Archaeological and Anthropological Sciences (2021) 13: 8
https://doi.org/10.1007/s12520-020-01247-3

ORIGINAL PAPER

Residential mobility in Great Moravia: strontium isotope analysis of a population sample from the early medieval site of Mikulčice-Valy (ninth–tenth centuries)

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Received: 14 August 2020 / Accepted: 26 November 2020 / Published online: 4 January 2021

Abstract

Great Moravia was one of the first proto-states in East Central Europe. During the ninth century, Moravian settlements underwent rapid growth, development, and population increases. This study presents a first insight into early medieval population mobility in the area by investigating one of its major agglomerations and religious centres, the Mikulčice-Valy stronghold. According to strontium isotope analysis of human tooth enamel, 13–19% of 123 analysed individuals fall outside the estimated local $^{87}Sr/^{86}Sr$ ranges and represent migrants from at least three distinct areas. Furthermore, human $^{87}Sr/^{86}Sr$ ratios are shifted in comparison to faunal references, which could indicate a greater rate of migration from isotopically similar areas. No evidence supporting the presumed higher mobility of elite females was found, but immigration is more prevalent among elites, with an apparent lack of non-elite males among the non-locals. Possible factors contributing to mobility are questioned and might offer directions for future studies.

Keywords Early Middle Ages · Great Moravia · Strontium · $^{87}Sr/^{86}Sr$ · Migration

Introduction

Great Moravia plays a vital role in the historical development of East Central Europe. During its existence in the ninth–tenth centuries, this Slavic proto-state managed to expand for a short time from its core territory around the lower Morava river across a wide area encompassing Bohemia as well as parts of present day Austria, Poland, Hungary and Slovakia (Poláček 1999). During the ninth century, Christianity was introduced into this regional power with the cultural influence of both Frankish and more prominently Byzantine empires. The latter was mediated by the mission of Saints Constantin (Cyril) and Methodius, through which a Slavic Christian liturgy and the Glagolitic script were created, and which eventually led to the establishment of an archbishopric in Moravia (Betti 2013; Vavřínek 2014). In the course of the ninth century, multiple strongholds emerged in core Moravian territory along the Morava and Dyje rivers, serving as local power, production and trade centres, as well as military strongpoints (Macháček 2010; Štefan 2011; Herold 2012). Clear signs of urbanisation can be seen, as those centres underwent rapid population increases. Small agricultural settlements developed into fortified agglomerations, in some cases possibly with up to a tenfold increase in population, hosting several hundred inhabitants (Macháček 2010). Considering the relatively short time frame of the Great Moravian period, migration is the likely source of these new inhabitants. With the population increase, these centres became unable to sustain themselves and had to rely on a wider economic hinterland to provide them with basic needs. The distribution of those goods became a tool for elites, and the emergence of both local and long-distant trade can be assumed (Macháček 2010; Štefan 2011; Hladík 2020).

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The Mikulčice-Valy stronghold is one of the two most important settlements of Great Moravia, possibly a major religious centre and may even have served as the seat of rulers for some time (Poláček 2008, 2018). It has been subjected to several decades of intensive archaeological and anthropological study, which has managed to identify over 2500 graves, many containing the biological remains of the highest echelons of Moravian society (Poláček 2008). Considering the size and rapid growth of the settlement, the question of the residential mobility of the people buried therein is therefore particularly interesting, especially as several pieces of indirect evidence—higher stress induced asymmetry in skulls (Bigoni et al. 2013), the occurrence of more loaded muscle attachment sites, entheseal changes of the lower extremities (Havelková et al. 2011), and a more variable diet (Kaupová et al. 2018)—suggest greater mobility of elite females and probable patrilocality. This study thus aims to examine the mobility of elites and especially elite females, as well as to provide a general overview of migration dynamics in the urban centres of Great Moravian society, using strontium isotope analysis.

The site of Mikulčice-Valy and its geological background

The study site is situated on the bank of the Morava river in the south-eastern part of the Czech Republic near the town of Hodonín (site GPS coordinates: 48° 48′ 14″ N and 17° 05′ 19″ E), as shown in Fig. 1. The ongoing excavations began in 1954 and have revealed a long-term historical occupation, reaching its greatest extent from the ninth to first half of the tenth century AD. As was common in early medieval Moravia, the fortified core of the settlement was elevated from the surrounding terrain by being located on four sand dunes in the approximate middle of the 6 km wide floodplain of the Morava (Havlíček 2001). With population increase in the ninth century, the settlement eventually expanded from the dunes to encompassing flood-loams (Havlíček et al. 2003; Poláček et al. 2019). The general structure of the settlement, as can be seen in Fig. 2, consisted of a fortified "castle"—a bailey and acropolis with a palace and basilica, and suburban areas separated by branches of the Morava. The area of approximately 10 km around Mikulčice-Valy is considered an economic hinterland and includes, amongst other things, the Great Moravian burial sites in Josefov and Prušánky (Poláček 2008; Hladík 2020), shown in Fig. 1.

Within the settlement, 10 church buildings have been excavated so far, with several more in close proximity to the fortress, one of them still standing today. Compared to other Great Moravian sites, Mikulčice-Valy represents a completely unique concentration of sacral buildings. The basilica (Church 3), the largest ninth century Moravian church, is also considered a possible bishop's church. The total number of graves in accompanying cemeteries and additional burial grounds exceeds 2500, attesting to the size of the site. Inhumations are generally characterised by the presence of grave goods such as weapons or jewellery, varying in character and quantity, which are believed to reflect the social status of the deceased. The graves themselves also attest to their standing by their means of construction or localisation. Those located within churches are presumed to be dynastic burials and therefore reserved for the most prominent individuals in Great Moravian society, as burials in the interior of the churches were at that time a privilege of the highest strata of society. A few burials found in the main parts of the Great Moravian churches (Mikulčice, Staré Město–Uherské Hradiště, Břeclav-Pohansko) are presumably considered to be dynastic graves of members of the ruling Mojmírid family (Schulze-Dörrlamm 1995; Štefan 2011; Herold 2012; Poláček 2020). The similar link between church burials and the expression of elite status of the deceased has also been described in, e.g., Frankish empire (Effros 2003; Halsall 2010). The religious and military importance of the site is further underlined by the high number of excavated artefacts with Christian symbolism such as pectoral and processional crosses, cross forgings or Christian motifs on jewellery, weapons, and other militaria (Poláček 2008, 2018).

The surface geology of the site, as shown in Fig. 3, is characterized by predominant Quaternary (Late Pleistocene to Holocene) fluvial deposits (Kadlec et al. 2015; Havlíček et al. 2016). These sandy gravels and loams are interrupted by sand dunes of mixed low-kinetic fluvial and aeolian origin, dating back to the last Glacial (Havlíček 2001; Havlíček et al. 2016; Šušolová et al. 2016). All these rock types are composed mainly of quartz, accompanied by fragments of Palaeozoic bedrock metamorphic and magmatite rocks (e.g., granite, granulite, amphibolite) with only a subordinate admixture of conglomerate, graywackes, and silicites. Outside the floodplain, the underlying bedrock is composed of Neogene (Miocene-Pliocene) sediments including clay and clayey sands, with gravels of mixed marine, brackish, and fluvial provenance (Chlupáč 2002; Kováč et al. 2004), partially covered by Quaternary aeolian sands and, north of Josefov and Prušánky, by loess. The same situation appears further up the Morava river, where a vast area of Quaternary aeolian sands (occasionally called the "Moravian Sahara") is located, with loess being more prevalent further north. Further upstream, there are Cretaceous-Paleogene Carpathian flysch belt formations represented by sandstone and claystone formations, especially on the eastern bank of the river. A smaller river, the Kyjovka, which runs parallel to the Morava in the Mikulčice area, enters the Morava floodplain from the north, and its course also comprises Neogene sediments covered by loess and aeolian sands (Czech Geological Survey 2019).

$^{87}Sr/^{86}Sr$ analysis in bioarchaeology

Analysis of strontium isotopes is an invaluable tool in studies aimed at past human migrations and relies mostly on one of

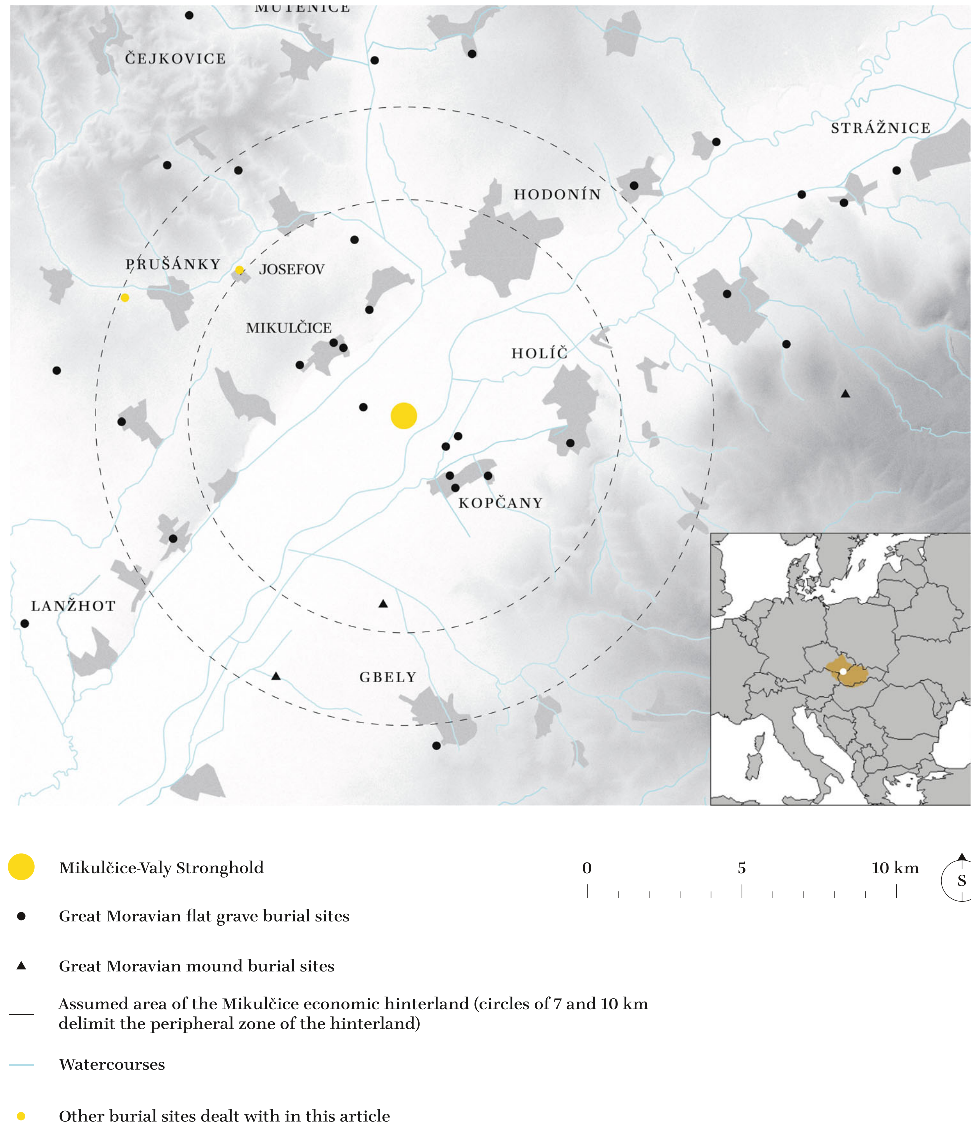

Fig. 1 Location of analysed sites and the extent of Mikulčice-Valy hinterland and Great Moravia (after Hladík et al. 2020)

