeatability precisions were $\delta^{13}\text{C} = \pm 0.2\text{‰}$, $\delta^{15}\text{N} = \pm 0.3\text{‰}$ and $\delta^{34}\text{S} = \pm 0.6\text{‰}$.

Pre-treatment and Measurement of Enamel Carbonate

- The enamel surface of each tooth was cleaned by abrasion with a tungsten carbide dental burr to a depth of >100 μm , and the removed material was discarded. Slices of enamel were then cut from each tooth using a flexible diamond-edged rotary dental saw.
- The surfaces of each sample were then abraded to remove any dentine. Samples were transferred to a clean (class 100, laminar flow) working area. The samples were ultrasonicated in high-purity water, rinsed, dried, and then weighed into pre-cleaned Teflon beakers. The samples were mixed with ^{84}Sr tracer solution and dissolved in Teflon-distilled 8 N HNO_3 . Sr was collected using Dowex resin columns and loaded onto a single Re Filament with TaF, following the method of Birck (1986). The isotope composition and concentrations were determined by Thermal Ionisation Mass spectroscopy (TIMS) using a Thermo Triton multi-collector mass spectrometer. The international standard for $^{87}\text{Sr}/^{86}\text{Sr}$, NBS987, gave a value of 0.710251 ± 0.000005 ($n=19$, 2σ) during the analysis of these samples. Blank values were in the region of 100 pg.

Pre-treatment and Isotope Analysis of Oxygen in Structural Carbonate

- Approximately 3 mg of each prepared enamel sample was loaded into a glass vial and sealed with septa. The vials were transferred to a hot block at 90°C on a GV Multiprep system, subsequently evacuated, and four drops of anhydrous phosphoric acid were added. The resultant CO_2 was collected cryogenically for 14 minutes and transferred to a GV IsoPrime dual-inlet mass spectrometer.
- The resultant isotope values are treated as a carbonate. d^{18}O is reported as per mil (‰), normalised to the PDB scale using a within-run calcite laboratory standard (KCM) calibrated against SRM19 NIST reference material and converted to the SMOW scale using the published conversion equation of Coplen (1988):

$$\text{d}^{18}\text{O}_{\text{SMOW(C)}} = 1.03091 * \text{d}^{18}\text{O}_{\text{VPDB}} + 30.91.$$
- Analytical reproducibility for this run of laboratory standard calcite (KCM) is $\text{d}^{18}\text{O}_{\text{SMOW}} = \pm 0.04\text{‰}$ (1σ , $n=9$) and $\text{d}^{13}\text{C}_{\text{PDB}} = \pm 0.02\text{‰}$ (1σ , $n=9$). The carbonate oxygen results $\text{d}^{18}\text{O}_{\text{SMOW(C)}}$ were converted to phosphate values $\text{d}^{18}\text{O}_{\text{SMOW(P)}}$ using the equation in Chenery et al. (2012): $\text{d}^{18}\text{O}_{\text{SMOW(P)}} = 1.0322 * \text{d}^{18}\text{O}_{\text{SMOW(C)}} - 9.6849.$

Parameter	Description
$\Delta^{15}\text{N}_{\text{diet-consumer}}$	$5.5 \pm 0.5\text{‰}$
$\Delta^{13}\text{C}_{\text{diet-consumer}}$	$4.8 \pm 0.5\text{‰}$
Food source isotope values – C_3 Plants	$\delta^{13}\text{C}_{\text{protein}} = -24.0 \pm 1.0\text{‰}$; $\delta^{13}\text{C}_{\text{energy}} = -21.5 \pm 1.0\text{‰}$; $\delta^{15}\text{N} = 4.3 \pm 1.0\text{‰}$
Food source isotope values – C_4 Plants	$\delta^{13}\text{C}_{\text{protein}} = -10.3 \pm 1.0\text{‰}$; $\delta^{13}\text{C}_{\text{energy}} = -7.8 \pm 1.0\text{‰}$; $\delta^{15}\text{N} = 4.3 \pm 1.0\text{‰}$
Food source isotope values – Terrestrial animals	$\delta^{13}\text{C}_{\text{protein}} = -21.5 \pm 1.0\text{‰}$; $\delta^{13}\text{C}_{\text{energy}} = -27.5 \pm 1.0\text{‰}$; $\delta^{15}\text{N} = 6.3 \pm 1.0\text{‰}$
Food source isotope values – Aquatic	$\delta^{13}\text{C}_{\text{protein}} = -18.2 \pm 1.0\text{‰}$; $\delta^{13}\text{C}_{\text{energy}} = -24.2 \pm 1.0\text{‰}$; $\delta^{15}\text{N} = 13.0 \pm 1.0\text{‰}$
Food source nutrient concentrations – C_3 Plants	Protein:energy – 10:90
Food source nutrient concentrations – C_4 Plants	Protein:energy – 10:90
Food source nutrient concentrations – Terrestrial animals	Protein:energy – 70:30
Food source nutrient concentrations – Fish	Protein:energy – 85:15
Prior	$0.05 \leq \text{protein intake} \leq 0.35$

