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ORIGINAL PAPER

Isotopic evidence for changing human mobility patterns after the disintegration of the Western Roman Empire at the Upper Rhine

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Abstract
The dissolution of the Western Roman Empire and the rise of Early Medieval kingdoms during the fifth and sixth century AD were accompanied by profound social, economic, and cultural changes. While several studies focus on the investigation of the reasons explaining the underlying cause of this transition based on written and archeological evidence, it is still unclear in how far this major political turnover affected communities on a regional and local level. Here, we conduct strontium, oxygen, and carbon isotope analyses of human tooth enamel from 95 individuals from two Early Medieval cemeteries located in the northern Upper Rhine region in order to investigate population dynamics during a period of political upheaval. The strontium isotopic analysis has revealed that a high number of individuals born outside the Upper Rhine region, but relative few individuals indigenous to the area, were interred in cemeteries newly founded at the end of the fifth century AD. During the sixth century AD, the cemeteries are dominated by individuals local to the Upper Rhine region. However, the presence of individuals with strontium isotope values below the biologically available strontium isotopic range indicates the arrival of newcomers from different regions compared to earlier periods which may reflect a change of contacts and relationships in the course of the sixth century AD. Overall, the results of this study suggest that the change of human mobility patterns in this region is a reaction to the socio-political dynamics of the transformation period between Late Antiquity and the Early Middle Ages.

Keywords Upper Rhine · Early Middle Ages · Strontium isotopes · Oxygen isotopes · Carbon isotopes · Enamel

Introduction

The dissolution of the Western Roman Empire during the second half of the fifth century AD marked a period of profound transformations that forever changed the political landscape of Europe. At this time, the Western Roman Empire was replaced by a series of competing post-Roman successor kingdoms (James 1988, 2009; Wood 1994; Pohl 2002). The decline of the overarching political Roman system, and thus administrative, military, and fiscal structures, further sparked a cascade of changes in social and economic systems, as well as cultural practices (Cleary 2013). While these transformations varied in pace and scale in the different provinces of the Western Roman Empire, they were most pronounced in peripheral regions such as northern Gaul which became increasingly isolated from Imperial rule already during the middle of the fifth century AD (Halsall 2007; Konrad and Witschel 2011; Fehr 2015). For example, the settlement structure of single farmsteads (villa-type) was replaced by multi-farmstead villages (Schreg 2006; Fehr 2015). Furthermore, burial traditions also changed from inhumation with relatively few or no grave goods associated with Late Roman mortuary practices to furnished inhumations often placed in large cemeteries used by an entire community in the sixth century AD, known as "row-grave" cemeteries (*Reihengräberfelder*) in some of the post-Roman provinces (Halsall 1995; Ament 2003; Fehr 2008).

One of the questions surrounding this dynamic period that encapsulated the decline of the Western Roman Empire and the subsequent increase in power of successor kingdoms focuses on the extent to which this major political turnover affected the continuity of communities on regional and local levels. This is of special concern for peripheral regions, such as the west bank

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of the Upper Rhine, which was the frontier zone of the Western Roman Empire, where Roman administration relied more heavily on military support from non-indigenous populations in order to maintain economic and political stability. Several objects of Germanic cultural tradition recovered from military as well as civil Late Roman contexts have been interpreted as indicating the incorporation of individuals from regions outside the Roman Empire including mercenaries, federates, and their families into Roman society (Bernhard 1981, 1982, 2006, 2007; Grünewald and Hahn 2006).

Written and archeological evidence indicates that Roman military impact rapidly destabilized in the middle of the fifth century AD in the northern Upper Rhine area, which is presumed to have resulted in a power vacuum for several decades (Oldenstein 1992; Bernhard 1997; Bakker 2012; Fehr 2015). However, urban settlements were continuously settled during the fifth and sixth century AD, although there is a scarcity of archeological evidence for this (Bernhard 2007; Grünewald and Koch 2009; Knöchlein 2011; Grünewald and Wieczorek 2012). In rural areas, single graves connected to Roman villas dated after 450 AD suggest that Late Roman communities were still present after the cessation of Roman administrative structures (Bernhard 1981, 1997, 2006, 2008). Shortly after the middle of the fifth century AD, new cemeteries were established in a limited area in the rural landscape of the northern Upper Rhine region (Lange 2004; Engels 2005, 2008, 2012; Grünewald and Koch 2009; Koch 2013). These graves introduce the Early Medieval or (Proto-) Merovingian period in the region (Ament 1992; Bernhard 1997; Fehr 2010).

Based on the scant archeological and written evidence, it has been speculated as to what extent these burials sites reflect the arrival of groups from east of the Rhine such as the Franks and Alamanni or were founded by local communities including the former Roman inhabitants of the regions and/or former members of federate non-Roman soldiers or a combination of both (Wieczorek 1996a; Bernhard 1997; Grünewald and Koch 2009). While the ethnic affiliations of these individuals and groups remain elusive, it is still an open question as to how far the foundation of these burial sites in this region were connected to the arrival of newcomers or, instead, indicate the adoption of a new burial rite by local communities that stemmed from socio-political changes during that time (Brather 2004; Halsall 2007; Fehr 2008; James 2009).

Starting at the beginning of the sixth century AD, this new burial practise flourished across the region and, in many cases, produced large “row-grave” cemeteries containing more than 500 burials and were in use until the eighth century AD (Riemer 2008; Grünewald and Koch 2009). The explosion of these newly established cemeteries broadly coincided with the placement of the Upper Rhine region and adjacent areas under the sovereignty of the Merovingian dynasty documented in historical sources (Grünewald and Koch 2009). Previous archeological research has suggested that this increase in burial sites was associated with an inflow of new settlers, a process supported by an administrated process backed by the Merovingian king (Wieczorek 1996b; Grünewald and Koch 2009; Leithäuser 2011; Engels 2012).

Archeological and written evidence documenting community continuity and mobility during the fifth and sixth century AD in the Upper Rhine region remain few (Schuh and Makarewicz, 2016). However, the analysis of stable and radiogenic isotopes, which provide insights into human mobility (Ericson 1985; Beard and Johnson 2000), can provide much needed information on human movement during this period (Hakenbeck et al. 2010; Vohberger 2011; Knipper et al. 2012; Ortega et al. 2013; Alt et al. 2014; Stauch 2017). Here, we investigate the strontium, oxygen, and carbon isotopic composition of human tooth enamel from individuals recovered from burials of two cemeteries dating to the late fifth and sixth century AD and located in the northern Upper Rhine Valley in order to investigate their spatial and dietary biographies and link these findings to shifts in political terrains associated with the dissolution of the Western Roman Empire and the subsequent rise of Merovingian power.

Isotopic analysis of human mobility

The analysis of radiogenic strontium isotopes (^{87}Sr/^{86}Sr) of tooth enamel is a well-established tool to investigate human mobility by taking advantage of spatially defined variation across landscapes caused by differences in the age and composition of underlying geological formations (Ericson 1985; Faure and Mensing 2005; Bentley 2006; Montgomery 2010; Slovak and Paytan 2012). Through weathering, water soluble strontium becomes bioavailable and is transmitted from rocks and minerals to soil, water, plants, and animals and finally into the human body where it is incorporated into biogenic tissues such as the mineral component of teeth as a substitute for calcium (Graustein 1989; Capo et al. 1998; Bentley 2006; Montgomery 2010). Mass-dependent fractionation of strontium isotopes is corrected by normalization during analysis (Knudson et al. 2010; Slovak and Paytan 2012; Lewis et al. 2017) and thus, the ^{87}Sr/^{86}Sr ratio of dental enamel, which is more resistant to diagenesis compared to bone and dentine (Budd et al. 2000; Trickett et al. 2003), reflects the places from which an individual ingested local food and water during the time of tooth mineralization. By comparing the distribution of bioavailable strontium isotopes to the ^{87}Sr/^{86}Sr ratio obtained from enamel, it is possible to establish residential mobility in human groups.

The biologically available strontium isotope range of the Upper Rhine Valley, which is composed of young deposits including Quaternary and Tertiary sediments (Landesamt für Geologie und Bergbau 2005), can be estimated to vary between 0.7086 and 0.7104 based on published ^{87}Sr/^{86}Sr values from archeological samples including human and faunal bones and teeth (Price et al. 2001, 2003; Bentley et al. 2003, 2004; Bentley and Knipper 2005; Turck et al. 2012; Bickle and Whittle 2013; Schuh and Makarewicz 2016) (Fig. 1). Based on strontium isotope measurements of modern and archeological faunal material, the ^{87}Sr/^{86}Sr values of the eastern and western shoulder areas of the valley which are composed of crystalline and Triassic Buntsandstein geological complexes, are above 0.71 and markedly distinct from the Rhine lowland (Bentley and Knipper 2005; Schuh and Makarewicz 2016) (Fig. 1).

The analysis of oxygen isotopes is increasingly used in studies of past mobility as they may provide additional evidence for changes in geographic residence of humans in ancient communities (Chenery et al. 2010, 2011; Müldner et al. 2011; Laffoon et al. 2013). Oxygen isotope ratios (δ^{18}O) of human biogenic tissues such as tooth enamel are determined by the isotopic composition of body water which is influenced by imbibed water, food, and atmospheric oxygen during tissue mineralization (Luz et al. 1984; Luz and Kolodny 1985; Kohn 1996; Daux et al. 2008; Chenery et al. 2010). The oxygen isotopic composition of meteoric water is influenced by altitude, continental positioning, surface air temperature, rainfall amount and seasonality (Dansgaard 1964; Rozanski et al. 1993; Gat 1996; Bowen and Wilkinson 2002). Water imbibed by mammals broadly corresponds to the oxygen isotopic composition of local precipitation (Longinelli 1984; Luz et al. 1984; Bryant and Froelich 1995; Kohn 1996; Sponheimer and Lee-Thorp 1999). In northwestern Europe, mean annual meteoric water δ^{18}O values decrease with a corresponding increase in distance away from the northern coast and with an increase in altitude in the Alps (Förstel and Hützen 1983; Rozanski et al. 1993). Variation in mean precipitation oxygen isotope values is relatively low with values of around −7‰ at the North Sea and − 11‰ in the Alps (IAEA/WMO 2018). While higher precipitation δ^{18}O values are present in western and southern Europe, lower δ^{18}O values have been modeled for northern and northeastern Europe (Evans et al. 2012, Fig. 12; Lightfoot and O'Connell 2016, Fig. 6). Given that δ^{18}O values of local drinking water sources used by a community approximate the oxygen isotopic composition of local precipitation and there are marked differences in δ^{18}O of local precipitation between regions, the oxygen isotopic signature of human tooth enamel may help to evaluate if an individual obtained childhood drinking water locally and thus, to explore residential mobility during childhood (Chenery et al. 2010; Müldner et al. 2011). However, the interpretation of human oxygen isotope values is not straightforward due to physiological factors and culturally-mediated consumption practices, which may include the ingestion of food and beverages that have gone under oxygen fractionation through processing (e.g., stewing, brewing, boiling) or biological processes (Wright and Schwarcz 1998; Lin et al. 2003; Brettell et al. 2012b; Lightfoot and O'Connell 2016). For example, the consumption of milk results in an increase of δ^{18}O values of the analyzed tissue as milk is enriched in ^{18}O compared to local water (Roberts et al. 1988; Wright and Schwarcz 1998; Lin et al. 2003). In addition, local drinking water sources can be sourced from several reservoirs with different δ^{18}O values