the four stable strontium isotopes, ^{87}Sr. This isotope is created by decay of rubidium-87 with a half-life of almost 50 billion years (Bentley 2006; Villa et al. 2015), resulting in differences of ^{87}Sr abundance and therefore of ^{87}Sr/^{86}Sr ratios in various rocks, based on their age and initial Rb content (Bentley 2006). As those rocks are eroded, strontium is released, and due to its chemical similarity to calcium enters the biosphere (Bentley 2006). With the addition of strontium from other sources such as air or water, a pool of local bioavailable strontium is formed, more or less following the variability of local geological conditions and bedrock types. Typically, ^{87}Sr content is reported using its relative abundance to another stable isotope, strontium-86, in form of the ^{87}Sr/^{86}Sr ratio, which remains practically unchanged through the food chain (Blum et al. 2000; Flockhart et al. 2015; Lewis et al. 2017) even as the total volume of strontium decreases with each trophic step (Blum et al. 2000; Evans and Tatham 2004; Bentley 2006). By measuring ^{87}Sr/^{86}Sr ratios in human tissues and comparing them to local bioavailable values, a non-local individual can be identified. Although bone is susceptible to diagenetic changes, and therefore biogenic strontium values might not be preserved in migrants, tooth enamel has proven itself to be much more resistant to such contamination (Budd et al. 2000; Price et al. 2002; Hoppe et al. 2003) and is usually used in migration analyses. Due to its lack of remodelation during life, enamel provides information about person's childhood (Slovak and Paytan 2012); therefore, if the ^{87}Sr/^{86}Sr ratio falls outside the local range, it can be assumed that such an individual did not spend their early life in the area of their burial.

Unfortunately, the ^{87}Sr/^{86}Sr composition of Quaternary and Neogene rocks in the Mikulčice area cannot be accessed directly due to a lack of data; nevertheless, an approximate prediction of the locally bioavailable strontium range can be made using several geochemical proxies. Firstly, as the

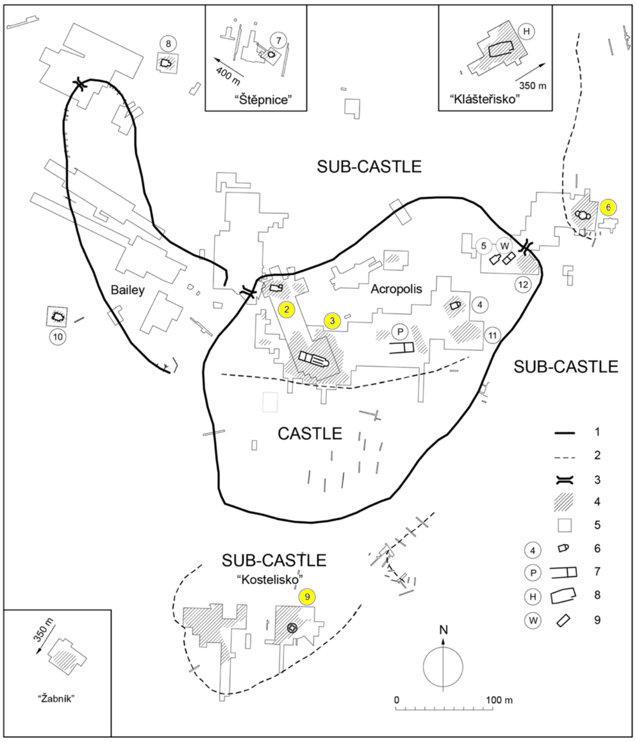

Fig. 2 Schematic plan of the Mikulčice-Valy stronghold showing features found: 1, fortification; 2, significant terrain boundaries; 3, derelict gateways; 4, burial grounds; 5, excavated areas; 6, churches with numbering (2–12); 7, palace (P); 8, wooden building feature (H); 9, metal-casting workshop (W). Highlighted church numbers denote sampled associated cemeteries (after Poláček 2018; graphics by Z. Pavková)

$^{87}Sr/^{86}Sr$ composition of global oceanic water during the Neogene has gradually risen from approx. 0.7082 to 0.7092 (Hodell et al. 1991), marine sediments in the target area should mimic these values. Furthermore, the statistically modelled isoscape of biologically available strontium in European soils predicts $^{87}Sr/^{86}Sr$ ratios of around 0.709 in Southern Moravia (Hoogewerff et al. 2019). Similarly, measurements of mineral waters related to the basic geological map of Europe estimate local $^{87}Sr/^{86}Sr$ values to lie between 0.7090 and 0.7110 (Voerkelius et al. 2010), and Price and collaborators in 2004 report estimates of fluvial deposits ranging from 0.708 to 0.709 and of loess and aeolian sands with a range of 0.709–0.740, although their work encompasses a vast area of South-Central Europe and highly radiogenic values are connected rather to material brought from the Alpine area by the Danube (e.g., Schatz et al. 2015). Finally, Morava river water sampled downstream of Mikulčice in Austria has an $^{87}Sr/^{86}Sr$ ratio of 0.7111 (Zitek et al. 2015). From a bioarchaeological perspective, the human enamel and bone samples from an individual buried close to Mikulčice published in Price et al. (2004), have strontium values of 0.7101 and 0.7104 respectively. However, measurement of tooth enamel $^{87}Sr/^{86}Sr$ ratios of local non-migrating fauna are considered a more reliable reference for migration studies (Price et al. 2002; Evans and Tatham 2004), and should be used in preference to statistical predictions, as they more precisely reflect strontium entering the food chain. Still, it seems reasonable to expect local $^{87}Sr/^{86}Sr$ in the range of 0.7090–0.7110 at the target site.

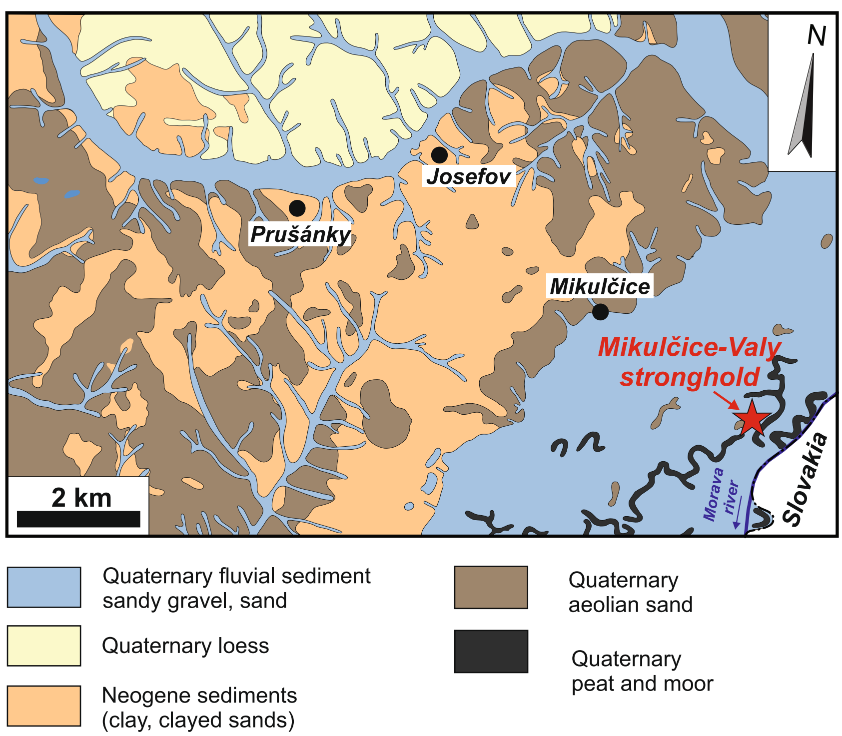

Fig. 3 Geological map of the Mikulčice area (modified after Czech Geological Survey 2019)

Material and methods

To provide an estimate of local bioavailable strontium, tooth enamel $^{87}Sr/^{86}Sr$ ratios were measured for 27 animal specimens excavated on the site. The selected fauna consisted of 12 x *Sus scrofa domesticus*, 4 x *Ovis aries*, 4 x *Capra aegagrus hircus*, and 7 x *Bos primigenius taurus* individuals. Further, 10 human bone samples from the sites of Josefov and Prušánky were analysed, in order to provide insight into strontium values in the settlement hinterland; these sites are located approximately 7 km from Mikulčice-Valy, outside the Morava floodplain. Unfortunately, archaeological evidence in this part of the economic hinterland is limited to Great Moravian cemeteries that lack animal remains suitable for strontium analysis; considering that diagenetic changes taking place after bone burial tend to shift the $^{87}Sr/^{86}Sr$ ratio towards local values (Budd et al. 2000; Hoppe et al. 2003; Trickett et al. 2003), human bones were used instead.