Table S1. Parameters used in the FRUITS models of diet (offsets, uncertainties and prior from Fulgoni 2008; Fernandes et al. 2012, 2014, 2015; Soncin et al. 2021) (author C. Pickard)

Diet and mobility in the Danube Delta region in Late Antiquity: A multi-isotope approach

Taxon	Common Name	Site	Date	Sample ID	Sample	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N	n	Reference
TERRESTRIAL ANIMALS												
<i>Bos taurus</i>	Cattle	Sărata Monteoru, Romania	c. 1750–1500 cal BC	8-SM	Bone	-20.0	6.6	38.1	13.6	3.3	1	Agurauja et al. 2018
<i>Bos taurus</i>	Cattle	Sărata Monteoru, Romania	c. 1750–1500 cal BC	10-SM	Bone	-20.0	6.3	39.9	14.1	3.3	1	Agurauja et al. 2018
<i>Bos taurus</i>	Cattle	Sărata Monteoru, Romania	c. 1750–1500 cal BC	14-SM	Bone	-20.7	7.8	41.4	14.7	3.3	1	Agurauja et al. 2018
<i>Bos taurus</i>	Cattle	Sărata Monteoru, Romania	c. 1750–1500 cal BC	15-SM	Bone	-19.5	6.4	41.1	14.5	3.3	1	Agurauja et al. 2018
<i>Bos taurus</i>	Cattle	Sărata Monteoru, Romania	c. 1750–1500 cal BC	20-SM	Bone	-20.5	6.4	40.1	14.0	3.4	1	Agurauja et al. 2018
<i>Bos taurus</i>	Cattle	Cărlomănești, Romania	c. 2280–1800 cal BC	22-CRL	Bone	-20.6	6.5	42.0	14.9	3.3	1	Agurauja et al. 2018
<i>Bos taurus</i>	Cattle	Cărlomănești, Romania	c. 2280–1800 cal BC	30-CRL	Bone	-20.3	7.7	36.7	13.0	3.3	1	Agurauja et al. 2018
<i>Cervus</i>	Deer	Cărlomănești, Romania	c. 2280–1800 cal BC	33-CRL	Bone	-20.8	4.3	28.8	10.2	3.3	1	Agurauja et al. 2018
<i>Equus caballus</i>	Horse	Sărata Monteoru, Romania	c. 1750–1500 cal BC	21-SM	Bone	-19.9	6.4	41.1	14.4	3.3	1	Agurauja et al. 2018
<i>Equus caballus</i>	Horse	Cărlomănești, Romania	c. 2280–1800 cal BC	25-CRL	Bone	-19.6	4.8	16.0	5.5	3.4	1	Agurauja et al. 2018
<i>Equus caballus</i>	Horse	Cărlomănești, Romania	c. 2280–1800 cal BC	29-CRL	Bone	-19.5	2.8	42.4	15.0	3.3	1	Agurauja et al. 2018
<i>Ovis aries</i>	Sheep	Cărlomănești, Romania	c. 2280–1800 cal BC	24-CRL	Bone	-20.1	5.8	41.8	14.9	3.3	1	Agurauja et al. 2018
<i>Ovis aries/Capra hircus</i>	Sheep/goat	Cărlomănești, Romania	c. 2280–1800 cal BC	25-CRL	Bone	-19.9	6.0	41.9	14.9	3.3	1	Agurauja et al. 2018
<i>Ovis aries/Capra hircus</i>	Sheep/goat	Sărata Monteoru, Romania	c. 1750–1500 cal BC	2-SM	Bone	-19.4	6.1	42.2	14.8	3.3	1	Agurauja et al. 2018
<i>Ovis aries/Capra hircus</i>	Sheep/goat	Sărata Monteoru, Romania	c. 1750–1500 cal BC	3-SM	Bone	-20.0	5.9	40.0	14.1	3.3	1	Agurauja et al. 2018
<i>Ovis aries/Capra hircus</i>	Sheep/goat	Sărata Monteoru, Romania	c. 1750–1500 cal BC	6-SM	Bone	-19.1	6.4	41.8	14.9	3.3	1	Agurauja et al. 2018
<i>Ovis aries/Capra hircus</i>	Sheep/goat	Sărata Monteoru, Romania	c. 1750–1500 cal BC	7-SM	Bone	-19.6	5.9	41.1	14.4	3.3	1	Agurauja et al. 2018
<i>Ovis aries/Capra hircus</i>	Sheep/goat	Sărata Monteoru, Romania	c. 1750–1500 cal BC	11-SM	Bone	-19.0	5.4	41.1	14.6	3.3	1	Agurauja et al. 2018
<i>Ovis aries/Capra hircus</i>	Sheep/goat	Sărata Monteoru, Romania	c. 1750–1500 cal BC	13-SM	Bone	-18.9	5.7	34.3	12.1	3.3	1	Agurauja et al. 2018
<i>Ovis aries/Capra hircus</i>	Sheep/goat	Sărata Monteoru, Romania	c. 1750–1500 cal BC	19-SM	Bone	-20.2	7.4	40.4	14.1	3.4	1	Agurauja et al. 2018
<i>Sus scrofa domesticus</i>	Pig	Sărata Monteoru, Romania	c. 1750–1500 cal BC	4-SM	Bone	-19.9	7.4	40.5	14.4	3.3	1	Agurauja et al. 2018
<i>Sus scrofa domesticus</i>	Pig	Sărata Monteoru, Romania	c. 1750–1500 cal BC	5-SM	Bone	-19.1	9.8	39.6	13.5	3.4	1	Agurauja et al. 2018