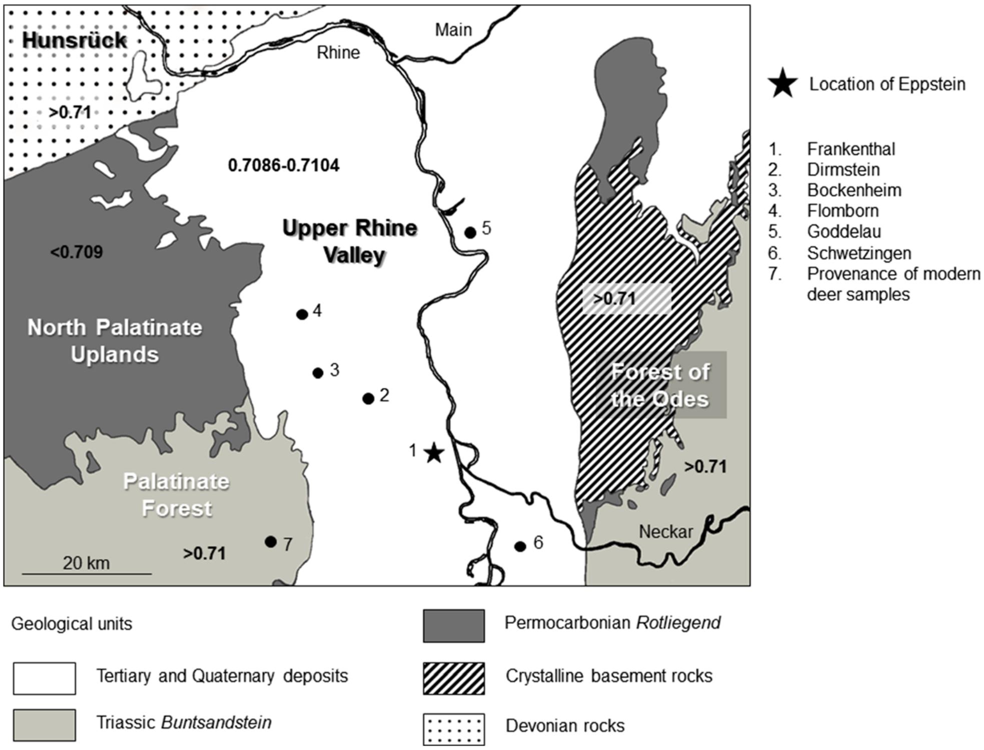

Fig. 1 Geology of the Upper Rhine Valley and adjacent areas with supposed strontium isotope values

including groundwater, running waters (e.g., streams and rivers), standing waters (e.g., lakes or ponds), or water containers such as barrels. For example, ponds and lakes can be enriched in ^{18}O compared to groundwater and precipitation as result of evaporative effects (e.g., Horton et al. 2016). Due to these difficulties, the oxygen isotopic composition of humans that inhabit temperate climates such as northern Europe, which are characterized by relatively small spatial and temporal oxygen isotope variability (e.g., seasonally, inter-annually), may be a poor monitor of mobility.

The spatial information derived from strontium and oxygen isotopes can be combined with dietary and environmental data obtained from carbon stable isotopes ($\delta^{13}C$). The carbon isotopic composition incorporated into the structural carbonate fraction of enamel bioapatite is derived from dissolved blood carbonates and bicarbonates and reflects the total macronutrient content of the diet during childhood (Lee-Thorp et al. 1989; Ambrose and Norr 1993; Tieszen and Fagre 1993; Jim et al. 2004). The carbon isotopic variation at the base of the foodweb is determined predominantly by photosynthetic pathway (O'Leary 1988; Farquhar et al. 1989), but also by environmental factors such as water availability, light intensity, and salinity (Tieszen 1991; Heaton 1999). C_3 plants average −26.5‰ in carbon isotopes compared to C_4 plants which average −12.5‰ (O'Leary 1988; Farquhar et al. 1989). Temperate Europe during the Early Medieval period was a C_3 environment and the only C_4 plant was millet grown as a crop. Thus, in regions where there is pronounced, environmentally defined geographical variation in $\delta^{13}C$ of ingested plants and animals, carbon isotopes of tooth enamel may also be used as an additional line of evidence to differentiate between local and incoming residents (Hakenbeck et al. 2010; Laffoon et al. 2013). Metabolic fractionation effects generate an offset between dietary and carbonate bioapatite $\delta^{13}C$ values (Passey et al. 2005; Prowse et al. 2007; Dupras and Tocheri 2007). The precise fractionation factor for humans is unknown but has been estimated to be around +11.5‰ (Krueger and Sullivan 1984; Passey et al. 2005; Dupras and Tocheri 2007).

Material and methods

Sites and sample collection

Human skeletal remains sampled for this study were obtained from the Early Medieval cemeteries of Eppstein and Bockenheim (Rhineland-Palatinate, Germany) located in the north-western Upper Rhine Valley (Fig. 1). Both sites date from the late fifth to the eighth century AD on the basis of material cultural analyses (Riemer 2008; Engels 2012). The cemetery of Eppstein was almost completely excavated between 1983 and 1988 and yielded more than 477 burials (Engels 2012). Graves dating to the late fifth and sixth century AD which correspond to the SD (Süddeutsch) chronological periods 2 to 6 after Koch (2001) are represented by ca. 112 burials. A group of ten graves, dating to the SD-periods 2–3 (460–480/510 AD) and located in the south-eastern section of the cemetery have been identified as the founder community of the Eppstein cemetery. Due to the various cultural influences, it has been postulated that the cemetery was founded by settlers of diverse provenance (Engels 2005, 2012). Graves dating to the first half of the sixth century AD (SD-period 4/4–5; 510–530/555 AD; $n = 23$) are situated west of the founder graves. Thuringian style pottery in some of these burials has been interpreted as evidence for the presence of settlers from Middle Germany (Engels 2012). In the middle of the sixth century AD (SD period 5/5–6, 530–555/580 AD; $n = 29$), the burial site has been extended to the west and north. The increase in the number of graves, compared to earlier periods, has been explained by the arrival of newcomers from the North Sea region due to the presence of hand-made pottery in North Sea Germanic tradition (Engels 2005, 2012). Graves dating to the second half of the sixth century AD (SD-periods 6/6–7, 555–580/600 AD; $n = 50$) are mainly located in the northern burial section although single graves can also be found in southern burial area.

A total of 65 individuals from the Eppstein cemetery have been selected for this study. The collection included all individuals with well-preserved teeth and skeletons of 30 males, 25 females and ten undetermined individuals of varying ages at death (Table 1). This sample set consists of eight burials from the earliest SD-periods 2–3 (ca. 460–510 AD), 26 dating to the first half of the sixth century (SD-periods 4, 4–5, 5 and 5–6; ca. 510–555/580 AD) and 31 from the second half of the sixth century (SD-period 6, 6–7; ca. 555/580–600 AD). A clear assignment to a certain period is often not possible, due to the strong disturbance and robbery of the graves (Engels 2012). The Bockenheim cemetery was excavated between 1980 and 1991 and, with 583 graves, is the largest Early Medieval cemetery in the Upper Rhine region (Riemer 2008). The earliest known graves of the cemetery, dating to the late fifth and early sixth century AD (SD-period 3–4; 580–530 AD; $n = 6$), are located in the western part of the burial place. There may be an earlier foundation date of the cemetery, as the western part of the site remains unexcavated. Sixth century AD graves ($n =$ ca. 90) and graves dating to the seventh and eighth century AD can be found in the central and eastern part of the cemetery (Riemer 2008, Riemer personal communication). In order to have a contemporary sample set from a location close to Eppstein, we selected 30 individuals, including 15 females, nine males, and three undetermined individuals of varying ages at death. Five individuals date to the late fifth/early sixth century AD (SD-periods 2–4) and 25 to the sixth century AD (Table 2). The imbalance in the number of graves between the different SD-period groups is due to the general lack of graves dating to the earliest periods as well as due to preservation issues (no teeth or poor preservation of teeth).

Table 1 Results of the isotope analyses on human teeth and context information from the Eppstein and Bockenheim cemeteries (context information from Riemer (personal communication) and Engels (2012))