The human dataset consists of 123 tooth enamel samples, predominantly M2 supplemented by M1 where second molars were not available. Individuals were sorted into four groups based on their sex and social status. Overall, the dataset comprises 32 elite males, 38 elite females, 25 non-elite males, 27 non-elite females, and 1 non-sexed elite individual. Of the elites, six church interior burials were included in the dataset. These burials are believed to have been reserved for the highest sections of Great Moravian society and are probably of dynastic character (Schulze-Dörrlamm 1995; Štefan 2011; Herold 2012; Poláček 2020). Sex was determined by current anthropological measurements (Brůžek 2002; Murail et al. 2005). The division into elite and non-elite graves is based on the classification of grave goods and selected features of the funeral rite. The presence of the following artefacts was considered to be an attribute of an elite grave: gold, tableware, luxury textiles, earrings of the Veligrad type, spherical hollow buttons (so-called gombíky), lavish belt fittings, calf straps, swords, spears, spurs, or other luxury goods. Graves from the interior of the churches and burials in coffins with iron fittings were considered elite as well. Graves that did not meet these criteria classified as non-elite (Kouřil 2005; Poláček 2020). The majority of the sampled inhumations came from cemeteries located inside the stronghold, associated with churches II. and III., these being supplemented by individuals from the suburbs, predominantly the "Kostelisko" and church VI. areas (Velemínský et al. 2005; Brůžek 2013; Zazvonilová et al. 2020).

Enamel was sampled as described in Slovak and Paytan (2012). In brief, teeth crown surfaces were mechanically abraded and ultrasonically cleaned in deionised water for at least 30 min, with frequent changing of water. Using a diamond-coated drill, a groove was drilled in middle of the non-abrasive surface of each tooth crown, and the released enamel powder was collected in sealed microtubes. The Sr isotopic compositions of the gathered enamel samples were determined at the Institute of Geology of the Czech Academy of Sciences. About 25 mg of the powder was weighed and decomposed in concentrated HNO_3 for ~ 18 h on a hot plate at 70 °C. Afterwards, the resulting clear solution was dried down and re-dissolved in 1 ml of 1 M HNO_3. Strontium was isolated from the matrix by ion exchange chromatography using an Sr resin (Triskem) with 2 ml of 0.05 M HNO_3 used for Sr collection (Pin et al. 2014). The $^{87}Sr/^{86}Sr$ analyses were performed on W filaments in the presence of a Ta activator loaded into a Thermo Triton Plus thermal ionization mass spectrometer (TIMS). An $^{88}Sr/^{86}Sr$ of 8.3752 was used for mass fractionation correction. During the course of this study, the NIST SRM 987 yielded an $^{87}Sr/^{86}Sr$ of 0.710252 ± 0.000006 (2σ, n = 6).

Results

Faunal enamel $^{87}Sr/^{86}Sr$ values range from 0.7089 to 0.7125 with an average of 0.7103 ± 0.0007 (1SD). The highest value, from sample MRF2, is a distinct outlier, well outside the rest of faunal samples, marking this *Sus scrofa domesticus* as of non-local origin. This sample was therefore not used in estimation of the local bioavailable strontium. The lowest $^{87}Sr/^{86}Sr$ value, from *Bos primigenius taurus* MRF27, differs by 0.0005 from the second lowest, and its area of origin is ambiguous as it stands well apart from the other faunal samples but does not represent a clear statistical outlier. Species-wise, non-significant (ANOVA, p = 0.337) differences were noted in the faunal samples, supporting constant bioavailable strontium values through the grazing areas of the settlement. The $^{87}Sr/^{86}Sr$ ranges for Mikulčice-Valy estimated using the faunal sample mean ± 2SD (Price et al. 2002), both including and excluding MRF27, thus ranged from 0.70906 to 0.71134 and from 0.70922 to 0.71129, respectively. The differences between the cutoff points of both ranges are 0.00015 in the lower and 0.00005 in the upper values. Human bone samples from Josefov and Prušánky fall well within these ranges, averaging 0.7100 ± 0.0002 (1SD). This suggests a comparable isotopic background in Mikulčice-Valy and the wider area outside the floodplain. The measured $^{87}Sr/^{86}Sr$ for reference samples values are presented in Table 1.

The majority of the human enamel $^{87}Sr/^{86}Sr$ ratios, as shown in Table 2, lie within the estimated bioavailable ranges of the site, with an average of 0.7010 ± 0.0010 (1SD). Nevertheless, as can be seen on Fig. 4, several individuals with "non-local" $^{87}Sr/^{86}Sr$ ratios are present in the dataset. When the wider range of estimated local strontium values is applied, 18 human samples fall outside it (both with lower and higher $^{87}Sr/^{86}Sr$ than the local range). Two of these samples (MH116, MH118) stand very close to the lower limit (< 0.00001). Using the narrower local range, which considers animal sample MRF27 as non-local, the total number of potential immigrants increases to 21, with 3 additional samples (MH4, MH36, MH52) being

Table 1 $^{87}Sr/^{86}Sr$ values of reference samples

Location	Sample	$^{87}Sr/^{86}Sr$	2SE	Species	Tissue
Mikulčice-Valy	MRF1	0.709629	0.000007	*Sus scrofa domesticus*	Tooth enamel
	MRF2	0.712480	0.000007	*Sus scrofa domesticus*	Tooth enamel
	MRF3	0.710213	0.000007	*Sus scrofa domesticus*	Tooth enamel
	MRF4	0.709559	0.000006	*Sus scrofa domesticus*	Tooth enamel
	MRF5	0.710166	0.000007	*Sus scrofa domesticus*	Tooth enamel
	MRF6	0.710265	0.000006	*Sus scrofa domesticus*	Tooth enamel
	MRF7	0.709815	0.000007	*Sus scrofa domesticus*	Tooth enamel
	MRF8	0.709465	0.000007	*Sus scrofa domesticus*	Tooth enamel
	MRF9	0.709994	0.000008	*Sus scrofa domesticus*	Tooth enamel
	MRF10	0.710386	0.000007	*Sus scrofa domesticus*	Tooth enamel
	MRF11	0.709412	0.000007	*Sus scrofa domesticus*	Tooth enamel
	MRF12	0.711183	0.000007	*Sus scrofa domesticus*	Tooth enamel
	MRF13	0.710640	0.000007	*Ovis aries*	Tooth enamel
	MRF14	0.709957	0.000008	*Capra aegagrus hircus*	Tooth enamel
	MRF15	0.710992	0.000007	*Ovis aries*	Tooth enamel
	MRF16	0.710984	0.000006	*Capra aegagrus hircus*	Tooth enamel
	MRF17	0.710390	0.000007	*Ovis aries*	Tooth enamel
	MRF18	0.709579	0.000006	*Ovis aries*	Tooth enamel
	MRF19	0.710879	0.000007	*Bos primigenius taurus*	Tooth enamel
	MRF20	0.710436	0.000007	*Capra aegagrus hircus*	Tooth enamel
	MRF21	0.710972	0.000007	*Capra aegagrus hircus*	Tooth enamel
	MRF22	0.710091	0.000005	*Bos primigenius taurus*	Tooth enamel
	MRF23	0.709986	0.000007	*Bos primigenius taurus*	Tooth enamel
	MRF24	0.710832	0.000007	*Bos primigenius taurus*	Tooth enamel
	MRF25	0.709944	0.000007	*Bos primigenius taurus*	Tooth enamel
	MRF26	0.710539	0.000007	*Bos primigenius taurus*	Tooth enamel
	MRF27	0.708920	0.000007	*Bos primigenius taurus*	Tooth enamel
Josefov	MRB1	0.709912	0.000006	*H. sapiens*	Bone
	MRB2	0.709739	0.000007	*H. sapiens*	Bone
	MRB3	0.710148	0.000007	*H. sapiens*	Bone
	MRB4	0.709936	0.000007	*H. sapiens*	Bone
	MRB5	0.709971	0.000008	*H. sapiens*	Bone
Prušánky	MRB6	0.710477	0.000007	*H. sapiens*	Bone
	MRB7	0.710159	0.000007	*H. sapiens*	Bone
	MRB8	0.709957	0.000008	*H. sapiens*	Bone
	MRB9	0.709958	0.000007	*H. sapiens*	Bone
	MRB10	0.710076	0.000006	*H. sapiens*	Bone

located in the very close vicinity of lower limit (< 0.00004), but still within the range of "local values." This means that at least 13% and possibly up to 19% of the analysed individuals spent their childhoods at, or consumed foodstuffs from, an area isotopically different to Mikulčice-Valy. All socioeconomic groups are represented among non-locals, with 7 (9) elite females, 6 elite males, 4 (5) non-elite females, and 1 non-elite male; numbers in brackets denote non-locals when the narrower local $^{87}Sr/^{86}Sr$ range is applied. The general spread of their $^{87}Sr/^{86}Sr$ ratios implies that these immigrants came from at least three isotopically distinct areas, as they can be organised in three groups. The first of these comprises 10 individuals with lower $^{87}Sr/^{86}Sr$ ratios than the local minimum, while the second includes samples MH37, MH54, and possibly MH117, which are slightly more radiogenic than the local maximum. The third group includes 8 clearly non-local immigrants, with the highest $^{87}Sr/^{86}Sr$ ratios, comparable to that of faunal outlier MRF2. When the narrower local range is considered, only two church interior burials (MH40, MH117) fell outside the local $^{87}Sr/^{86}Sr$ range, both being located close to the cutoff points (0.70902

Table 2 Analysed human samples. “Potential immigrant” denotes an individual with $^{87}Sr/^{86}Sr$ values outside the narrower but within the wider local ranges. “Interior grave” indicates burials located inside church buildings