Taxon	Common Name	Site	Date	Sample ID	Sample	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N	n	Reference
<i>Sus scrofa domestica</i>	Pig	Sărata Monteoru, Romania	c. 1750–1500 cal BC	9-SM	Bone	-19.5	7.6	40.1	14.1	3.3	1	Agurauja et al. 2018
<i>Sus scrofa domestica</i>	Pig	Cârlomănești, Romania	c. 2280–1800 cal BC	31-CRL	Bone	-13.5	6.2	42.4	15.3	3.2	1	Agurauja et al. 2018
<i>Sus scrofa domestica</i>	Pig	Cârlomănești, Romania	c. 2280–1800 cal BC	32-CRL	Bone	-18.5	5.2	41.7	15.1	3.2	1	Agurauja et al. 2018
<i>Sus scrofa domestica</i>	Pig	Cârlomănești, Romania	c. 2280–1800 cal BC	34-CRL	Bone	-19.5	7.9	26.2	9.1	3.4	1	Agurauja et al. 2018
<i>Sus scrofa domestica</i>	Pig	Cârlomănești, Romania	c. 2280–1800 cal BC	36-CRL	Bone	-18.6	6.3	41.4	14.9	3.2	1	Agurauja et al. 2018
					MEAN	-19.5	6.3					
					S.D.	1.3	1.3					
					S.E.	0.2	0.2					
AQUATIC RESOURCES												
<i>Acipenser stellatus</i>	Starry sturgeon	Romanian Coast, Black Sea	AD 2004-2006		Muscle	-18.0	16.2				12	Bănar, Harmelin-Vivien 2009
<i>Lophius budegassa</i>	Black-bellied angler	Sea of Marmara	AD 2017-2018		Muscle	-17.8	14.3				6	Gül, Demirel 2022
<i>Merlangius merlangius</i>	Whiting	Romanian Coast, Black Sea	AD 2004-2006		Muscle	-18.1	15.1				175	Bănar, Harmelin-Vivien 2009
<i>Mullus barbatus</i>	Red Mullet	Romanian Coast, Black Sea	AD 2004-2006		Muscle	-17.4	14.6				141	Bănar, Harmelin-Vivien 2009
<i>Mullus</i> sp.	Mullet	Sea of Marmara	AD 2017-2018		Muscle	-18.3	10.7				1	Gül, Demirel 2022
<i>Neogobius melanostomus</i>	Round Goby	Romanian Coast, Black Sea	AD 2004-2006		Muscle	-17.7	14.0				211	Bănar, Harmelin-Vivien 2009
<i>Platichthys flesus</i>	Flounder	Romanian Coast, Black Sea	AD 2004-2006		Muscle	-17.9	14.3				35	Bănar, Harmelin-Vivien 2009
<i>Raja clavata</i>	Thornback Ray	Sea of Marmara	AD 2017-2018		Muscle	-17.6	13.3				8	Gül, Demirel 2022
<i>Solea solea</i>	Common Sole	Romanian Coast, Black Sea	AD 2004-2006		Muscle	-17.3	14.4				30	Bănar, Harmelin-Vivien 2009
<i>Scophthalmus maximus</i>	Turbot	Romanian Coast, Black Sea	AD 2004-2006		Muscle	-17.7	16.3				61	Bănar, Harmelin-Vivien 2009
<i>Serranus hepatus</i>	Brown Comber	Romanian Coast, Black Sea	AD 2004-2006		Muscle	-17.7	12.8				3	Gül, Demirel 2022