Grave	Site	SD-period	Tooth	Sex[a]	Sex[b]	Age	$\delta^{13}C_{VPDB}$ (‰)	±1σ	$\delta^{18}O_{VPDB}$ (‰)	±1σ	$^{87}Sr/^{86}Sr$	2SE	Sr (ppm)
SD-2-3 (*n* = 8)													
52	Eppstein	2	M/1?	m?	nd	Adult	−14.9	0.1	−4.9	0.0	0.71199	0.00002	86
67C	Eppstein	2	M/2?	f	f	Adult I	−13.3	0.0	−5.6	0.1	0.70861	0.00001	69
275	Eppstein	2	M/3?	nd	nd	Adult	−14.3	0.0	−4.3	0.1	0.71028	0.00002	176
396	Eppstein	2	M/2	nd	m	Juvenile	−13.6	0.1	−5.1	0.0	0.71107	0.00002	119
280	Eppstein	2?	P/2	f?	(f)	Adult	−12.8	0.0	−4.5	0.0	0.70907	0.00002	54
50	Eppstein	2–3	M/3?	nd	nd	Adult	−9.7	–	−5.6	–	0.70821	0.00002	204
66	Eppstein	2–3?	M/2?	nd	nd	nd	−13.7	0.1	−2.7	0.1	0.71336	0.00002	99
83	Eppstein	3	M/2	f	f	Adult I	−11.2	0.0	−5.3	0.1	0.71031	0.00003	73
SD 4, 4–5 (*n* = 12)													
35*	Eppstein	4	M/2	m	m	Adult	−13.5	0.0	−4.3	0.0	0.71242	0.00002	122
48	Eppstein	4	M/2	m	(m)	Adult I	−12.7	–	−2.3	–	0.70910	0.00002	156
433*	Eppstein	4	M/2	f	f	Adult I	−13.3	0.0	−3.8	0.1	0.70976	0.00002	149
49	Eppstein	4?	M/2	m?	(m)	Adult	−13.3	0.0	−5.0	0.1	0.70898	0.00002	221
425	Eppstein	4?	M/2	m	m	Juvenile	−11.9	–	−3.6	–	0.70873	0.00002	130
431	Eppstein	4?	P/1	f	f	Adult	−10.9	–	−4.3	–	0.71578	0.00002	83
437	Eppstein	4?	M/2	m	m	Adult I	−14.1	0.0	−3.7	0.0	0.71364	0.00002	79
436	Eppstein	4–5	M/2	m	m	Senile	−12.5	0.0	−5.4	0.1	0.70924	0.00002	63
37	Eppstein	4–5?	M/2	nd	m	Adult I	−13.9	0.1	−4.1	0.1	0.70937	0.00002	146
47	Eppstein	4–5?	M/2	m?	nd	Adult	−13.1	0.0	−5.1	0.1	0.71010	0.00002	91
58	Eppstein	4–5?	P/2	m?	f	Adult	−11.7	0.0	−4.1	0.1	0.70905	0.00002	88
428*	Eppstein	3–5?	m/1?	nd	nd	Infants	−12.9	–	−3.0	–	0.70944	0.00002	128
SD 5, 5–6 (*n* = 14)													
38	Eppstein	5	M/2	m	nd	Adult	−14.3	0.0	−3.5	0.0	0.70923	0.00002	117
46	Eppstein	5	M/2	m	nd	Juvenile?	−13.9	–	−3.7	–	0.70927	0.00002	223
111	Eppstein	5	M/2	m	M	Adult I	−13.1	0.0	−5.2	0.0	0.70954	0.00002	102
189**	Eppstein	5	M/1	F?	M	Infants II	−14.5	0.0	−4.1	0.0	0.70946	0.00001	86
192**	Eppstein	5	M/1	F?	(F)	Infants I	−14.3	0.1	−3.0	0.0	0.70951	0.00002	148
222	Eppstein	5	P/1	m	Nd	Adult	−12.8	–	−4.2	–	0.70930	0.00001	128
411	Eppstein	5	M/1	f	nd	Infants	−13.1	–	−3.8	–	0.70947	0.00002	135
418	Eppstein	5	M/2?	f?	nd	Adult	−13.4	–	−5.1	–	0.7099	0.00001	105
67A	Eppstein	5?	C?	f	f	Mature II	−13.2	0.0	−4.2	0.0	0.70846	0.00002	252
413	Eppstein	5?	M/2	f	f	Adult I	−14.0	0.0	−5.5	0.0	0.70889	0.00002	109
426B	Eppstein	5?	P/2	m	m	Adult I	−12.5	0.0	−4.5	0.1	0.70949	0.00002	168
211	Eppstein	5(−6)	P/1	f?	(m)	Adult II	−14.2	–	−4.5	–	0.70976	0.00002	111
62	Eppstein	5–6	M/2	m	m	Juvenile	−13.3	–	−4.3	–	0.71115	0.00002	127
208	Eppstein	5–6	M/2	nd	nd	Adult	−13.9	0.0	−4.8	0.1	0.70916	0.00001	101
SD 6, 6–7 (*n* = 31)													
29	Eppstein	6	M	f	f	Adult	−12.9	–	−4.2	–	0.70863	0.00002	135
30	Eppstein	6	P	f	f	Mature II	−13.8	0.2	−4.3	0.0	0.70996	0.00002	184
55	Eppstein	6	P/2	f	f	Adult	−12.9	0.2	−4.5	0.5	0.7094	0.00001	146
61	Eppstein	6	M/2	nd	(f)	Juvenile?	−12.4	0.0	−4.8	0.1	0.70843	0.00001	326
70	Eppstein	6	M/1?	f	f	Senile	−12.7	0.0	−4.0	0.1	0.70850	0.00002	106
162	Eppstein	6	M/2	m	m	Adult I	−14.2	0.0	−4.1	0.1	0.70922	0.00001	243
167	Eppstein	6	P/2	(m)	f?	Adult I	−13.1	0.2	−4.1	0.0	0.70879	0.00002	145
168	Eppstein	6	M/1	m	nd	Infants II	−13.1	0.3	−3.3	0.1	0.70948	0.00001	156
182	Eppstein	6	M/1	m	m	Infants II	−13.9	0.0	−2.6	0.0	0.70968	0.00002	116
197	Eppstein	6	M/2?	f	f	Juvenile	−12.9	0.2	−3.7	0.0	0.70904	0.00001	166
198	Eppstein	6	M/2	nd	f	Adult I	−11.2	0.0	−3.2	0.0	0.70931	0.00001	120
217	Eppstein	6	M/1?	f	nd	Infants	−14.3	0.1	−3.6	0.1	0.70963	0.00002	187
224	Eppstein	6	m/1	m	nd	Infants	−12.7	0.1	−3.2	0.2	0.70932	0.00001	163
226	Eppstein	6	M/2	f	nd	Adult	−13.3	0.0	−4.9	0.1	0.70985	0.00001	118
228	Eppstein	6	M/2	f	f	Juvenile	−13.6	0.1	−3.9	0.1	0.70914	0.00002	167
246	Eppstein	6	M/2	m	m	Adult II	−13.5	0.1	−3.6	0.1	0.70925	0.00002	117
279	Eppstein	6	M	m	m	Mature I	−13.8	0.0	−3.5	0.2	0.70936	0.00002	113
391	Eppstein	6	P?	m	m	Adult	−11.1	0.7	−4.3	0.0	0.70868	0.00002	211
405	Eppstein	6	M/2	m	m	Senile	−13.7	0.3	−4.2	0.2	0.71258	0.00002	235
421	Eppstein	6	P?	f	f	Adult	−12.7	1.0	−4.0	0.1	0.70971	0.00001	151
422	Eppstein	6	M/1	m	nd	Infants	−13.9	0.0	−3.9	0.2	0.70954	0.00002	196
435	Eppstein	6	M/1	f	nd	Infants	−13.3	0.0	−4.1	0.1	0.70898	0.00001	154
25	Eppstein	6?	M/2	m	m	Infants II	−13.8	0.0	−4.9	0.0	0.70959	0.00002	281
39	Eppstein	6?	M/2	nd	f	Senile	−12.6	0.0	−4.1	0.1	0.70932	0.00002	207
188	Eppstein	6?	M/2?	f	f	Adult	−14.0	0.0	−4.9	0.0	0.70918	0.00002	97

Table 1 (continued)

Grave	Site	SD-period	Tooth	Sex[a]	Sex[b]	Age	$\delta^{13}C_{VPDB}$ (‰)	±1σ	$\delta^{18}O_{VPDB}$ (‰)	±1σ	$^{87}Sr/^{86}Sr$	2SE	Sr (ppm)
3	Eppstein	6–7	M/2	m	m	Adult	−13.4	0.0	−4.1	0.1	0.70916	0.00001	99
4C	Eppstein	6–7	M/2	f	f	Juvenile	−13.5	–	−4.8	–	0.70900	0.00001	171
74	Eppstein	6–7	M/2	m?	m	Adult	−13.5	0.2	−4.5	0.0	0.71028	0.00002	126
245	Eppstein	6–7	M/1	nd	nd	Infants	−12.8	0.5	−3.3	0.2	0.70958	0.00001	149
233	Eppstein	6–7	P/2	m	m	Mature	−12.5	–	−4.4	–	0.70928	0.00002	152
71	Eppstein	6/7?	M/2	nd	m	Mature II	−13.5	0.0	−4.3	0.0	0.70898	0.00003	178
SD 3, 3–4 (*n* = 5)													
391	Bockenheim	3	M/2	f?	nd	At least adult II	−13.4	0.0	−4.0	0.1	0.70936	0.00001	88
482	Bockenheim	3	M/2	f	f/m	Adult I–II	−11.9	–	−2.8	–	0.71032	0.00002	119
486	Bockenheim	3	M/2	f	f	Adult II–mature I	−11.8	0.0	−6.8	0.0	0.70886	0.00001	78
488	Bockenheim	3	M/2	f	f	Juvenile–adult I	−14.2	0.1	−5.4	0.1	0.70902	0.00001	64
449	Bockenheim	3–4	M/1	f	nd	Infants I	−14.1	0.0	−4.2	0.1	0.70965	0.00001	127
SD 4–5 (*n* = 2)													
406	Bockenheim	4–5	M/2	f	f	Senile	−13.2	0.0	−3.4	0.0	0.70970	0.00001	72
457	Bockenheim	4–5	M/2?	m	m/f	Juvenile–adult I	−13.7	0.1	−4.7	0.1	0.70947	0.00002	94
SD 5, 5–6 (*n* = 6)													
424	Bockenheim	5	M/2	f	f	Adult II–mature I	−10.4	–	−3.9	–	0.70977	0.00001	82
454*	Bockenheim	5	P/2	m	m/f	At least adult	−12.8	0.1	−4.6	0.1	0.70964	0.00002	231
464	Bockenheim	5	M/2	m	f	Adult I	−13.5	0.0	−4.9	0.2	0.70906	0.00002	197
22	Bockenheim	5–6	M/2	m	m	Adult II	−13.6	0.1	−4.1	0.1	0.70934	0.00001	114
395	Bockenheim	5–6	M/1	f	nd	Infants I	−13.1	0.0	−4.2	0.0	0.70938	0.00002	98
423	Bockenheim	5–6	M/1	nd	nd	Infants I	−14.0	0.0	−4.1	0.1	0.70928	0.00001	61
SD 6, 6–7 (*n* = 9)													
459	Bockenheim	6	M/2	m	m	Adult II–mature I	−12.3	0.0	−5.7	0.2	0.70916	0.00002	71
466	Bockenheim	6	P/2?	m	m	Adult II–mature I	−12.8	0.0	−2.8	0.2	0.70835	0.00001	74
470*	Bockenheim	6	M/2	f	f	Juvenile–adult I	−13.5	0.0	−5.3	0.0	0.70923	0.00002	152
382	Bockenheim	6–7	M/2	f	f	Mature II	−13.4	0.0	−4.8	0.2	0.70994	0.00002	59
386	Bockenheim	6–7	P/1	nd	nd	Adult I–II	−13.4	0.1	−3.6	0.1	0.70936	0.00002	151
421	Bockenheim	6–7	P/2	m	m	Adult I	−14.3	0.0	−3.8	0.1	0.70927	0.00001	130
478	Bockenheim	6–7	M/2	f	f/m	Adult II–mature I	−12.4	0.0	−4.9	0.1	0.70848	0.00002	201
492	Bockenheim	6–7	P/2	f	m/f	Mature I–II	−13.3	0.1	−4.3	0.1	0.70987	0.00001	143
398	Bockenheim	7–8	P/2	m	m	Senile	−12.7	0.0	−4.8	0.2	0.70819	0.00001	92
SD 4–7 (*n* = 8)													
392	Bockenheim	4–7	M/2	f	f	Senile	−10.4	0.0	−2.8	0.1	0.70976	0.00002	44
396	Bockenheim	4–7	M/2	f	nd	Infants II	−13.7	0.0	−4.8	0.1	0.70820	0.00001	77
397	Bockenheim	4–7	P/2	f	f	Adult I	−13.6	0.0	−4.1	0.2	0.70911	0.00002	79
461	Bockenheim	4–7	M/1	nd	nd	Infants I/II	−13.8	0.1	−4.9	0.2	0.70987	0.00002	114
474	Bockenheim	4–7	M/2	f	f	Adult I–II	−12.9	0.1	−4.4	0.2	0.70935	0.00002	157
480	Bockenheim	4–7	M/1	m?	nd	Infants I	−14.2	0.0	−3.7	0.0	0.70958	0.00002	93
497	Bockenheim	4–7	P/2	f	f/m	Adult II–mature II	−13.0	0.0	−5.1	0.0	0.70974	0.00003	126
473	Bockenheim	5–7	M/1	f	nd	Infants I	−13.8	0.0	−4.0	0.2	0.70928	0.00002	118