Sample	Grave no.	Sex	Status	Burial	$^{87}Sr/^{86}Sr$	2SE	Notes
MH1	6/VI	Female	Elite	Sub-castle	0.709748	0.000006	
MH2	126/VI	Female	Elite	Sub-castle	0.709458	0.000006	
MH3	183/VI	Female	Elite	Sub-castle	0.709339	0.000005	
MH4	1481/VI	Female	Elite	Sub-castle	0.709223	0.000006	
MH5	275	Female	Elite	Castle	0.710216	0.000007	
MH6	216	Female	Elite	Castle	0.712626	0.000006	Non-local
MH7	505	Female	Elite	Castle	0.709349	0.000006	
MH8	366	Female	Elite	Castle	0.709279	0.000005	
MH9	659	Female	Elite	Castle	0.711053	0.000006	
MH10	625	Female	Elite	Castle	0.709646	0.000008	
MH11	286	Female	Elite	Castle	0.709583	0.000007	
MH12	32/VI	Male	Elite	Sub-castle	0.709408	0.000005	
MH13	50/VI	Male	Elite	Sub-castle	0.709357	0.000007	
MH14	105/VI	Male	Elite	Sub-castle	0.710333	0.000008	
MH15	114/VI	Male	Elite	Sub-castle	0.710131	0.000006	
MH16	122/VI	Male	Elite	Sub-castle	0.709478	0.000006	
MH17	165/VI	Male	Elite	Sub-castle	0.709931	0.000006	
MH18	85/VI	Male	Non-elite	Sub-castle	0.709401	0.000007	
MH19	44	Male	Elite	Castle	0.709586	0.000007	
MH20	390	Male	Elite	Castle	0.709818	0.000006	
MH21	398	Male	Elite	Castle	0.709380	0.000007	
MH22	433	Male	Elite	Castle	0.709357	0.000006	
MH23	606	Male	Elite	Castle	0.709682	0.000007	
MH24	205	Female	Non-elite	Castle	0.709378	0.000006	
MH25	475	Female	Elite	Castle	0.710553	0.000004	
MH26	464	Male	Elite	Castle	0.709963	0.000007	
MH27	272	Male	Elite	Castle	0.709568	0.000007	
MH28	412	Female	Non-elite	Castle	0.709432	0.000007	
MH29	21	Female	Elite	Castle	0.709624	0.000007	
MH30	51	Female	Elite	Castle	0.710612	0.000007	
MH31	223	Male	Elite	Castle	0.708750	0.000007	Non-local
MH32	149	Female	Non-elite	Castle	0.710630	0.000007	
MH33	167	Female	Non-elite	Castle	0.709561	0.000008	
MH34	96	Male	Elite	Castle	0.708943	0.000007	Non-local
MH35	649	Female	Non-elite	Castle	0.709375	0.000008	
MH36	232	Male	Elite	Castle	0.709225	0.000007	
MH37	280	Male	Elite	Castle	0.711794	0.000009	Non-local
MH38	182	Male	Non-elite	Castle	0.709779	0.000007	
MH39	689	Female	Non-elite	Castle	0.709611	0.000006	
MH40	265	Male	Elite	Castle	0.709023	0.000007	Interior grave, non-local
MH41	602	Female	Non-elite	Castle	0.709531	0.000007	
MH42	711	Female	Non-elite	Castle	0.713228	0.000006	Non-local
MH43	719	Female	Non-elite	Castle	0.710338	0.000007	
MH44	742	Female	Non-elite	Castle	0.709532	0.000006	
MH45	1196	Female	Non-elite	Castle	0.710255	0.000007	
MH46	82/VI	Female	Non-elite	Sub-castle	0.708671	0.000008	Non-local
MH47	102/VI	Female	Non-elite	Sub-castle	0.709434	0.000006	
MH48	119/VI	Female	Non-elite	Sub-castle	0.709763	0.000007	

Table 2 (continued)

Sample	Grave no.	Sex	Status	Burial	$^{87}Sr/^{86}Sr$	2SE	Notes
MH49	3/VI	Male	Non-elite	Sub-castle	0.709459	0.000007	
MH50	53/VI	Male	Non-elite	Sub-castle	0.709923	0.000006	
MH51	15/VI	Female	Non-elite	Sub-castle	0.709446	0.000007	
MH52	115/VI	Male	Non-elite	Sub-castle	0.709249	0.000007	
MH53	30/VI	Female	Non-elite	Sub-castle	0.710899	0.000007	
MH54	92/VI	Female	Non-elite	Sub-castle	0.711590	0.000007	Non-local
MH55	25/VI	Male	Non-elite	Sub-castle	0.710056	0.000007	
MH56	34/VI	Male	Non-elite	Sub-castle	0.709667	0.000008	
MH57	9/VI	Male	Non-elite	Sub-castle	0.711017	0.000008	
MH58	8/VI	Male	Non-elite	Sub-castle	0.712989	0.000009	Non-local
MH59	87/VI	Male	Non-elite	Sub-castle	0.710005	0.000007	
MH60	143/VI	Male	Non-elite	Sub-castle	0.709517	0.000008	
MH61	72/VI	Male	Non-elite	Sub-castle	0.710904	0.000007	
MH62	71/VI	Male	Non-elite	Sub-castle	0.710032	0.000007	
MH63	14/VI	Male	Non-elite	Sub-castle	0.710070	0.000005	
MH64	419	Female	Non-elite	Castle	0.709173	0.000007	Potential immigrant
MH65	353	Male	Non-elite	Castle	0.710990	0.000006	
MH66	701	Male	Non-elite	Castle	0.709955	0.000005	
MH67	520	Female	Non-elite	Castle	0.709606	0.000007	
MH68	736	Male	Non-elite	Castle	0.710319	0.000008	
MH69	645	Male	Non-elite	Castle	0.709447	0.000006	
MH70	721	Male	Non-elite	Castle	0.709761	0.000007	
MH71	559	Male	Elite	Castle	0.709580	0.000007	
MH72	627	Male	Non-elite	Castle	0.709303	0.000006	
MH73	90	Male	Elite	Castle	0.709275	0.000006	
MH74	269	Male	Elite	Castle	0.710051	0.000007	
MH75	186	Male	Non-elite	Castle	0.709521	0.000007	
MH76	738	Female	Non-elite	Castle	0.709713	0.000007	
MH77	104/VI	Female	Non-elite	Sub-castle	0.709662	0.000007	
MH78	571	Male	Non-elite	Castle	0.709322	0.000006	
MH79	135/VI	Female	Non-elite	Sub-castle	0.709908	0.000006	
MH80	35/VI	Female	Non-elite	Sub-castle	0.710005	0.000008	
MH81	141/VI	Female	Non-elite	Sub-castle	0.709867	0.000008	
MH82	145/VI	Female	Non-elite	Sub-castle	0.713018	0.000007	Non-local
MH83	470	Female	Elite	Castle	0.709793	0.000007	
MH84	1181	Female	Elite	Castle	0.709708	0.000007	
MH85	363	Male	Non-elite	Castle	0.709653	0.000007	
MH86	396	Male	Elite	Castle	0.709421	0.000008	
MH87	500	Male	Elite	Castle	0.708767	0.000007	Non-local
MH88	727	Female	Elite	Castle	0.712952	0.000007	Non-local
MH89	673	Male	Non-elite	Castle	0.709637	0.000008	
MH90	248	Male	Elite	Castle	0.710893	0.000006	
MH91	125/VI	Male	Non-elite	Sub-castle	0.709311	0.000007	
MH92	675	Female	Elite	Castle	0.709725	0.000007	
MH93	510	Female	Elite	Castle	0.709402	0.000006	
MH94	240	Female	Elite	Castle	0.710337	0.000007	
MH95	717	Male	Elite	Castle	0.709727	0.000007	
MH96	328	Female	Elite	Castle	0.709459	0.000007	
MH97	567	Female	Elite	Castle	0.709586	0.000007	

Table 2 (continued)

Sample	Grave no.	Sex	Status	Burial	$^{87}Sr/^{86}Sr$	2SE	Notes
MH98	855	Female	Elite	Castle	0.709648	0.000007	
MH99	592	Female	Elite	Castle	0.712429	0.000008	Non-local
MH100	65	Female	Elite	Castle	0.709465	0.000006	
MH101	67	Female	Elite	Castle	0.709438	0.000007	
MH102	250	Female	Elite	Castle	0.709293	0.000007	
MH103	282	Male	Elite	Castle	0.70935	0.000006	Interior grave
MH104	283	Female	Elite	Castle	0.70941	0.000006	Interior grave
MH105	544	Male	Elite	Castle	0.709481	0.000006	Interior grave
MH106	714	Female	Elite	Castle	0.709065	0.000006	Potential immigrant
MH107	786	Male	Elite	Castle	0.712568	0.000007	Non-local
MH108	1833	Female	Non-elite	Sub-castle	0.709922	0.000006	
MH109	1959	Female	Elite	Sub-castle	0.709458	0.000006	
MH110	420 h	Female	Elite	Castle	0.708872	0.00001	Non-local
MH111	512	Female	Elite	Castle	0.709434	0.000007	
MH112	1665a	N/a	Elite	Sub-castle	0.709431	0.000006	
MH113	1958	Female	Elite	Sub-castle	0.709479	0.000006	
MH114	1656	Female	Elite	Sub-castle	0.709808	0.000009	
MH115	1750	Male	Elite	Sub-castle	0.70989	0.000006	
MH116	1994	Female	Elite	Sub-castle	0.709054	1.16E−05	Non-local
MH117	588	Female	Elite	Castle	0.71133	8.31E−06	Interior grave, potential immigrant
MH118	1702	Female	Elite	Sub-castle	0.709058	5.88E−06	Non-local
MH119	555	Male	Elite	Castle	0.710821	6.27E−06	Interior grave
MH120	1241	Male	Elite	Sub-castle	0.710025	5.07E−06	
MH121	1728	Female	Non-elite	Sub-castle	0.710614	4.64E−06	
MH122	480	Male	Elite	Castle	0.709455	7.03E−06	
MH123	488	Female	Elite	Castle	0.712955	6.75E−06	Non-local