Taxon	Common Name	Site	Date	Sample ID	Sample	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N	n	Reference
<i>Trachurus</i> sp.	Horse Mackerel	Sea of Marmara	AD 2017-2018		Muscle	-19.4	11.8				4	Gül, Demirel 2022
<i>Donax turunculus</i>	Donax	Sea of Marmara	AD 2017-2018		Muscle	-19.2	8.4				2	Gül, Demirel 2022
<i>Liocarcinus depurator</i>	Harbour Crab	Sea of Marmara	AD 2017-2018		Muscle	-18.1	11.3				3	Gül, Demirel 2022
<i>Loligo</i> sp.	Squid	Sea of Marmara	AD 2017-2018		Muscle	-19.1	12.3				4	Gül, Demirel 2022
<i>Parapenaeus longirostris</i>	Pink shrimp	Sea of Marmara	AD 2017-2018		Muscle	-18.5	9.8				5	Gül, Demirel 2022
<i>Phocoena phocoena</i>	Harbour Porpoise	Ukranian Coast, Black Sea	AD 1997-1998		Muscle	-19.7	12.0				46	Das et al. 2004
					MEAN	-18.2	13.0					
					S.D.	0.7	2.2					
					S.E.	0.2	0.5					
PLANTS C3												
<i>Hordeum vulgare</i> var. <i>nudum</i>	Naked barley	Azmaç, Bulgaria	c. 5700–5400 cal BC	n/a	Grain	-24.1	7.1	48.7	2.0	28.0	1	Bogaard et al. 2013
<i>Hordeum vulgare</i> var. <i>nudum</i>	Naked Barley	Gumelnița, Romania	c. 4700–3900 cal BC	GUM-66	Grain	-25.8	6.0	18.4	4.2		1	García-Vázquez et al. 2023
<i>Hordeum vulgare</i> var. <i>nudum</i>	Naked Barley	Gumelnița, Romania	c. 4700–3900 cal BC	GUM-67	Grain	-24.5	13.4	25.1	3.3		1	García-Vázquez et al. 2023
<i>Hordeum vulgare</i> var. <i>nudum</i>	Naked Barley	Gumelnița, Romania	c. 4700–3900 cal BC	GUM-68	Grain	-23.8	5.4	21.1	3.9		1	García-Vázquez et al. 2023
<i>Hordeum vulgare</i> var. <i>nudum</i>	Naked Barley	Gumelnița, Romania	c. 4700–3900 cal BC	GUM-69	Grain	-26.1	3.9	11.8	6.5		1	García-Vázquez et al. 2023
<i>Hordeum vulgare</i>	Hulled barley	Koufovouno, Greece	c. 5800-5000 cal BC	n/a	Grain	-24.6	0.7	43.4	2.0	25.7	1	Bogaard et al. 2013
<i>Hordeum vulgare</i>	Hulled barley	Koufovouno, Greece	c. 5800-5000 cal BC	n/a	Grain	-24.5	3.1	49.8	2.3	25.3	1	Bogaard et al. 2013
<i>Hordeum vulgare</i>	Hulled barley	Koufovouno, Greece	c. 5800-5000 cal BC	n/a	Grain	-25.1	1.6	56.0	1.6	40.3	1	Bogaard et al. 2013
<i>Hordeum vulgare</i>	Hulled barley	Koufovouno, Greece	c. 5800-5000 cal BC	n/a	Grain	-24.2	4.2	54.3	2.3	27.4	1	Bogaard et al. 2013
<i>Hordeum vulgare</i>	Hulled barley	Koufovouno, Greece	c. 5800-5000 cal BC	n/a	Grain	-24.4	3.5	44.1	2.2	23.1	1	Bogaard et al. 2013
<i>Hordeum vulgare</i>	Hulled barley	Koufovouno, Greece	c. 5800-5000 cal BC	n/a	Grain	-24.4	2.7	45.1	2.0	26.1	1	Bogaard et al. 2013