SD-period: SD 2 = 460–480 AD, SD 3 = 480–510 AD, SD 4 = 510–530, SD 5 = 530–555 AD, SD 6 = 555–580 AD, SD 7 = 580–600 AD

Tooth: *M* permanent molar, *P* permanent premolar, *C* permanent canine, *m* deciduous molar

Sex[a] sex estimation based on grave goods, *Sex*[b] sex estimation based on osteological assessment; *m* male, *f* female, *nd* not determinable, () tendency, ? probably

*Hand-made pottery "Thuringian type"

**Hand-made pottery "North Sea" type

From all selected individuals (*n* = 95), one tooth was sampled. If possible, a permanent second molar (M/2) or premolar (P/2), which mineralize between 3 and 7 years of age (AlQahtani et al. 2010), was collected. If these teeth were not available, a different permanent tooth was chosen in the order of preference: first premolar (P/1), third molar (M/3), first molar (M/1), and canine (C). First molars and canines mineralize between the first (4.5 and 7.5 months after birth, respectively) and third year of life. Mineralizing of the first premolar starts during the second year of life and ends during the fifth year of life. Third molars form during later childhood and youth (between the seventh and 14–18th years of age). Two deciduous first molars were also analyzed and mineralize before birth and in the first 4 and 5 months after birth (AlQahtani et al. 2010). We sampled tooth enamel, which does not remodel after mineralization and reflects dietary intake during childhood and adolescence dependent on the sampled tooth. Only bulk enamel samples were taken from human dentition, which reflects an average isotopic signal over several years. Unlike bone, tooth enamel is more likely to retain

Table 2 Strontium isotope data for samples used for the establishment of the biologically available strontium isotope range (context information from Riemer (personal communication) and Engels (2012))

Grave	Location	Material	Species	Tooth	Date	Context	$^{87}Sr/^{86}Sr$	2SE	Sr (ppm)
269	Eppstein cemetery	Enamel	Cattle	P (bulk)	?	Stray find, single tooth	0.70953	0.00002	293
358	Eppstein cemetery	Enamel	Cattle	M/1 (bulk)	?	Stray find, single tooth	0.70876	0.00002	232
358	Eppstein cemetery	Enamel	Cattle	M/1 (cusp)	?	Stray find, single tooth	0.70877	0.00002	257
358	Eppstein cemetery	Enamel	Cattle	M/1 (cervix)	?	Stray find, single tooth	0.70877	0.00001	219
15	Eppstein cemetery	Enamel	Horse	M (bulk)	Early Medieval	Horse burial	0.70983	0.00002	575
11	Eppstein cemetery	Enamel	Pig	M (bulk)	Early Medieval	Grave offering?	0.70923	0.00001	335
249	Eppstein cemetery	Enamel	Pig	M/3 (bulk)	?	Stray find, single tooth	0.70969	0.00002	256
270	Eppstein cemetery	Enamel	Pig	I (bulk)	?	Stray find, single tooth	0.71042	0.00001	142
270	Eppstein cemetery	Enamel	Pig	I (cusp)	?	Stray find, single tooth	0.71160	0.00002	197
270	Eppstein cemetery	Enamel	Pig	I (cervix)	?	Stray find, single tooth	0.70993	0.00001	198
358	Eppstein cemetery	Enamel	Sheep/goat	M/2 (bulk)	?	Stray find, single tooth	0.70955	0.00002	372
255	Eppstein cemetery	Eggshell	Duck/goose	–	Early Medieval	Stray find, food offering?	0.70931	0.00001	274
236	Eppstein cemetery	Eggshell	Domestic chicken	–	Early Medieval	Food offering	0.70935	0.00001	471
217	Eppstein cemetery	Eggshell	Domestic chicken	–	Early Medieval	Food offering	0.70936	0.00001	468
292	Eppstein cemetery	Eggshell	Domestic chicken	–	Early Medieval	Stray find, food offering?	0.70942	0.00001	331
222	Eppstein cemetery	Eggshell	Duck/goose	–	Early Medieval	Stray find, food offering?	0.70943	0.00001	368
411	Eppstein cemetery	Eggshell	Domestic chicken	–	Early Medieval	Food offering	0.70948	0.00001	844
422	Eppstein cemetery	Eggshell	Domestic chicken	–	Early Medieval	Food offering	0.70969	0.00001	909
358	Eppstein cemetery	Dentine	Cattle	M/1	?	Stray find, single tooth	0.70916	0.00001	581
15	Eppstein cemetery	Dentine	Horse	M	Early Medieval	Horse burial	0.70957	0.00002	830
249	Eppstein cemetery	Dentine	Pig	M/3	?	Stray find, single tooth	0.70947	0.00002	494
270	Eppstein cemetery	Dentine	Pig	I	?	Stray find, single tooth	0.70964	0.00001	408
3	Eppstein cemetery	Dentine	Human	M/2	Early Medieval	Human burial	0.70940	0.00002	403
38	Eppstein cemetery	Dentine	Human	M/2	Early Medieval	Human burial	0.70923	0.00002	288
50	Eppstein cemetery	Dentine	Human	M/3?	Early Medieval	Human burial	0.70863	0.00001	292
71	Eppstein cemetery	Dentine	Human	M/2	Early Medieval	Human burial	0.70944	0.00002	443
189	Eppstein cemetery	Dentine	Human	M/1	Early Medieval	Human burial	0.70933	0.00001	270
198	Eppstein cemetery	Dentine	Human	M/2	Early Medieval	Human burial	0.70935	0.00002	339
246	Eppstein cemetery	Dentine	Human	M/2	Early Medieval	Human burial	0.70940	0.00002	266
426B	Eppstein cemetery	Dentine	Human	P/2	Early Medieval	Human burial	0.70965	0.00002	292
22	Bockenheim cemetery	Enamel	Cattle	M/2 (bulk)	?	Stray find, single tooth	0.70989	0.00002	178
181	Bockenheim cemetery	Enamel	Cattle	M/3 (bulk)	?	Stray find, single tooth	0.70976	0.00002	179
195	Bockenheim cemetery	Enamel	Cattle	M/2 (bulk)	?	Stray find, single tooth	0.70975	0.00001	314
274	Bockenheim cemetery	Enamel	Cattle	M/3 (bulk)	?	Stray find, complete jaw	0.71107	0.00002	115
363	Bockenheim cemetery	Enamel	Dog	M (bulk)	?	Dog burial	0.70916	0.00001	380
261	Bockenheim cemetery	Enamel	Pig	I (bulk)	?	Dog burial	0.70982	0.00002	160
311	Bockenheim cemetery	Enamel	Pig	M/3 (bulk)	?	Stray find, complete skull	0.70986	0.00001	178
533	Bockenheim cemetery	Enamel	Sheep/goat	M (bulk)	?	Pit with two sheep/goat	0.70967	0.00002	389
342		Eggshell		–		Food offering?	0.70985	0.00002	430

Table 2 (continued)

Grave	Location	Material	Species	Tooth	Date	Context	$^{87}Sr/^{86}Sr$	2SE	Sr (ppm)
	Bockenheim cemetery		Domestic chicken		Early Medieval?				
451	Bockenheim cemetery	Eggshell	Domestic chicken	–	Early Medieval?	Food offering?	0.70986	0.00002	517
479	Bockenheim cemetery	Eggshell	Duck/goose	–	Early Medieval?	Food offering?	0.70912	0.00002	392
485	Bockenheim cemetery	Eggshell	Domestic chicken	–	Early Medieval?	Food offering?	0.70957	0.00001	348
509	Bockenheim cemetery	Eggshell	Exotic?	–	Early Medieval?	Food offering?	0.70884	0.00001	802
181	Bockenheim cemetery	Dentine	Cattle	M/3	?	Stray find, single tooth	0.70971	0.00002	463
195	Bockenheim cemetery	Dentine	Cattle	M/2	?	Stray find, single tooth	0.70971	0.00001	545
274	Bockenheim cemetery	Dentine	Cattle	M/3	?	Stray find, single tooth	0.70970	0.00002	499
261	Bockenheim cemetery	Dentine	Pig	I	?	Stray find, single tooth	0.70989	0.00002	531
22	Bockenheim cemetery	Dentine	Human	M/2	Early Medieval	Human burial	0.70945	0.00001	246
391	Bockenheim cemetery	Dentine	Human	M/2	Early Medieval	Human burial	0.70941	0.00002	170
392	Bockenheim cemetery	Dentine	Human	M/2	Early Medieval	Human burial	0.70952	0.00002	50
454	Bockenheim cemetery	Dentine	Human	M/1	Early Medieval	Human burial	0.70949	0.00003	333
464	Bockenheim cemetery	Dentine	Human	M/2	Early Medieval	Human burial	0.70925	0.00001	254
488	Bockenheim cemetery	Dentine	Human	M/2	Early Medieval	Human burial	0.70933	0.00002	377

an original isotopic signal due to its dense structure and low porosity that is less susceptible to diagenetic processes that destroy in vivo isotopic signals (Budd et al. 2000; Hoppe et al. 2003; Chiaradia et al. 2003).