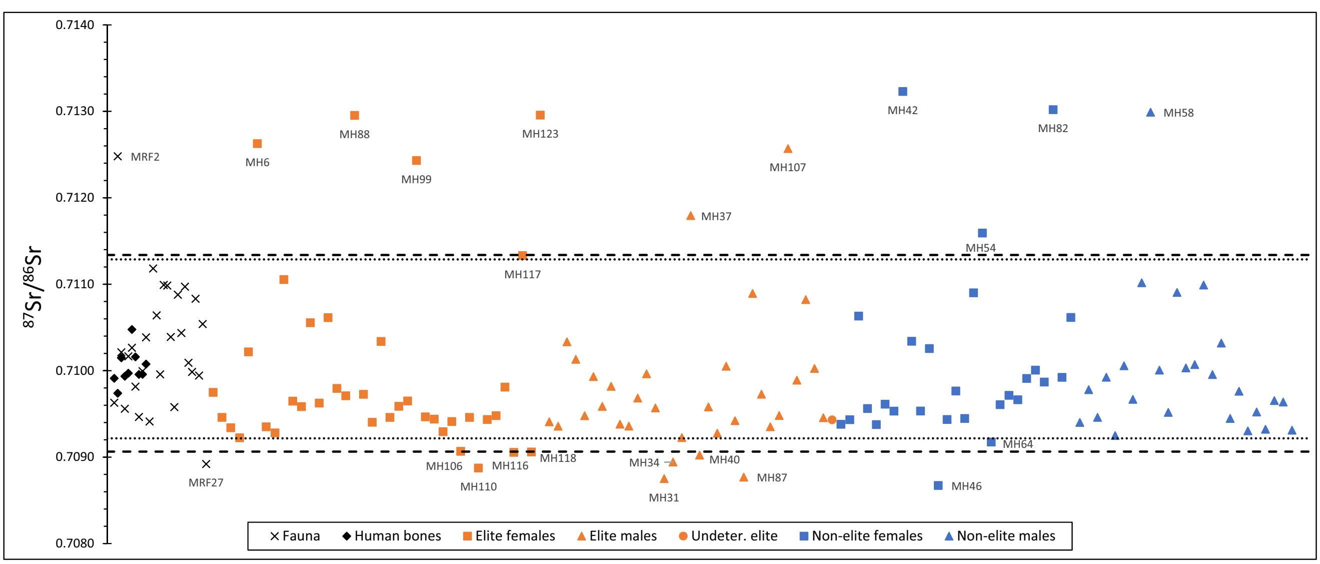

Fig. 4 $^{87}Sr/^{86}Sr$ ratios of analysed samples. Dashed lines denote local range estimated from faunal enamel, excluding the outlier MRF2. The narrower local range (samples MRF2 and MRF27 excluded) is marked by dotted lines. Analytical errors for individual sample points are smaller than symbol size

and 0.71133, respectively). Surprisingly, in comparison to animals, human enamel strontium ratios within the defined local ranges have on average significantly (Kruskal-Wallis, $p < 0.0001$) less radiogenic $^{87}Sr/^{86}Sr$ values. No statistically significant differences were detected between the studied socioeconomic groups (Kruskal-Wallis, $p = 0.3927$), as shown in Fig. 5, suggesting that migration was not more prevalent in any of those groups, although elite males seem to have more lower $^{87}Sr/^{86}Sr$ values, as they have a lower mean (0.7098 ± 0.0008, 1SD) than the others (non-elite males: 0.7010 ± 0.0008, elite females: 0.7010 ± 0.0011, non-elite females: 0.7101 ± 0.0011, 1SD). However, this trend disappears when outliers are omitted, and might therefore be a result of their different areas of origin. With the outlying non-local samples not considered, differences between socioeconomic groups remain insignificant (Kruskal-Wallis, $p = 0.4205$) and variabilities of males and females do not differ (Levene's test, $p = 0.5161$), even when their social status is considered (Levene's test, $p = 0.8045$), providing no support for greater mobility of any of those groups obscured within local $^{87}Sr/^{86}Sr$ range.

Discussion

The estimation of the local range of bioavailable strontium in the area of Mikulčice proved to be problematic. In our faunal dataset, the presence of non-local *Sus scrofa domesticus* and ambiguous *Bos primigenius taurus*, for which a provenience of Mikulčice-Valy cannot be safely presumed, brings a degree of uncertainty to the estimate. To address this problem, two separate local $^{87}Sr/^{86}Sr$ range estimations were created and caution when interpreting human sample results was applied. The archaeological evidence reveals that with the rapid population increase taking place during Great Moravian period,

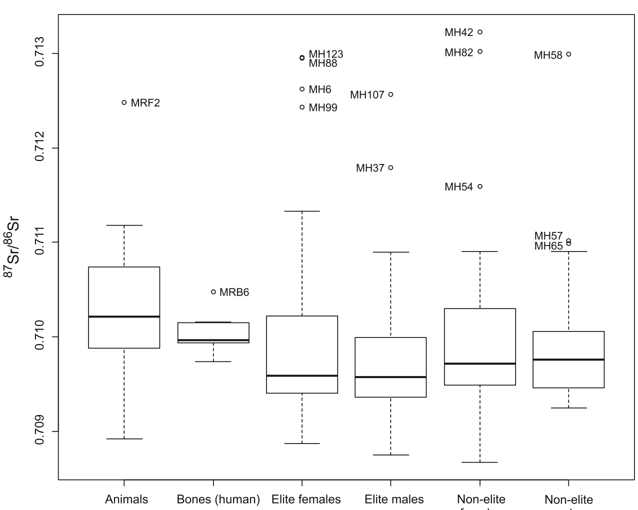

Fig. 5 Boxplot comparison of analysed social groups and reference material

Moravian strongholds had to rely on a wider area for food production (Macháček 2010). Additionally, animal or animal product mobility was not uncommon in the Early Middle Ages, as such cases have been reported on several occasions throughout Europe (e.g., Groves et al. 2013; van der Jagt et al. 2012), and this is the likely explanation for the outlying samples at Mikulčice-Valy. With the strontium isotope ratios of those two specimens corresponding well with $^{87}Sr/^{86}Sr$ ratios of identified human migrants, it could also be theorized that animal mobility followed human, possibly not only via trade but also through household translocations. Unfortunately, not enough data is available to support such a theory or determine the total extent of such exchanges. Nevertheless, given the increased variability of fauna from Mikulčice-Valy compared to the "local" human samples from the economic hinterland, and the estimated local ranges of bioavailable strontium on some other European sites (Price et al. 2011; McManus et al. 2013; Alt et al. 2014; Schuh and Makarewicz 2016), it cannot be excluded that even more animals were actually not native to the study site, but originated from areas with a pool of bioavailable strontium closely resembling that of Mikulčice-Valy. Previous archaeozoological and isotopic analyses of the pig remains from the area suggest that the main production has been located within the floodplain, partially supplemented by the settlement itself (Kaupová et al. 2018; Kovačiková et al. 2020). On the other hand, various other sites have reported similarly broad or wider (Groves et al. 2013; Price et al. 2018; Krzewińska et al. 2018) local $^{87}Sr/^{86}Sr$ ranges, and the stronghold being located in the middle of a relatively large floodplain with historically shifting watercourses could well explain the variability in faunal $^{87}Sr/^{86}Sr$ ratios. Furthermore, the detected slight differences in $\delta^{15}N$ between pigs consumed in different areas of Mikulčice-Valy are likely the result of the different breeding regimes within Mikulčice settlement (Kovačiková et al. 2020), although migration cannot be excluded as an alternative explanation.

While the wider area surrounding the stronghold of Mikulčice-Valy is somewhat lacking in geological diversity, nearby bedrock Neogene sediments contain variable clay component which could potentially bear variable Rb/Sr (and in turn $^{87}Sr/^{86}Sr$). However, they are mostly covered by Quaternary quartz-dominated aeolian sands or loess fields, where $^{87}Sr/^{86}Sr$ is not expected to differ significantly. The isoscapes modelled so far support this (Voerkelius et al. 2010; Hoogewerff et al. 2019). Furthermore, analysed human bones from the Great Moravian cemeteries at Josefov and Prušánky show no differences in the $^{87}Sr/^{86}Sr$ ratios between the floodplain and the surrounding terrain, suggesting that newcomers from the wider vicinity (at least 10 and possibly up to 30 km) of Mikulčice stronghold might be practically indistinguishable from natives. The inhabitants of the White Carpathians, which emerge some 15 km east of Mikulčice-Valy, might be an exception, but no definitive conclusions can be drawn as additional data from this area are practically non-existent and more isotopic measurements are therefore needed. Revealing a long-range migration could also prove difficult, especially in relation to migration by, e.g., Avars or other migratory tribes, as similar local strontium ratios have been reported for the Great Hungarian plain (Giblin et al. 2013) as well as for multiple locations on the Eurasian steppe (Gerling 2014).

Using the local $^{87}Sr/^{86}Sr$ ranges defined on the basis of animal tooth enamel, the majority of the analysed humans seem to be local to Mikulčice-Valy. The authors find it noteworthy that isotopically local human samples are not evenly spread within the estimated local $^{87}Sr/^{86}Sr$ ranges, but tend to pool around lower limit. For the reasons outlined above, the total number of non-local individuals buried within the settlement might therefore be underestimated, as this decrease could be attributed to regional migration from areas with $^{87}Sr/^{86}Sr$ ratios resembling the local range from Mikulčice-Valy. Another possible explanation for the shift in human $^{87}Sr/^{86}Sr$ values in comparison to fauna could lie in agricultural production, where plant products used in human diet might have been grown in an area with an isotopic background slightly differing from that of the pastures, e.g., the floodplain vs the wider hinterland. An example of this could be, as suggested by the isotopic data, the consumption of C_4 plants such as millet, which is lacking or very limited in the domestic animals but present in humans (Kaupová et al. 2018; Kovačiková et al. 2020). The comparison of human carbon and nitrogen isotopic values between Mikulčice-Valy and its hinterland does not add up to this issue. The isotopic difference was found only in $\delta^{15}N$, which was, however, motivated by the distinct socioeconomic status of both groups rather than by isotopically different agricultural production areas (Kaupová et al. 2018). Furthermore, the very limited strontium data of the hinterland, presented in this study, do not suggest notable dissimilarity with the bioavailable strontium of the settlement and the surrounding area.