Taxon	Common Name	Site	Date	Sample ID	Sample	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N	n	Reference
<i>Lathyrus sativus/cicera</i>	Grass pea	Aznak, Bulgaria	c. 5700–5400 cal BC	n/a	Grain	-25.0	1.9	72.6	8.6	9.9	1	Bogaard et al. 2013
<i>Lens culinaris</i>	Lentil	Gumelnita, Romania	c. 4700–3900 cal BC	GUM-70	Grain	-22.8	8.2	10.6	6.7		1	García-Vázquez et al. 2023
<i>Lens culinaris</i>	Lentil	Karanovo, Bulgaria	c. 5500–5300 cal BC	n/a	Grain	-24.1	1.4	40.5	4.5	10.4	1	Bogaard et al. 2013
<i>Lens culinaris</i>	Lentil	Karanovo, Bulgaria	c. 5500–5300 cal BC	n/a	Grain	-23.6	0.8	39.3	4.6	10.0	1	Bogaard et al. 2013
<i>Lens culinaris</i>	Lentil	Karanovo, Bulgaria	c. 5500–5300 cal BC	n/a	Grain	-25.1	1.6	36.8	3.4	12.7	1	Bogaard et al. 2013
<i>Pisum sativum</i>	Pea	Aznak, Bulgaria	c. 5700–5400 cal BC	n/a	Grain	-23.9	2.9	74.9	8.5	10.3	1	Bogaard et al. 2013
<i>Pisum sativum</i>	Pea	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-24.8	1.4	46.6	4.3	12.6	1	Bogaard et al. 2013
<i>Pisum sativum</i>	Pea	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-23.4	1.2	54.1	5.3	11.9	1	Bogaard et al. 2013
<i>Pisum sativum</i>	Pea	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-24.8	1.7	39.4	6.8	6.7	1	Bogaard et al. 2013
<i>Pisum sativum</i>	Pea	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-26.1	0.9	48.2	6.0	9.3	1	Bogaard et al. 2013
<i>Pisum sativum</i>	Pea	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-25.1	1.3	28.1	3.6	9.1	1	Bogaard et al. 2013
<i>Pisum sativum</i>	Pea	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-25.9	1.6	50.4	4.4	13.4	1	Bogaard et al. 2013
<i>Pisum sativum</i>	Pea	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-24.4	1.1	45.3	4.5	11.8	1	Bogaard et al. 2013
<i>Pisum sp.</i>	Pea	Gumelnita, Romania	c. 4700–3900 cal BC	GUM-71	Grain	-23.3	6.9	18.1	4.0		1	García-Vázquez et al. 2023
<i>Pisum sp.</i>	Pea	Gumelnita, Romania	c. 4700–3900 cal BC	GUM-72	Grain	-23.4	7.1	16.2	4.4		1	García-Vázquez et al. 2023
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-23.4	5.9	48.6	3.1	18.3	1	Bogaard et al. 2013
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-22.4	4.9	46.9	2.8	19.6	1	Bogaard et al. 2013
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-22.3	7.1	48.1	3.2	17.5	1	Bogaard et al. 2013
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-23.0	5.5	50.6	2.8	21.3	1	Bogaard et al. 2013
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-23.4	5.4	49.0	3.1	18.3	1	Bogaard et al. 2013
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-22.5	5.8	51.3	2.9	20.6	1	Bogaard et al. 2013
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-22.2	5.6	40.1	3.4	13.6	1	Bogaard et al. 2013
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-23.3	6.6	36.0	2.2	19.5	1	Bogaard et al. 2013