The bioavailable strontium isotope range at Eppstein and Bockenheim was determined from archeological faunal remains recovered from grave infillings. Bulk tooth enamel samples from three pigs, two cattle, one horse as well as one sheep/goat were sampled from the Eppstein cemetery. In addition to bulk samples, the teeth of a pig and cattle were sampled at two points along the tooth crown. Five archeological eggshells of domestic chickens and two anseriform bird species were also sampled which have been placed in the graves as food offerings (Table 2). Due to the porous structure of eggshells, it is possible that these samples have been subject to diagenetic alteration and may represent a mixture of biogenic and soil derived strontium. From Bockenheim, bulk tooth enamel samples from four cattle, two pigs, one dog, and one sheep/goat were collected. Further, eggshells of two domestic chickens, one anseriform bird as well as one unidentified, possible exotic, bird species were sampled (personal communication J. Stewart). Using tooth enamel from archeological specimens of domestic animals to estimate the bioavailable strontium isotope range of a region has its caveats as studies have shown that animals have been moved over substantial distances, were imported or used for transport (e.g., Viner et al. 2010; Stephan et al. 2012; Madgwick et al. 2017). The use of modern biosphere samples such as plants, water or small animals with limited home ranges such as snails or rodents was excluded due to the strong anthropogenic overprint (agricultural and building activities) in the areas where the cemeteries had been excavated. Therefore, archeological faunal enamel was the best proxy available for the estimation of the bioavailable strontium isotope range. In addition, a total of 22 human and faunal dentine samples from both cemeteries were analyzed for the validation of the bioavailable strontium isotope range at each site. Previous research has demonstrated that dentine $^{87}Sr/^{86}Sr$ values are often adjusted to the $^{87}Sr/^{86}Sr$ ratios of burial soil due to its high susceptibility of post-mortem strontium uptake (Budd et al. 2000; Chiaradia et al. 2003; Nehlich et al. 2009), which may lead to an underestimation of the bioavailable strontium isotope range. However, if the uptake by the dentine sample is not complete, this could result in intermediate values that lie between the strontium isotope value of enamel and the expected soil value (Montgomery et al. 2007).

Sample preparation and measurement

Teeth and eggshell samples were mechanically and ultrasonically cleaned and dried at 60 °C. Bulk enamel samples from human and animal teeth were removed by separating a small slice along the entire vertical extent of the tooth crown with a circular diamond-edged dental saw. Sequential samples from the animal teeth were obtained by cutting a small horizontal slice of enamel through the whole thickness of the enamel layer. The surfaces of the enamel and eggshell pieces were carefully abraded with a dental saw in order to remove contaminants. Dentine samples were taken from the primary crown dentine. The eggshell, enamel, and dentine pieces were finally cleaned ultrasonically in ultrapure water, dried down at room temperature and stored in clean containers until further preparation.

Radiogenic strontium isotope analysis was conducted at the GEOMAR Helmholtz Centre for Ocean Research Kiel. Samples were weighed into clean Teflon beakers and dissolved in 8 M HNO_3 and H_2O_2, evaporated to dryness, redissolved in 8 M HNO_3, and finally loaded on chromatographic columns filled with Eichrom strontium-specific resin. Strontium was separated from the sample matrix by washing the column with 8 M HNO_3 and eluted using 0.05 M HNO_3. After separation, the solutions were dried down, followed by heating with a mixture of concentrated HNO_3 and H_2O_2. Sr concentrations were determined by quadrupole ICP-MS (Agilent 7500cx). Radiogenic strontium isotope ratios ($^{87}Sr/^{86}Sr$) were determined by multicollector ICP-MS (AXIOM) and were normalized to a $^{86}Sr/^{88}Sr$ ratio of 0.1194. Samples were also corrected for session drift and the offset from the international standard NIST-SRM987. Measurements of the NIST-SRM987 standard gave an average $^{87}Sr/^{86}Sr$ values of 0.71026 ± 0.00003 (2σ, *n* = 20).

Oxygen and carbon isotopes were analyzed from the structural carbonate fraction of enamel bioapatite. Powdered enamel samples were treated with 0.1 M acetic acid to remove potential exogenous carbonate, rinsed, centrifuged, and finally freeze-dried. Stable isotope measurements were conducted at the Leibniz-Laboratory for Radiometric Dating and Isotope Research Kiel with a Finnigan MAT 253 isotope ratio mass spectrometer interfaced to a Kiel IV carbonate device. The results were expressed relative to the international VPDB standard. Analytical precision was better than ± 0.07‰ for $\delta^{18}O$ and ± 0.05‰ for $\delta^{13}C$.

Results and discussion

Bioavailable strontium isotope range

Results of the samples analyzed for the definition of the bioavailable strontium isotope range are reported in Table 2 and Fig. 2. At Eppstein, faunal enamel, eggshell as well as human and faunal dentine samples exhibit $^{87}Sr/^{86}Sr$ values between 0.7086 and 0.7116 (mean = 0.7095 ± 0.0005, 1σ; *n* = 31). The faunal enamel, eggshell as well as human and faunal dentine samples collected from the Bockenheim cemetery yielded a similar range between 0.7088 and 0.7111 (mean = 0.7096 ± 0.0004, 1σ; *n* = 23). By excluding two highly radiogenic $^{87}Sr/^{86}Sr$ values of 0.7116 and 0.7111 from a pig from Eppstein and a Bockenheim cattle which have been identified as outliers (more than 3SD from the mean) and obtained food from regions outside the Upper Rhine region, the strontium isotope range of all analyzed samples is between 0.7086 and 0.7104 (mean = 0.7095 ± 0.0003, 1σ; *n* = 54). This range is identical to the bioavailable strontium isotope range established by earlier studies (Price et al. 2001, 2003; Bentley et al. 2003, 2004; Bentley and Knipper 2005; Turck et al. 2012; Bickle and Whittle 2013; Schuh and Makarewicz 2016).

Human samples

Results of the strontium concentration measurements as well as the strontium, oxygen, and carbon isotope analyses of the 95 Eppstein and Bockenheim individuals are summarized in Table 1 and Figs. 3–6. Strontium concentrations of the Eppstein human enamel samples range between 54 and 326 ppm (mean = 144 ± 53, 1σ), while the Bockenheim samples exhibit a slightly smaller range between 44 and 231 ppm (mean = 110 ± 45, 1σ). Differences in diet or food obtained from different soils but also diagenetic contamination could be responsible for the different strontium concentrations between sites and periods. Strontium concentrations are enriched compared to enamel samples taken from the same individual indicating that the dentine samples have taken up strontium from the burial soil and that enamel samples are less susceptible to the uptake of labile strontium from the local soil (see Tables 1 and 2). Strontium concentrations from enamel and dentine are only available from a subset of individuals and other tests to evaluate diagenetic contamination have not been performed. Therefore, it cannot be excluded that some enamel samples are contaminated and have taken up the strontium isotope ratio of the burial soil which may result to the underestimation of individuals with childhood origins outside the Upper Rhine region.

Strontium isotope results

At Eppstein, the 65 human enamel samples exhibit a large strontium isotope range between 0.7082 and 0.7158 (mean = 0.7097 ± 0.0013, 1σ). A total of 12 individuals (~ 18.5%) have $^{87}Sr/^{86}Sr$ values outside the established biologically available strontium isotope range for the northern Upper Rhine region. Most of the individuals with non-local $^{87}Sr/^{86}Sr$ values belong to the earliest SD-periods (SD 2–3 = 50%; SD 4, 4–5 = 25%; SD 5, 5–6 = 14.3%; SD 6, 6–7 = 9.7%) which correspond to the time when Roman administrative structures have finally

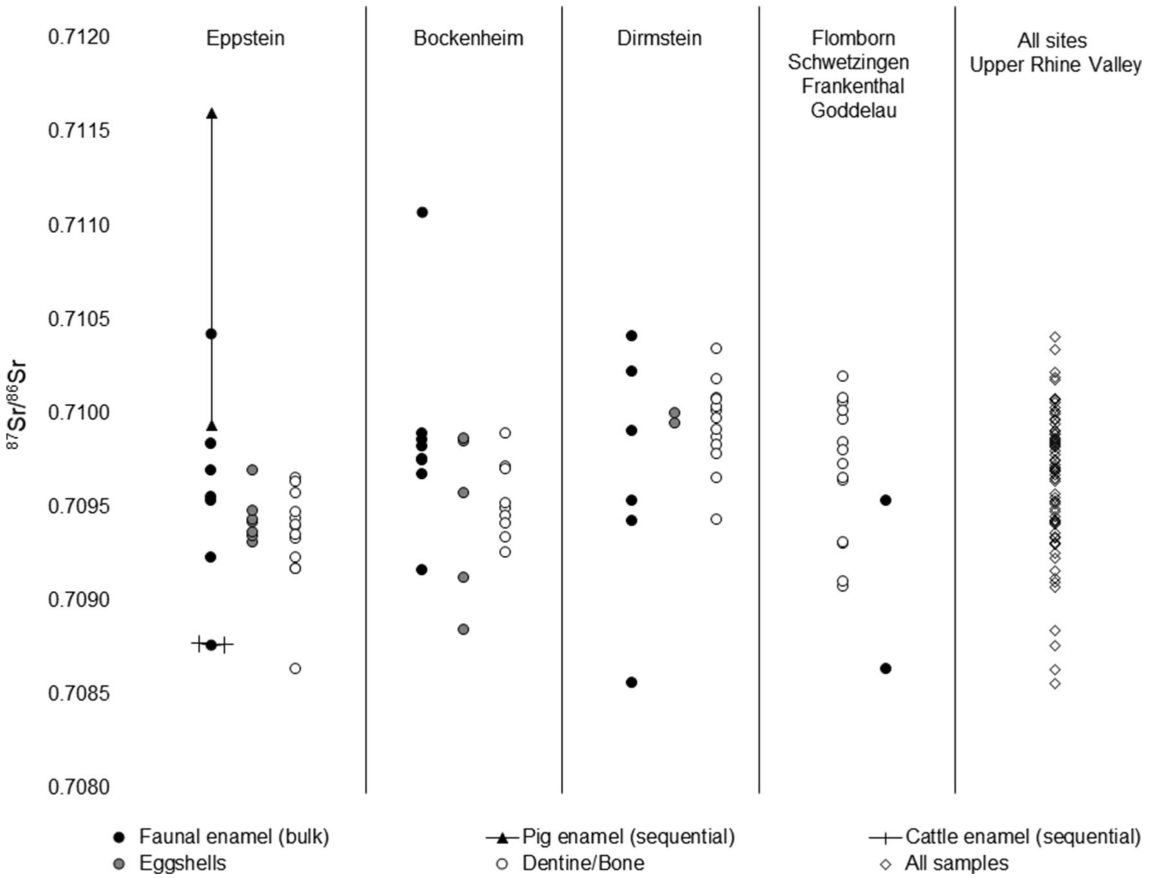

Fig. 2 Strontium isotope (^{87}Sr/^{86}Sr) results for faunal and human dentine samples, faunal tooth enamel and eggshells samples from several sites located in the Upper Rhine Valley

ceased and new power relations emerged. Furthermore, the first two SD-periods (SD-period 2–3 and 4/4–5) show also a wider variation in ^{87}Sr/^{86}Sr ratios compared to the last two SD-periods (SD 5/5–6 to 6/6–7) indicating that food was obtained