Still, migration was present in Great Moravian society, as 13 to 19% of the sampled individuals exhibit distinctly non-local strontium values. With the $^{87}Sr/^{86}Sr$ ratios of identified non-locals being both less and more radiogenic than the locally defined range of bioavailable strontium, immigration must have been multidirectional, and those new inhabitants came to the Mikulčice-Valy stronghold from at least three isotopically distinct areas. Unfortunately, determining those areas is problematic, as not enough isotopic studies have been conducted to date in the Czech Republic or Slovakia, and no isoscape of bioavailable strontium is available. Lower values (0.7080–0.7094) of bioavailable strontium have been reported for Radovesice in north-western Bohemia (Scheeres et al. 2014), but similar isotopic ranges could be expected across a much wider area, covering most of the Central and Eastern European loess as well as the Carpathian flysch, which seems a more plausible source of newcomers. Loess fields around the city of Olomouc, approximately 90 km north of Mikulčice with slightly more radiogenic $^{87}Sr/^{86}Sr$ ratios than the local maximum (unpublished data) might have been the area of origin for individuals MH37 and MH54, or in case of the former, the vicinity of Vedrovice, around 60 km north-west of the stronghold, where local ratios of between 0.7108 and 0.7115 have been reported (Richards et al. 2008). The most radiogenic group of immigrants in the Mikulčice population sample may have originated from the areas of Bohemian Massif, where older rock formations with high Rb/Sr are present (e.g., the granitic rocks around Brno, about 45 km north-east, with present-day $^{87}Sr/^{86}Sr$ ratios up to ~ 0.725; Soejono et al. 2017) or even more distant regions, especially given that the presence of Christian missions is documented in Great Moravia.

The strontium analysis failed to provide sufficient evidence for the hypothesis of patrilocality and the higher mobility of elite females or females in general in Great Moravian society. In such cases, females would be expected to display higher variability in their $^{87}Sr/^{86}Sr$ ratios than other groups and to constitute a majority of non-local individuals (Bentley et al. 2012; Alt et al. 2014). Though the slightly increased variability of female $^{87}Sr/^{86}Sr$ ratios was present in the Mikulčice dataset, this is more likely caused by differences in the provinciality of immigrants, as identified elite male non-locals tend to originate from less radiogenic areas, whereas females make up the majority of the highest $^{87}Sr/^{86}Sr$ values. Variabilities in both sexes become practically identical when non-locals are omitted, providing no evidence for the higher regional mobility of females, obscured within the estimated local $^{87}Sr/^{86}Sr$ range. A higher number of female migrants becomes apparent only when the narrower local range is applied, which could point to the hidden regional migration. But presented alone it is not a convincing evidence for the presumed patrilocality. Furthermore, in the case of more pronounced female mobility, it can be expected of female migrants to comprise the majority of non-locals even when more rigorous criteria for their identification are applied.

On the other hand, migration seems to be more prevalent, but not exclusive, in elites, as they outnumber non-elite migrants by almost 3:1. This goes well with the image of the Mikulčice-Valy stronghold as one of the most important religious and power centres of Great Moravia, at which lower ranking elites congregated. Conversely, only two of the six analysed church interior burials (MH40, MH117) fall outside the local range, and in both cases the difference from the cut-off points is minimal. This implies that the highest ranks of Moravian society were most likely local, which would provide more evidence in favour of the lower Morava being the core territory of Great Moravia, a subject of ongoing debate among some historians (Bowlus 2009; Curta 2009; Macháček 2009). Regrettably, the three most prominent graves from within the basilica, the largest and most "prestigious" church in Mikulčice-Valy, failed to provide sufficiently well-preserved teeth for Sr analysis. It must also be noted, however, that the higher migration rate among the elite may simply represent an analytical bias, as elites form the majority (58%) of individuals selected for strontium analysis. The non-local elite individuals identified at Mikulčice-Valy could, in theory, have their origin traced to the Avar region in the case of the earliest graves (from the beginning of the ninth century), to the Frankish and Byzantine Empires (ninth century) or to the Old Hungarian or generally eastern nomadic millieu (the latest graves from the tenth century). Furthermore, comparison with other Great Moravian archaeological sites is unfortunately not possible, this study being a pioneering work into the field of migration studies in the early medieval archaeology of today's Czech Republic, and no other Great Moravian site has yet been subjected to strontium analysis.

In the wider context of early medieval Europe, however, several analogous cases can be found, although various circumstances such as the geological diversity of bedrocks, the types and numbers of reference samples, and overall differences in local conditions throughout Europe might present certain challenges to inter-site comparability. It should, therefore, be approached with caution. The medieval site of Sigtuna in modern Sweden, being among the first urbanised centres in its region and an important centre of administration and Christianity with multiple churches and associated cemeteries (Krzewińska et al. 2018), shares many similarities with Mikulčice-Valy. A strontium and genetic analysis of its population suggests that more than half of the sampled individuals were either regional or long distance immigrants (Krzewińska et al. 2018). Likewise, at the important trade hub of Birka, Sigtuna's predecessor, the situation is similar (Price et al. 2018), while at the early medieval royal site of Bamburgh in England more than half of the analysed individuals were non-local (Groves et al. 2013). Although in these cases the characteristics and developments such as urbanisation and population increase appear similar to Mikulčice-Valy, the reported migration ratios are higher. The reasons could be, except for the already mentioned obscured regional migration, that those sites are not entirely comparable to the Mikulčice-Valy or, more likely, that the development processes were not completed in Great Moravia due to the interruption caused by its collapse (Štefan 2011).

Another analogue for mobility in Great Moravia can be seen in the tenth century Danish fortress of Trelleborg, where in the analysed sample of interred population, presumed to originate in the military garrison and its train, the majority of individuals were non-locals (Price et al. 2011). The presence of such military garrisons is suggested in Great Moravian strongholds, but the character of these settlements was urban rather than purely military (Macháček 2010).

Mobility connected with religion also offers an interesting consideration for Mikulčice-Valy. At Bamburgh, the role of Christianity and the mobility of Christian clergy or religious communities have been considered (Groves et al. 2013), and long-range pilgrimages to important religious centres in preceding centuries are implied by isotopic data (Sheridan and Gregoricka 2015). Historical evidence documents the presence of Christian missions from both the Frankish and Byzantine Empires in Great Moravia, as well as Papal interests (Betti 2013; Ivanič and Hetényi 2017), and the Mikulčice-Valy stronghold was one of its most important religious centres. It is extremely tempting to link the least radiogenic group of immigrants with a Byzantine mission to Great Moravia, especially as similar $^{87}Sr/^{86}Sr$ ratios have been reported in some parts of Greece (Whelton et al. 2018; Wang et al. 2019); unfortunately, this would be closer to wishful thinking than solid scientific hypothesis, as such strontium values are fairly common throughout Europe and the available evidence, or more precisely the lack thereof, does not allow for such conclusions to be drawn.

The presence of newcomers and long-range migrants in Mikulčice-Valy might be more likely linked to trade. For example, mercantile connections are believed to account for the very high number of "non-locals" at the important byzantine port of Aila (Perry et al. 2017) and isotopic evidence suggesting the presence of far-reaching trade networks in Early Medieval Western Europe predating the ninth century has been published (McManus et al. 2013). The historical sources mention the enigmatic "market of the Moravians" (Štefan 2011; Herold 2012; Fontaine 2017) and Great Moravia was connected to the Danubian trade network and as well as the amber road (McCormick 2001; Štefan 2011). The Mikulčice-Valy settlement itself is believed to have been located on a trade route, but the large collection of find does not provide a great quantity of direct archaeological evidence for long-distance trade (e.g., in comparison with maritime emporia).

The engagement of the stronghold in trade offers another, although highly speculative, view of the results of isotopic analysis. As some historians consider slaves an important part of Great Moravian long distance trade (e.g., Macháček 2010; Štefan 2011), the apparent lack of non-elite males among the identified non-locals at Mikulčice-Valy is striking, as only one such case has been observed. Such individuals could be expected to represent a most suitable work force and their absence may indicate that slaves were not an integral part of Moravian society. Alternatively, they could have evaded the scope of this study, which concentrated mainly on the inner castle, by being buried within the sub-castle area rather than in the stronghold itself. Slave interments within the settlement area itself are also questionable, as Mikulčice-Valy might be expected to serve as a slave "transfer point" rather than a final residence area. Moreover, other demographic groups could have been enslaved as well, and slaves were most likely not the sole or main commodity traded by merchants (Macháček 2010; Fontaine 2017; Raffield 2019); thus, the noticeable scarcity of non-elite male newcomers might not be connected to the slave trade at all. It must be concluded, in agreement with Killgrove and Montgomery (2016), that slavery provides an interesting, albeit highly problematic issue for investigation.

Conclusion

This paper presents a pioneering study on the mobility dynamics of Great Moravian society. The local range of the bioavailable strontium isotopic signature has been estimated using tooth enamel samples from domestic animals. Although the geological conditions in the vicinity of Mikulčice-Valy stronghold are unfavourable to mobility analysis and regional migration might thus not be detectable, the $^{87}Sr/^{86}Sr$ ratios obtained from the enamel of 123 individuals suggest that 13–19% of the analysed humans buried within the settlement were of non-local origin. Migration was more prevalent in elites, but the highest elements of Moravian society, buried within church interiors, seem to have been local. This accords with the image of Mikulčice-Valy as an important regional seat of power and Christianity, to which the "lower" ranking elites of the society were drawn. Insufficient evidence was found to support the predicted patrilocality and higher mobility of females suggested in several other studies. Overall, the societal changes taking place in ninth century Great Moravia appear to have followed similar patterns to Western Europe or later Scandinavia, and multiple factors could have contributed to the population increase accompanying ongoing urbanisation. While more work is needed to fully understand those processes, the results presented here provide a valuable insight into developments in the Early Middle Ages in Eastern Central Europe.

Acknowledgements The authors appreciate the assistance of Alastair Millar in reviewing the manuscript for English language. LA acknowledges Institutional support RVO67985831 of the Institute of Geology of the Czech Academy of Sciences.