Diet and mobility in the Danube Delta region in Late Antiquity: A multi-isotope approach

Taxon	Common Name	Site	Date	Sample ID	Sample	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N	n	Reference
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-23.0	7.0	51.5	2.9	20.4	1	Bogaard et al. 2013
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-22.3	5.2	40.1	2.9	16.2	1	Bogaard et al. 2013
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-22.3	5.5	46.2	2.8	19.2	1	Bogaard et al. 2013
<i>Triticum aestivum/durum</i>	Bread/durum wheat	Koufovouno, Greece	c. 5800–5000 cal BC	n/a	Grain	-22.5	5.9	50.8	3.1	19.0	1	Bogaard et al. 2013
<i>Triticum dicoccum</i>	Emmer	Gumelnița, Romania	c. 4700–3900 cal BC	GUM-54	Grain	-28.7	3.7	15.7	4.6		1	García-Vázquez et al. 2023
<i>Triticum dicoccum</i>	Emmer	Gumelnița, Romania	c. 4700–3900 cal BC	GUM-55	Grain	-22.4	6.6	15.0	5.4		1	García-Vázquez et al. 2023
<i>Triticum dicoccum</i>	Emmer	Gumelnița, Romania	c. 4700–3900 cal BC	GUM-56	Grain	-24.0	3.8	23.2	3.5		1	García-Vázquez et al. 2023
<i>Triticum dicoccum</i>	Emmer	Karanovo, Bulgaria	c. 5500–5300 cal BC	n/a	Grain	-22.8	3.2	62.5	4.3	17.1	1	Bogaard et al. 2013
<i>Triticum dicoccum</i>	Emmer	Karanovo, Bulgaria	c. 5500–5300 cal BC	n/a	Grain	-23.0	3.5	63.0	3.8	19.2	1	Bogaard et al. 2013
<i>Triticum dicoccum</i>	Emmer	Karanovo, Bulgaria	c. 5500–5300 cal BC	n/a	Grain	-22.8	3.4	36.8	2.3	18.3	1	Bogaard et al. 2013
<i>Triticum dicoccum</i>	Emmer	Karanovo, Bulgaria	c. 5500–5300 cal BC	n/a	Grain	-23.1	3.1	41.1	2.4	20.2	1	Bogaard et al. 2013
<i>Triticum monococcum</i>	Einkorn	Gumelnița, Romania	c. 4700–3900 cal BC	GUM-63	Grain	-25.7	6.1	23.4	3.4		1	García-Vázquez et al. 2023
<i>Triticum monococcum</i>	Einkorn	Gumelnița, Romania	c. 4700–3900 cal BC	GUM-64	Grain	-23.5	6.7	11.8	6.7		1	García-Vázquez et al. 2023
<i>Triticum monococcum</i>	Einkorn	Gumelnița, Romania	c. 4700–3900 cal BC	GUM-65	Grain	-23.4	5.1	16.4	4.8		1	García-Vázquez et al. 2023
<i>Triticum monococcum</i>	Einkorn (one-seeded)	Karanovo, Bulgaria	c. 5500–5300 cal BC	n/a	Grain	-23.7	3.9	39.6	2.5	18.3	1	Bogaard et al. 2013
<i>Triticum monococcum</i>	Einkorn (one-seeded)	Karanovo, Bulgaria	c. 5500–5300 cal BC	n/a	Grain	-23.9	3.3	45.8	3.5	15.3	1	Bogaard et al. 2013
<i>Triticum monococcum</i>	Einkorn (one-seeded)	Slatina, Romania	c. 5800–5000 cal BC	n/a	Grain	-23.3	5.3	62.7	3.7	19.7	1	Bogaard et al. 2013
<i>Triticum monococcum</i>	Einkorn (one-seeded)	Slatina, Romania	c. 5800–5000 cal BC	n/a	Grain	-24.0	5.9	56.5	3.8	17.4	1	Bogaard et al. 2013
<i>Triticum monococcum</i>	Einkorn (one-seeded)	Slatina, Romania	c. 5800–5000 cal BC	n/a	Grain	-23.5	2.2	65.0	3.8	20.1	1	Bogaard et al. 2013
<i>Triticum monococcum</i>	Einkorn (one-seeded)	Slatina, Romania	c. 5800–5000 cal BC	n/a	Grain	-24.1	3.5	58.1	3.6	19.0	1	Bogaard et al. 2013