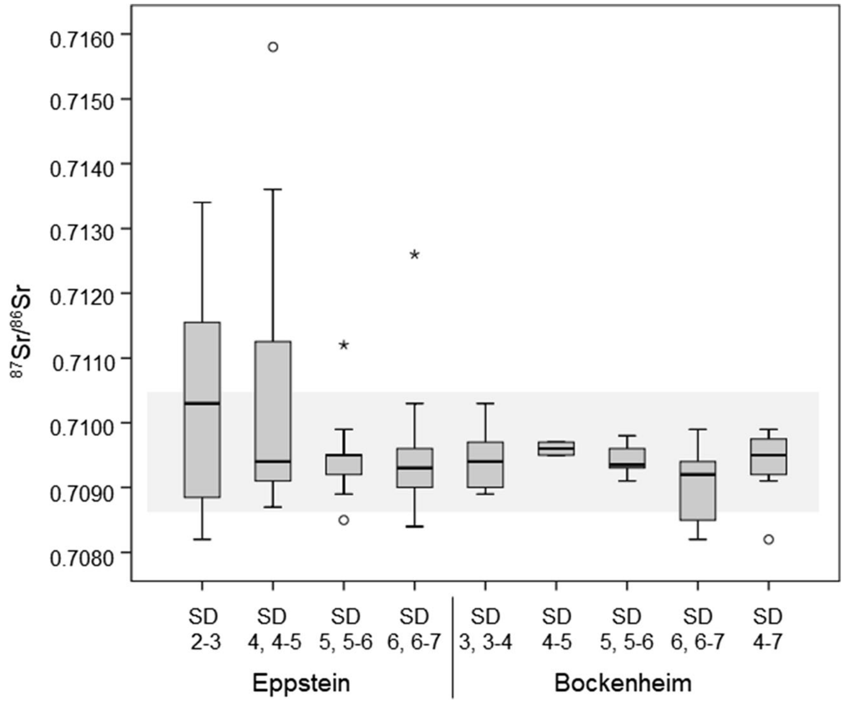

Fig. 3 Boxplots showing the strontium isotopic (^{87}Sr/^{86}Sr) results for the Eppstein and Bockenheim cemeteries sorted after SD period. The light gray bar marks the biologically available ^{87}Sr/^{86}Sr range in the Upper Rhine Valley based on faunal enamel samples

from diverse geological regions during childhood. Non-local individuals of all SD-periods are represented by both sexes (males: $n = 6$; females: $n = 4$; not determinable: $n = 2$) which suggests that women were not more mobile than men. This contrasts to other isotopic studies of late Roman and early Medieval cemeteries in Bavaria which indicate greater mobility among females (Hakenbeck et al. 2010; Schweissing and Grupe 2003). All investigated children ($n = 12$) exhibit a small $^{87}Sr/^{86}Sr$ range between 0.709 and 0.7097 (mean = 0.7095 ± 0.0002, 1σ) within the bioavailable strontium isotope range of the Upper Rhine.

The strontium isotope ratios of the 30 Bockenheim human enamel samples vary between 0.7082 and 0.7103 (mean = 0.7093 ± 0.0005, 1σ). The range of $^{87}Sr/^{86}Sr$ values is smaller (0.0021) compared to the Eppstein individuals (0.0076). Only four individuals (~ 13%) show $^{87}Sr/^{86}Sr$ ratios outside the established biologically available strontium isotope range. In contrast to the Eppstein cemetery, all of these individuals have $^{87}Sr/^{86}Sr$ values below the bioavailable strontium isotope range and do not belong to the founder community (SD-period 3) of this cemetery. Individuals of non-local childhood origins are represented by both sexes (males: $n = 2$; females: $n = 2$). The presence of a child (graves 396) among the non-locals with identical $^{87}Sr/^{86}Sr$ ratios may indicate the arrival of families as it is unlikely that children have traveled alone.

For both cemeteries, it has to be considered that the actual number of individuals with non-local childhood origin is likely to be underestimated as the bioavailable strontium isotope range of the Upper Rhine region is common for several regions throughout Europe (e.g., Gillmaier et al. 2009; Voerkelius et al. 2010; Vohberger 2011; Brettell et al. 2012a; Knipper et al. 2012; McManus et al. 2013).

Oxygen isotope results

Oxygen isotope values of the Eppstein human enamel samples average − 4.2 ± 0.7‰ (1σ, $n = 65$) and range between −5.6 and − 2.3‰. Teeth that form during the time when a child is nursed (deciduous and permanent first molars, permanent canine) are significantly enriched (−3.5 ± 0.5‰, 1σ, $n = 11$) in comparison to permanent premolars and second molars (−4.3 ± 0.7‰, 1σ, $n = 35$) which form after weaning (t test, $p =$ 0.000; only individuals with $^{87}Sr/^{86}Sr$ values within the bioavailable strontium isotope range are included). This is most likely the result of a breastfeeding effect as breast milk is isotopically enriched in ^{18}O compared to drinking water ingested by the mother (Wright and Schwarcz 1998). The $\delta^{18}O$ range of individuals with $^{87}Sr/^{86}Sr$ values within the bioavailable strontium isotope range for the Upper Rhine Valley (−5.6 to −2.3‰; −4.4 ± 0.7‰, 1σ, $n = 40$; early forming teeth excluded) is not different from those with $^{87}Sr/^{86}Sr$ values outside the bioavailable strontium isotope range (−5.6 to −2.7‰; −4.2 ± 0.8‰, 1σ, $n = 8$; early forming teeth excluded). When single chronological periods are considered, it is notable that $\delta^{18}O$ values of the earliest graves dating to the SD period 2–3 are lower than $\delta^{18}O$ values from individuals from later chronological periods but the difference is not significant (One-way ANOVA, $p = 0.28$; forming teeth are excluded). No outliers can be detected in Eppstein by using the outlier methods proposed by Lightfoot and O’Connell 2016 (1.5IQR and 3MAD$_{norm}$). Thus, at Eppstein, it is not possible to identify individuals that obtained drinking water from outside the Upper Rhine Valley during childhood on the basis of oxygen isotopes of tooth enamel.

Human enamel $\delta^{18}O$ values at Bockenheim range between −6.8 and − 2.8‰ with an average of −4.4 ± 0.9‰ (1σ, $n = 30$). Mean $\delta^{18}O$ values of permanent first molars (−4.2 ± 0.4‰, 1σ, $n = 6$) are enriched compared to later forming teeth of individuals with $^{87}Sr/^{86}Sr$ ratios within the bioavailable strontium isotope range (−4.4 ± 1.0‰, 1σ, $n = 20$), but the difference is not significant. The less pronounced difference may be either the result of the reduced number of samples compared to the Eppstein sample set or the presence of individuals of non-local origin that skew the oxygen isotopic range and are not detectable by means of strontium isotopes. The range of $\delta^{18}O$ values at Bockenheim does not change when individuals with non-local $^{87}Sr/^{86}Sr$ values and early forming teeth are excluded (range − 6.8 to −2.8‰; −4.4 ± 1.0‰, 1σ, n = 20). A single outlier with a $\delta^{18}O$ value of −6.8‰ (using 1.5IQR and 3MAD$_{norm}$) can be detected and it is likely that this adult woman of the Bockenheim founder community obtained drinking water from outside the Upper Rhine Valley during childhood. When this outlier is excluded, the range of $\delta^{18}O$ values at Bockenheim is between −5.7 and − 2.8‰ (−4.3 ± 0.8‰, 1σ, $n = 19$) and is almost identical to the $\delta^{18}O$ range of the Eppstein individuals (see above; early teeth and individuals outside the bioavailable strontium isotope range are excluded).

Overall, the similar range of $\delta^{18}O$ values at both cemeteries between individuals that have likely spent their childhood in the Upper Rhine region based on strontium isotopes and those that lived somewhere else as subadults indicates that oxygen isotopes of human tooth enamel from temperate region such as the Upper Rhine are rather unsuited to detect individuals with non-local childhood origins. This is probably due to the relatively small spatial and temporal oxygen isotope variability in northern Europe resulting in an overlap of local drinking water sources which will be additionally modified due to the mixing of different drinking water sources with different $\delta^{18}O$ values. These human modifications of $\delta^{18}O$ drinking water values, are probably also the reason for the relatively large oxygen isotopic ranges of 3.3 and 2.9‰ (excluding the Bockenheim outlier) at Eppstein and Bockenheim, respectively, which are larger than previous estimates of 2‰ (e.g. White et al. 2002, 2004) and confirm the results of a recent study stating that the interindividual variability of $\delta^{18}O$ values

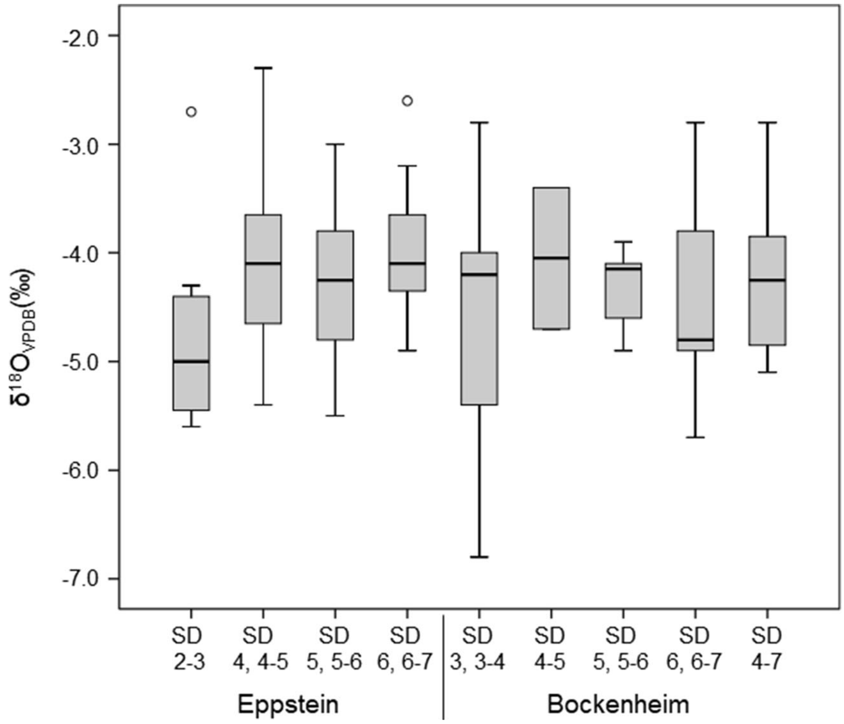

Fig. 4 Boxplots showing the oxygen isotopic ($\delta^{18}O$) results for the Eppstein and Bockenheim cemeteries sorted after SD period

within human communities are greater than 3‰ (Lightfoot and O'Connell 2016).