Funding Research was supported by Charles University, project GA UK No. 1076218, by the Ministry of Culture of the Czech Republic (DKRVO 2019-2023/7.I.b, 00023272) and by the Czech Academy of Sciences, Institute of Archaeology, Brno (RVO: 68081758).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Alt KW, Knipper C, Peters D, Müller W, Maurer AF, Kollig I, Nicklisch N, Müller C, Karimnia S, Brandt G, Roth C, Rosner M, Mende B, Schöne BR, Vida T, von Freeden U (2014) Lombards on the move – an integrative study of the migration period cemetery at Szólád, Hungary. PLoS One 9:e110793. https://doi.org/10.1371/journal.pone.0110793

Bentley RA (2006) Strontium isotopes from the Earth to the archaeological skeleton: a review. J Archaeol Method Theory 13:135–187. https://doi.org/10.1007/s10816-006-9009-x

Bentley RA, Bickle P, Fibiger L, Nowell GM, Dale CW, Hedges REM, Hamilton J, Wahl J, Francken M, Grupe G, Lenneis E, Teschler-Nicola M, Arbogast RM, Hofmann D, Whittle A (2012) Community differentiation and kinship among Europe's first farmers. Proc Natl Acad Sci 109:9326–9330. https://doi.org/10.1073/pnas.1113710109

Betti M (2013) The making of Christian Moravia (858–882): papal power and political reality. Brill, Leiden

Bigoni L, Krajíček V, Sládek V, Velemínský P, Velemínská J (2013) Skull shape asymmetry and the socioeconomic structure of an early medieval central european society. Am J Phys Anthropol 150:349–364. https://doi.org/10.1002/ajpa.22210

Blum JD, Taliaferro EH, Weisse MT, Holmes RT (2000) Changes in Sr/Ca, Ba/Ca and $^{87}Sr/^{86}Sr$ ratios between trophic levels in two forest ecosystems in the northeastern U.S.A. Biogeochemistry 49:87–101. https://doi.org/10.1023/A:1006390707989

Bowlus CR (2009) Nitra: when did it become a part of the Moravian realm? Evidence in the Frankish sources. Early Mediev Eur 17:311–328. https://doi.org/10.1111/j.1468-0254.2009.00279.x

Brůžek J (2002) A method for visual determination of sex, using the human hip bone. Am J Phys Anthropol 117:157–168. https://doi.org/10.1002/ajpa.10012

Brůžek J (2013) Odhad pohlavní příslušnosti a věku dožití u koster od II. a III. kostela na lokalitě Mikulčice-Valy. Unpublished report. Department of Anthropology, National Museum

Budd P, Montgomery J, Barreiro B, Thomas RG (2000) Differential diagenesis of strontium in archaeological human dental tissues. Appl Geochem 15:687–694. https://doi.org/10.1016/S0883-2927(99)00069-4

Chlupáč I (2002) Geologická minulost České republiky, Vyd. 1. Academia, Praha

Curta F (2009) The history and archaeology of Great Moravia: an introduction. Early Mediev Eur 17:238–247

Czech Geological Survey (2019) Geological map 1:50 000 [online]. Czech Geological Survey, Praha. Accessed 15.05.2020 from https://mapy.geology.cz/geocr50/

Effros B (2003) Merovingian mortuary archaeology and the making of the Early Middle Ages. University of California Press, Berkley and Los Angeles

Evans JA, Tatham S (2004) Defining 'local signature' in terms of Sr isotope composition using a tenth- to twelfth-century Anglo-Saxon population living on a Jurassic clay-carbonate terrain, Rutland, UK. Geol Soc Lond Spec Publ 232:237–248. https://doi.org/10.1144/GSL.SP.2004.232.01.21

Flockhart DTT, Kyser TK, Chipley D, Miller NG, Norris DR (2015) Experimental evidence shows no fractionation of strontium isotopes ($^{87}Sr/^{86}Sr$) among soil, plants, and herbivores: implications for tracking wildlife and forensic science. Isot Environ Health Stud 51:372–381. https://doi.org/10.1080/10256016.2015.1021345

Fontaine JM (2017) Early medieval slave-trading in the archaeological record: comparative methodologies. Early Mediev Eur 25:466–488. https://doi.org/10.1111/emed.12228

Gerling C (2014) A multi-isotopic approach to the reconstruction of prehistoric mobility and economic patterns in the West Eurasian steppes 3500 to 300 BC. Topoi, J Ancient Stud 3:1–21

Giblin JI, Knudson KJ, Bereczki Z, Pálfi G, Pap I (2013) Strontium isotope analysis and human mobility during the Neolithic and Copper Age: a case study from the Great Hungarian Plain. J Archaeol Sci 40:227–239. https://doi.org/10.1016/j.jas.2012.08.024

Groves SE, Roberts CA, Lucy S, Pearson G, Gröcke DR, Nowell G, Macpherson CG, Young G (2013) Mobility histories of 7^{th}–9^{th} century AD people buried at early medieval Bamburgh, Northumberland, England. Am J Phys Anthropol 151:462–476. https://doi.org/10.1002/ajpa.22290

Halsall G (2010) Cemeteries and society in Merovingian Gaul: selected studies in history and archaeology, 1992–2009. Brill, Leiden

Havelková P, Villotte S, Velemínský P, Poláček L, Dobisíková M (2011) Enthesopathies and activity patterns in the early medieval Great Moravian population: evidence of division of labour. Int J Osteoarchaeol 21:487–504. https://doi.org/10.1002/oa.1164

Havlíček P (2001) Geologická stavba okolí Mikulčic-Valů. Zprávy O Geol Výzkumech 34:73–75

Havlíček P, Poláček L, Vachek M (2003) Geologische Situation im Bereich des Burgwalls von Mikulčice. Stud Zum Burgwall Von Mikulčice V:11–38

Havlíček P, Břízová E, Hošek J, Sidorinová T (2016) Geologicky výzkum na soutoku Dyje, Kyjovky a Moravy. Zprávy O Geol Výzkumech 49:255–232

Herold H (2012) Fortified settlements of the 9^{th} and 10^{th} centuries AD in Central Europe: structure, function and symbolism. Mediev Archaeol 56:60–84. https://doi.org/10.1179/0076609712Z.0000000003

Hladík M (2020) Mikulčice and its hinterland: an archaeological model for medieval settlement patterns on the middle course of the Morava river (7^{th} to mid-13^{th} centuries). Brill, Leiden

Hladík M, Mazuch M, Poláček L (2020) Zázemí hradiště Mikulčice-Valy v 9. století. Mikulčice-průvodce V. Archeologický ústav AV ČR, Brno, Brno

Hodell DA, Mueller PA, Garrido JR (1991) Variations in the strontium isotopic composition of seawater during the Neogene. Geology 19: 24–27. https://doi.org/10.1130/0091-7613(1991)019<0024:VITSIC>2.3.CO;2

Hoogewerff JA, Reimann C, Ueckermann H, Frei R, Frei KM, van Aswegen T, Stirling C, Reid M, Clayton A, Ladenberger A, Albanese S, Andersson M, Baritz R, Batista MJ, Bel-lan A, Birke M, Cicchella D, Demetriades A, de Vivo B, de Vos W, Dinelli E, Ďuriš M, Dusza-Dobek A, Eggen OA, Eklund M, Ernstsen V, Filzmoser P, Flight DMA, Forrester S, Fuchs M, Fügedi U, Gilucis A, Gregorauskiene V, de Groot W, Gulan A, Halamić J, Haslinger E, Hayoz P, Hoffmann R, Hrvatovic H, Husnjak S, Janik L, Jordan G, Kaminari M, Kirby J, Kivisilla J, Klos V, Krone F, Kwećko F, Kuti L, Lima A, Locutura J, Lucivjansky DP, Mann A, Mackovych D, Matschullat J, McLaughlin M, Malyuk BI, Maquil R, Meuli RG, Mol G, Negrel P, Connor O, Oorts RK, Ottesen RT, Pasieczna A, Petersell W, Pfleiderer S, Poňavič M, Pramuka S, Prazeres C, Rauch U, Radusinović S, Reimann C, Sadeghi M, Salpeteur I, Scanlon R, Schedl A, Scheib AJ, Schoeters I, Šefčik P, Sellersjö E, Skopljak F, Slaninka I, Soriano-Disla JM, Šorša A, Srvkota R, Stafilov T, Tarvainen T, Trendavilov V, Valera P, Verougstraete V, Vidojević D, Zissimos A, Zomeni Z (2019) Bioavailable $^{87}Sr/^{86}Sr$ in European soils: a baseline for provenancing studies. Sci Total Environ 672:1033–1044. https://doi.org/10.1016/j.scitotenv.2019.03.387

Hoppe KA, Koch PL, Furutani TT (2003) Assessing the preservation of biogenic strontium in fossil bones and tooth enamel. Int J Osteoarchaeol 13:20–28. https://doi.org/10.1002/oa.663

Ivanič P, Hetényi M (2017) Invitation, arrival and activities of the byzantine missionaries in Great Moravia. Eur J Sci Theol 13:27–34

Kadlec J, Kocurek G, Mohrig D, Shinde DP, Murari MK, Varma V, Stehlík F, Beneš V, Singhvi AK (2015) Response of fluvial, aeolian, and lacustrine systems to late Pleistocene to Holocene climate change, Lower Moravian Basin, Czech Republic. Geomorphology 232:193–208. https://doi.org/10.1016/j.geomorph.2014.12.030

Kaupová S, Velemínský P, Herrscher E, Sládek V, Macháček J, Poláček L, Brůžek J (2018) Diet in transitory society: isotopic analysis of medieval population of Central Europe (ninth–eleventh century AD, Czech Republic). Archaeol Anthropol Sci 10:923–942. https://doi.org/10.1007/s12520-016-0427-8

Killgrove K, Montgomery J (2016) All roads lead to Rome: exploring human migration to the Eternal city through biochemistry of skeletons from two Imperial-Era cemeteries (1^{st}-3^{rd} c AD). PLoS One 11: e0147585. https://doi.org/10.1371/journal.pone.0147585

Kouřil P (2005) Die frühmittelalterliche Elite bei den Völkern des östlichen Mitteleuropas. Archeologický ústav AV ČR, Brno, Brno

Kováč M, Baráth I, Harzhauser M et al (2004) Miocene depositional systems and sequence stratigraphy of the Vienna Basin. Cour Forschungsinstitut Senckenberg 246:187–212

Kovačiková L, Kaupová SD, Poláček L, Velemínský P, Limburský P, Brůžek J (2020) Pig-breeding management in the early medieval stronghold at Mikulčice (eighth–ninth centuries, Czech Republic). Environ Archaeol 0:1–15. https://doi.org/10.1080/14614103.2020.1782583