Taxon	Common Name	Site	Date	Sample ID	Sample	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N	n	Reference
<i>Triticum monococcum</i>	Einkorn (one-seeded)	Slatina, Romania	c. 5800-5000 cal BC	n/a	Grain	-23.8	6.2	62.5	4.5	16.3	1	Bogaard et al. 2013
<i>Triticum monococcum</i>	Einkorn (one-seeded)	Slatina, Romania	c. 5800-5000 cal BC	n/a	Grain	-23.5	7.2	59.9	4.3	16.3	1	Bogaard et al. 2013
<i>Vicia ervilia</i>	Bitter vetch	Gumelnita, Romania	c. 5000-4500 cal BC	GUM-62	Grain	-26.7	1.3	11.4	6.6		1	Garcia-Vázquez et al. 2023
					MEAN	-24.0	4.3					
					S.D.	1.3	2.4					
					S.E.	0.2	0.3					
PLANT C3 (Other)												
<i>Olea europaea</i>	Olive	Greece	Modern		Oil	-25.1	-2.5				5	Dotsika et al. 2022
<i>Vitis vinifera</i>	Grape	Romania	Modern		Wine	-23.7					25	Horacek et al. 2022
<i>Vitis vinifera</i>	Grape	Greece	Modern		Fruit	-23.7	3.7				2	Dotsika et al. 2022
PLANTS C4												
<i>Panicum miliaceum</i>	Millet	Cornești, Romania	3048±18 BP	MAMS-35587	Grain	-10.0					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Cornești, Romania	3085±21 BP	MAMS-35958	Grain	-5.4					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Cornești, Romania	3087±22 BP	MAMS-35961	Grain	-7.4					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Cornești, Romania	3068±23 BP	MAMS-35963	Grain	-7.2					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Cornești, Romania	3049±22 BP	MAMS-35964	Grain	-10.6					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Cornești, Romania	3051±32 BP	MAMS-35966	Grain	-6.3					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Ivane-Puste, Ukraine	2490±30 BP	Poz-103286	Grain	-9.7					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Ivane-Puste, Ukraine	2495±30 BP	Poz-105276	Grain	-12.1					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Măgura-Buduiasca, Romania	3093±35 BP	OxA-26706	Grain	-9.7					1	Filipović et al. 2020

Taxon	Common Name	Site	Date	Sample ID	Sample	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N	n	Reference
<i>Panicum miliaceum</i>	Millet	Măgura-Buduiasca, Romania	398±26 BP	OXA-26707	Grain	-10.4					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Maidanetske, Ukraine	1110±30 BP	Poz-97625	Grain	-12.4					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Miercurea-Sibului, Romania	2180±30 BP	Poz-98086	Grain	-16.5					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Olbia, Ukraine	2020±30 BP	Poz-105012	Grain	-10.0					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Teleac, Romania	2755±30 BP	Poz-102424	Grain	-14.3					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Vinogradnyi Sad, Ukraine	3090±35 BP	KIA-53658	Grain	-8.5					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Vinogradnyi Sad, Ukraine	3160±30 BP	Poz-103215	Grain	-11.0					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Vinogradnyi Sad, Ukraine	3275±35 BP	Poz-105275	Grain	-15.0					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Yabalkovo, Bulgaria	1176±28 BP	OXA-26477	Grain	-9.8					1	Filipović et al. 2020
<i>Panicum miliaceum</i>	Millet	Yabalkovo, Bulgaria	1128±35 BP	OXA-26705	Grain	-9.6					1	Filipović et al. 2020
					MEAN	-10.3						
					S.D.	2.9						
					S.E.	0.7						

Table S2. Food source $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values used for FRUITS modelling of diets. Plant values corrected where appropriate for charring and modern food source $\delta^{13}\text{C}$ Suess effect corrected (author C. Pickard)