Carbon isotope results

The $\delta^{13}C$ values of the human enamel samples from Eppstein range between −14.9 and − 9.7‰ with a mean of −13.2 ± 0.9‰ (1σ). The range of $\delta^{13}C$ values is consistent with a terrestrial diet based on C_3 plants and/or animals feeding on them. However, the high ^{13}C values of some individuals may also indicate a small amount of C_4 plants such as millet or the consumption of animals that were fed with C_4 crop plants. In addition, variation in carbon isotope values can also indicate the consumption of plants from different environments. There

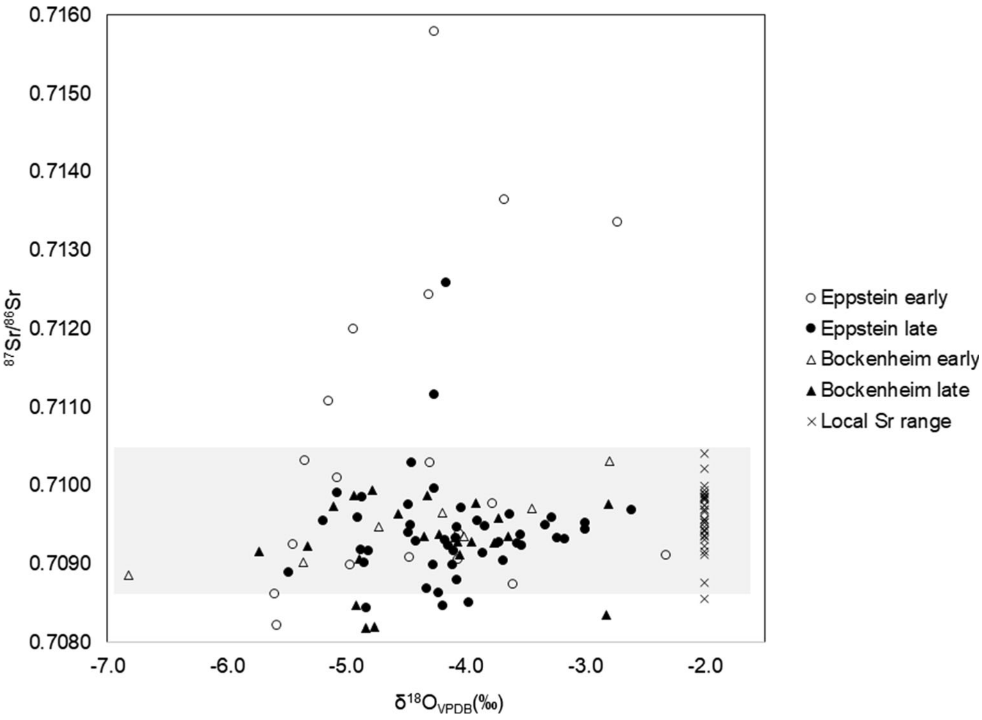

Fig. 5 Oxygen ($\delta^{18}O$) and strontium ($^{87}Sr/^{86}Sr$) isotope values of tooth enamel samples from the Eppstein and Bockenheim cemeteries sorted after earlier (SD 2, 3, 4–5) and later SD-periods (SD 5, 6, 6–7). The gray bar marks the biologically available strontium isotope range in the Upper Rhine Valley

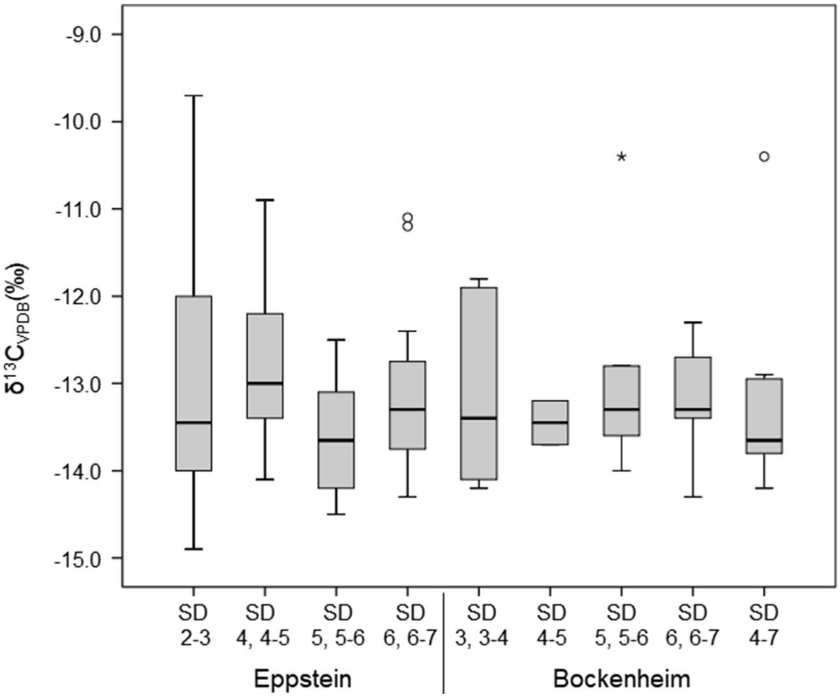

Fig. 6 Boxplots showing the carbon isotopic ($\delta^{13}C$) results for the Eppstein and Bockenheim cemeteries sorted after SD period

are no statistically significant differences in mean $\delta^{13}C$ values between chronological periods but it is notable that the individuals dating to the earliest periods (SD-period 2–3) exhibit higher variation in carbon isotope values which may indicate childhood dietary intake from diverse environments compared to later periods (Fig. 6). In addition, the lowest and highest $\delta^{13}C$ values of the Eppstein enamel samples belong to individuals with strontium isotope values outside the bioavailable range of the Upper Rhine Valley and thus, the carbon isotope values additionally support the consumption of childhood diets outside the region for these individuals.

The $\delta^{13}C$ values of the Bockenheim individuals are similar to those from Eppstein and range between −14.3 and − 10.4‰ with a mean of $-13.1 \pm 1.0‰$ (1σ) and reflect the consumption of a terrestrial C_3 diet with no or only minor contribution from C_4 vegetation or animals feeding on C_4 crop plants. Individuals with childhood diets outside the Upper Rhine Valley based on strontium isotope ratios do not have conspicuous $\delta^{13}C$ values. Only the individual with the outlying $\delta^{18}O$ value of −6.8‰ has a relatively high $\delta^{13}C$ values of −11.8‰ compared to the main bulk of Bockenheim samples underpinning a foreign childhood origin outside the Upper Rhine region.

Changing patterns of human residential mobility in the Upper Rhine Valley

The foundation period: late fifth and early sixth century AD

The multi-isotopic analysis of dental enamel from individuals dating to the late fifth and early sisxth century AD (SD-periods 2–3 = 460/480–510 AD) from the cemeteries of Eppstein and Bockenheim suggests that there was a high number of individuals with childhood origins from diverse regions outside the Upper Rhine that contributed to the foundation of the first few settlements and burial places during that time. It is conceivable that some of these individuals have already lived in the region when Roman political structures where still intact and may reflect former federates or mercenaries and their families (e.g., Wieczorek 1996a). In addition, some of them may also represent newcomers who took advantage of the unstable political situation and reconfigurations of territories and settled in the region. Concurrently, the presence of individuals with strontium isotope values identical to the established bioavailable strontium isotope range in the Upper Rhine region also indicates that locally born individuals contributed to the foundation of both cemeteries. However, these may also represent descendants of first-generation newcomers arriving in the region due to military services during the Late Roman period instead of reflecting an indigenous Roman provincial community. In addition, as stated above, it has to be considered that the bioavailable strontium isotope range of the Upper Rhine region is found in several regions throughout Europe, including possible areas of origin such as regions east of the Rhine, the Alemannic area, (Vohberger 2011), the North Sea coast and North German Plain (Gillmaier et al. 2009; Brettell et al., 2012a; McManus et al., 2013) as well as Middle Germany, the Thuringian settlement area (Haak et al. 2008; Knipper et al. 2012) and that individuals with putative local $^{87}Sr/^{86}Sr$ values are newcomers, too. The presence of individuals with childhood origins from regions with similar bioavailable strontium isotope ranges is likely indicated by the adult female of grave 486 with a local ^{87}Sr/^{86}Sr value but an outstanding low δ^{18}O value of −6.8‰. The existence of a high degree of overlap in human oxygen isotope values excludes the determination of the childhood origin of this woman (Lightfoot and O'Connell 2016).

Overall, the isotopic data of the Eppstein and Bockenheim cemeteries indicates the presence of a heterogenic settlement community at the turn from the fifth to the sixth century AD. This diversity of origins is also reflected in the material culture of the burial record in the Eppstein cemetery with cultural influences from e.g. southern (Alamannic) and Middle (Elbe-Germanic) Germany (Engels 2005, 2012). Bioavailable strontium isotope values consistent with the ^{87}Sr/^{86}Sr values of the non-local individuals are known for both regions (Bentley and Knipper 2005; Haak et al. 2008; Voerkelius et al. 2010; Oelze et al. 2011, 2012; Knipper et al. 2012) and an origin of some of the Eppstein cemetery founders from the Alemannic and Thuringian settlement areas cannot be excluded. From a geographical point of view, the nearest possible regions of childhood origin of the Eppstein founders with ^{87}Sr/^{86}Sr values above the bioavailable strontium isotope range are the Palatinate Forest and the Forest of Odes which build the eastern and western shoulder areas of the Rhine lowland (Bentley and Knipper 2005; Schuh and Makarewicz 2016). However, even if many of the individuals exhibit isotopic signatures outside the Upper Rhine Valley, this does not necessarily suggest that the foundation of these early cemeteries and rise of a new burial tradition in this area is exclusively connected to the arrival of newcomers. Instead, it may reflect the socio-cultural reorientation of rural communities of diverse backgrounds and origins living in this region as response to the socio-political dynamics and instability of this time (Brather 2004; Halsall 2007; Fehr 2008; James 2009).