Krzewińska M, Kjellström A, Günther T, Hedenstierna-Jonson C, Zachrisson T, Omrak A, Yaka R, Kılınç GM, Somel M, Sobrado V, Evans J, Knipper C, Jakobsson M, Storå J, Götherström A (2018) Genomic and strontium isotope variation reveal immigration patterns in a Viking Age town. Curr Biol 28:2730–2738. https://doi.org/10.1016/j.cub.2018.06.053

Lewis J, Pike AWG, Coath CD, Evershed RP (2017) Strontium concentration, radiogenic ($^{87}Sr/^{86}Sr$) and stable ($\delta^{88}Sr$) strontium isotope systematics in a controlled feeding study. STAR Sci Technol Archaeol Res 3:45–57. https://doi.org/10.1080/20548923.2017.1303124

Macháček J (2009) Disputes over Great Moravia: chiefdom or state? The Morava or the Tisza River? Early Mediev Eur 17:248–267. https://doi.org/10.1111/j.1468-0254.2009.00276.x

Macháček J (2010) The rise of medieval towns and states in East Central Europe: early medieval centres as social and economic systems. Brill, Leiden

McCormick (2001) Origins of the European economy. Communications and Commerce, A.D. 300–900. Cambridge University Press, Cambridge

McManus E, Montgomery J, Evans J, Lamb A, Brettell R, Jelsma J (2013) "To the land or to the sea": diet and mobility in early medieval Frisia. J Isl Coast Archaeol 8:255–277. https://doi.org/10.1080/15564894.2013.787565

Murail P, Brůžek J, Houët F, Cunha E (2005) DSP: a tool for probabilistic sex diagnosis using worldwide variability in hip-bone measurements. Bull Mém Société D'Anthropologie Paris 17:167–176

Perry MA, Jennings C, Coleman DS (2017) Strontium isotope evidence for long-distance immigration into the Byzantine port city of Aila, modern Aqaba, Jordan. Archaeol Anthropol Sci 9:943–964. https://doi.org/10.1007/s12520-016-0314-3

Pin C, Gannoun A, Dupont A (2014) Rapid, simultaneous separation of Sr, Pb, and Nd by extraction chromatography prior to isotope ratios determination by TIMS and MC-ICP-MS. J Anal At Spectrom 29: 1858–1870. https://doi.org/10.1039/C4JA00169A

Poláček L (1999) Großmährisches Reich. In: Hoops J (ed) Reallexikon der Germanischen Altertumskunde 13. Walter de Gruyter, Berlin - New York, pp 78–85

Poláček L (2008) Great Moravia, the power centre at Mikulčice and the issue of the socioeconomic structure. In: Studien zum Burgwall von Mikulčice VIII. Archeologický ústav AV ČR, Brno, Brno, pp 11–44

Poláček L (2018) The Mikulčice-Valy stronghold and Great Moravia. Archeologický ústav AV ČR, Brno, Brno

Poláček L (2020) Zur Problematik der Kirchenbestattungen in Mikulčice. Mitteilungen zur Christlichen Archäologie 26:9–30

Poláček L, Bartošková A, Mazuch M, et al (2019) Das Suburbium des Burgwalls von Mikulčice. In: Studien zum Burgwall von Mikulčice IX. Archeologický ústav AV ČR, Brno, Brno

Price TD, Burton JH, Bentley RA (2002) The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. Archaeometry 44:117–135. https://doi.org/10.1111/1475-4754.00047
Price TD, Knipper C, Grupe G, Smrčka V (2004) Strontium isotopes and prehistoric human migration: the Bell Beaker Period in Central Europe. Eur J Archaeol 7:9–40. https://doi.org/10.1177/1461957104047992
Price TD, Frei KM, Dobat AS, Lynnerup N, Bennike P (2011) Who was in Harold Bluetooth's army? Strontium isotope investigation of the cemetery at the Viking Age fortress at Trelleborg, Denmark. Antiquity 85:476–489. https://doi.org/10.1017/S0003598X00067880
Price TD, Arcini C, Gustin I, Drenzel L, Kalmring S (2018) Isotopes and human burials at Viking Age Birka and the Mälaren region, east central Sweden. J Anthropol Archaeol 49:19–38. https://doi.org/10.1016/j.jaa.2017.10.002
Raffield B (2019) The slave markets of the Viking world: comparative perspectives on an 'invisible archaeology. Slavery Abolit 40:682–705
Richards MP, Montgomery J, Nehlich O, Grimes V (2008) Isotopic analysis of humans and animals from Vedrovice. Anthropol 1962–46: 185–194
Schatz A-K, Qi Y, Siebel W, Wu J, Zöller L (2015) Tracking potential source areas of central European loess: examples from Tokaj (HU), Nussloch (D) and grub (AT). Open Geosci 7:678–720. https://doi.org/10.1515/geo-2015-0048
Scheeres M, Knipper C, Hauschild M, Schönfelder M, Siebel W, Pare C, Alt KW (2014) "Celtic migrations": fact or fiction? Strontium and oxygen isotope analysis of the Czech cemeteries of Radovesice and Kutná Hora in Bohemia. Am J Phys Anthropol 155:496–512. https://doi.org/10.1002/ajpa.22597
Schuh C, Makarewicz CA (2016) Tracing residential mobility during the Merovingian period: an isotopic analysis of human remains from the Upper Rhine Valley, Germany. Am J Phys Anthropol 161:155–169. https://doi.org/10.1002/ajpa.23017
Schulze-Dörrlamm M (1995) Bestattungen in den Kirchen Großmährens und Böhmens während des 9. Und 10. Jhs. Jahrb. RGZM 40(2): 557–620
Sheridan SG, Gregoricka LA (2015) Monks on the move: evaluating pilgrimage to Byzantine St. Stephen's monastery using strontium isotopes. Am J Phys Anthropol 158:581–591. https://doi.org/10.1002/ajpa.22827
Slovak NM, Paytan A (2012) Applications of Sr isotopes in archaeology. In: Baskaran M (ed) Handbook of environmental isotope geochemistry. Springer, Berlin, pp 743–768
Soejono I, Janoušek V, Žáčková E, Sláma J, Konopásek J, Machek M, Hanžl P (2017) Long-lasting Cadomian magmatic activity along an active northern Gondwana margin: U–Pb zircon and Sr–Nd isotopic evidence from the Brunovistulian Domain, eastern Bohemian Massif. Int J Earth Sci 106:2109–2129. https://doi.org/10.1007/s00531-016-1416-y
Štefan I (2011) Great Moravia, statehood and archaeology. The 'decline and fall'of one early medieval polity. In: Macháček J, Ungerman Š (eds) Frühgeschichtliche Zentralorte in Mitteleuropa. Rudolf Habelt, Bonn, pp 333–354
Šušolová J, Králová V, Hadacz R, Dundek P, Volařík D (2016) Srovnávací studie povrchu křemenných zrn na lokalitách jižní a jihovýchodní Moravy. Geol Výzk Na Moravě Ve Slez 23:29–38. https://doi.org/10.5817/GVMS2016-1-2-29
Trickett MA, Budd P, Montgomery J, Evans J (2003) An assessment of solubility profiling as a decontamination procedure for the $^{87}Sr/^{86}Sr$ analysis of archaeological human skeletal tissue. Appl Geochem 18: 653–658. https://doi.org/10.1016/S0883-2927(02)00181-6
van der Jagt IMM, Kootker LM, van Kolfschoten T, Kars H, Davies GR (2012) An insight into animal exchange in early medieval Oegstgeest: a combined archaeozoological and isotopic approach. In: Raemaekers D, Esser E, Lauwerier R, Zeiler J (eds) A bouquet of archaeological studies. Essays in honour of Wietske Prummel. Barkhuis, Groningen, pp 141–151
Vavřínek V (2014) Christianity and the Byzantine mission in Great Moravia. In: Kouřil P (ed) Great Moravia and the beginnings of Christianity. Archeologický ústav AV ČR, Brno, Brno, pp 84–87
Velemínský P, Likovský J, Trefný P, et al (2005) Anthropologische Analyse des großmährischen Gräberfeldes Kostelisko im Suburbium des Burgwalls von Mikulčice. Demogr Spuren Nicht Spezifischer Physiol Phys Belastungen En Skeletten Gesundheitszustand Burgwald Von Mikulčice VI:540–633
Villa IM, De Bièvre P, Holden NE, Renne PR (2015) IUPAC-IUGS recommendation on the half life of ^{87}Rb. Geochim Cosmochim Acta 164:382–385. https://doi.org/10.1016/j.gca.2015.05.025
Voerkelius S, Lorenz GD, Rummel S, Quétel CR, Heiss G, Baxter M, Brach-Papa C, Deters-Itzelsberger P, Hoelzl S, Hoogewerff J, Ponzevera E, van Bocxstaele M, Ueckermann H (2010) Strontium isotopic signatures of natural mineral waters, the reference to a simple geological map and its potential for authentication of food. Food Chem 118:933–940. https://doi.org/10.1016/j.foodchem.2009.04.125
Wang X, Zhang X, Fan A, Sampson A, Wu X, Gao J, Huang F, Jin Z (2019) Strontium isotopic evidence for the provenance of occupants and subsistence of Sarakenos cave in prehistoric Greece. Quat Int 508:13–22. https://doi.org/10.1016/j.quaint.2018.10.009
Whelton HL, Lewis J, Halstead P, Isaakidou V, Triantaphyllou S, Tzevelekidi V, Kotsakis K, Evershed RP (2018) Strontium isotope evidence for human mobility in the Neolithic of northern Greece. J Archaeol Sci Rep 20:768–774. https://doi.org/10.1016/j.jasrep.2018.06.020
Zazvonilová E, Velemínský P, Brůžek J (2020) Současný pohled na paleodemografickou interpretaci kosterních souborů minulých populací: nové hodnocení pohřebišť 3. a 6. kostela v Mikulčicích. Archeol Rozhl LXXII:67–101
Zitek A, Tchaikovsky A, Irrgeher J et al (2015) The $^{87}Sr/^{86}Sr$ river water isoscape of the Danube catchment. In: Liska I, Wagner F, Sengl M, Deutsch K, Slobodnik J (eds) Joint Danube survey 3: a comprehensive analysis of Danube water quality. ICPDR, Vienna, pp 349–354

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