The consolidation period: the first half of the sixth century AD

The presence of non-indigenous individuals in graves dating to the first half of the sixth century AD (SD-period 4, 4–5 = 510–530/550 AD) of the Eppstein cemetery, when the Upper Rhine region was finally under the control of the Merovingian Franks, may reflect a controlled settlement processes used by the new authoritative administration as a political strategy to stabilize the power relations in the region (Wieczorek 1996a, b; Grünewald and Koch 2009). The placing of hand-made pottery with stylistic similarities to pottery from Middle Germany (Thuringian type pottery) in some of these graves (graves 35, 428, 433), also found in graves of other cemeteries in the region and adjacent areas, have been seen as evidence for the arrival of non-Frankish settlers from these regions (Wieczorek 1989, 1996a, b; Koch 2000; Grünewald and Koch 2009; Engels 2012). From the three Eppstein newcomers with ^{87}Sr/^{86}Sr values above the bioavailable strontium isotope range of the Upper Rhine region, only the adult male of grave 35 contained Thuringian style pottery, while the others, a female and a male of adult age, revealed no unusual grave goods. The other individuals with Thuringian style pottery, a child (grave 428) and a female adult individual (grave 433) from Eppstein as well as male adult (graves 454) from the Bockenheim cemetery have ^{87}Sr/^{86}Sr values identical to the Upper Rhine range. The reasons for this discordance are manifold. First of all, it cannot be excluded that individuals with Thuringian style pottery and ^{87}Sr/^{86}Sr values identical to the Upper Rhine region originated from the Thuringian settlement area, located between the Thuringian Forest and the Elbe River, as regions in this area exhibit similar bioavailable strontium isotope ranges as the Upper Rhine (e.g., Knipper et al. 2012; Maurer et al. 2012). Furthermore, the graves with Thuringian style pottery may represent second-generation individuals (e.g., the child of grave 428) that have been furnished with heirlooms of their families. Funerary feasting and gift giving were also of importance during this period (Effros 2003; Halsall 2007) and the food and drinking containers may have been provided by other, non-local families. Thus, the presence of Thuringian type objects including handmade pottery or brooches outside the supposed core area of the Thuringian kingdom, located between the Thuringian Forest and the Elbe River, does not necessarily imply the movement of persons. Instead, it has also been suggested that the presence of Thuringian type material culture in the Upper Rhine region may be read in social terms and may symbolize that Thuringian power was drawn into this area which represented the fringes of Merovingian power during that time (Halsall 2007). For example, some people may have turned to the Thuringian kingdom in competition with those who sided with the growing Frankish power (Halsall 2007). While the Upper Rhine region may have been a competition area between the Thuringians and the Merovingians during the first decades of the sixth century AD, the Thuringian kingdom was finally defeated by the Merovingians in the early 530s AD (Halsall 2007; Ewig 2012). However, the presence of newcomers does not necessarily indicate a political motivated settlement as stated above. Alternatively, this may reflect residential changes due to exogamous marriage pattern, family ties or other personal connections and socio-economic reasons.

Time of change: the sixth century AD

The shift in the composition of cemeteries to include largely individuals from the Upper Rhine region as well as newcomers from regions with ^{87}Sr/^{86}Sr values below the established biologically available strontium isotopic range during the sixth century AD (SD-periods 5–6/7: 530–580/600 AD) may indicate a change in the socio-political situation, possibly the formation of new strategic alliances. Most of the individuals of the Bockenheim and Eppstein cemeteries with strontium isotope values identical to the Upper Rhine region are most likely the descendants of the settlers which are buried in the graves of the preceding periods. The only two individuals, a juvenile and a senile male, of the Eppstein cemetery with more radiogenic ^{87}Sr/^{86}Sr values (graves 62, 405) may reflect individual residential mobility, or alternatively, they may present late arrivals from the same regions as some of the non-locals from the late fifth/early sixth century AD with more radiogenic strontium isotopic signatures. The latter assumption may be supported by the fact that the graves of the two newcomers are located in the southern burial area together with graves from earlier periods. The presence of newcomers with strontium isotope values below the bioavailable strontium isotope range present in sixth century AD graves of the Eppstein and Bockenheim cemeteries compared to earlier periods may indicate that the network of contacts and relationships in the Upper Rhine region have changed in the course of the sixth century AD. Similar to the conclusions drawn on the Thuringian type cultural material, the presence of hand-made pottery with stylistic similarities to hand-made vessels from the North Sea area in several sixth century AD graves of the Upper Rhine region including Eppstein (e.g. graves 189, 192) and adjacent areas have been interpreted as reflecting the presence of settlers from the North Sea region in order to consolidate Merovingian power and as a political reward to loyal followers and military services (Gross 1999; Koch 2000; Stauch 2004; Heather 2010; Leithäuser 2011; Engels 2012). Instead of representing individual mobility, the presence of a non-local child as well as similar ^{87}Sr/^{86}Sr values among the newcomers of the Bockenheim cemetery may indicate the arrival of families in the Upper Rhine Valley during the sixth century AD.

Multiple regions in Europe share similar ranges of bioavailable strontium isotopes (e.g., Voerkelius et al. 2010, Fig.1) and thus, it not possible to allocate the childhood origin of the newcomers in the Eppstein and Bockenheim cemeteries. However, studies indicate that biologically available strontium isotope values of the North Sea region fall in the range between 0.709 and 0.710 or even higher and overlap with those of the Upper Rhine region (Gillmaier et al. 2009; Price et al. 2015; Kootker et al. 2016). This implies that childhood origins from the North Sea region for the sixth century AD newcomers with ^{87}Sr/^{86}Sr values below 0.7086 are unlikely. In addition, this means that individuals that have spent their childhood in the North Sea region will be not detected based on their strontium isotopic signature and that the number of possible newcomers will be underestimated.

A similar discordance between possible area of origin and material culture is known from the cemetery of Dirmstein which is located between the sites of Bockenheim and Eppstein. A small group of graves oriented along a south-north axis as well as hand-made pottery of Anglo-Saxon type has been associated with the arrival of a foreign family from the North Sea area (Leithäuser 2011). However, highly radiogenic ^{87}Sr/^{86}Sr values above the established biologically available strontium isotopic range of the Upper Rhine region of some of these individuals exclude an origin from the North Sea area for those newcomers (Schuh and Makarewicz 2016).

Conclusions

The isotopic analysis of human remains from the Upper Rhine Valley has provided important insights in the dynamics of mobility during times of socio-political changes between the late fifth and sixth century AD. The strontium isotopic analyses of human tooth enamel and, to a lesser extent oxygen and carbon isotopes, have revealed that the cemeteries were founded by heterogenic communities including individuals of diverse origins as well as those with childhood origins in the Upper Rhine region. Even if the complex situation of this border region during the fifth century AD makes the interpretation more complicated, we argue that the rise and spread of the new burial practice was connected to a socio-cultural reorientation of heterogenic settlement communities living at the Upper Rhine as a result of the instability of this transformative period. The change of mobility pattern in the course of the sixth century AD with a higher number of newcomers with childhood origins from regions with less radiogenic strontium isotopic signatures indicate that the network of contacts and relationships has changed compared to earlier periods. The origins of these newcomers with less radiogenic strontium isotopes remain unknown but the North Sea area, as supposed by the archeological record, can be excluded. The degree to which the presence of the newcomers is reflective of a controlled political motivated settlement of the Merovingian authority in order to consolidate power or as reward for military service remains, however, somewhat speculative. In addition, the presence of hand-made pottery and other foreign burial rites or objects cannot be used as an unambiguous evidence for the presence of non-local individuals as several other interpretations are possible. Furthermore, it needs to be stressed that this study is only a snapshot from two out of numerous Early Medieval cemeteries in the region. The investigation of further burials from other cemeteries may show different mobility patterns compared to these cemeteries. Nevertheless, this study has shown that stable isotopes, especially strontium isotopes, can provide important information for a more nuanced understanding of the dynamic transformation processes taking place between Late Antiquity and the Early Middle Ages.

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References

AlQahtani SJ, Hector MP, Liversidge HM (2010) Brief communication: the London atlas of human tooth development and eruption. Am J Phys Anthropol 142:481–490. https://doi.org/10.1002/ajpa.21258

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

Ambrose SH, Norr L (1993) Experimental evidence for the relationship of the carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate. In: Lambert JB, Grupe G (eds) Prehistoric human bone. Springer, Berlin/Heidelberg, pp 1–37

Ament H (2003) Reihengräberfriedhöfe. In: Reallexikon der Germanischen Altertumskunde 24. Walter de Gruyter, Berlin/New York, pp 362–365

Ament H (1992) Romanen an Rhein und Mosel im frühen Mittelalter. Archäologische Bemühungen um ihren Nachweis. Bonn Jahrb 192: 261–271

Bakker L (2012) Rädchenverzierte Argonnen-Terra-Sigillata aus dem Kastell Bad Kreuznach. In: Jung P, Schücker N (eds) Utere felix vivas: Festschrift für Jürgen Oldenstein. Habelt, Bonn, pp 1–22

Beard BL, Johnson CM (2000) Strontium isotope composition of skeletal material can determine the birth place and geographic mobility of humans and animals. J Forensic Sci 45:1049–1061

Bentley RA (2006) Strontium isotopes from the earth to the archaeological skeleton: a review. J Archaeol Method Theory 13:135–187

Bentley RA, Knipper C (2005) Geographical patterns in biologically available strontium, carbon and oxygen isotope signatures in prehistoric Sw Germany. Archaeometry 47:629–644. https://doi.org/10.1111/j.1475-4754.2005.00223.x

Bentley RA, Krause R, Price TD, Kaufmann B (2003) Human mobility at the early Neolithic settlement of Vaihingen, Germany: evidence from strontium isotope analysis. Archaeometry 45:471–486. https://doi.org/10.1111/1475-4754.00122

Bentley RA, Price TD, Stephan E (2004) Determining the 'local' ^{87}Sr/^{86}Sr range for archaeological skeletons: a case study from Neolithic Europe. J Archaeol Sci 31:365–375. https://doi.org/10.1016/j.jas.2003.09.003

Bernhard H (1981) Die spätrömischen Burgi von Bad Dürkheim-Ungstein und Eisenberg. Eine Untersuchung zum spätantiken Siedlungswesen in ausgewählten Teilgebieten der Pfalz. Saalburg Jahrb 37:23–85

Bernhard H (1982) Germanische Funde der Spätantike zwischen Straßburg und Mainz. Saalburg Jahrb 38:72–109

Bernhard H (1997) Die Merowingerzeit in der Pfalz. Bemerkungen zum Übergang von der Spätantike zum frühen Mittelalter und zum Stand der Forschung. Mitteilungen Hist Ver Pfalz 95:7–106

Bernhard H (2006) Die spätantiken Burgi von Eisenberg und Ungstein in der Pfalz. In: Haupt P, Jung P (eds) Alzey Geschichte der Stadt, Band 3: Alzey und Umgebung in römischer Zeit. Verlag der Rheinhessischen Druckwerkstätte, Alzey, pp 136–141

Bernhard H (2007) Das Oberrheingebiet zwischen Straßburg und Bingen im 5. Jh.: historische Überlieferung und archäologischer Befund. In: Attila und die Hunnen. Begleitband zur Ausstellung im historischen Museum der Pfalz, Theiss Verlag, Stuttgart, pp 117–125

Bernhard H (2008) Die Römerzeit in der nördlichen Vorderpfalz und im Nordpfälzer Bergland. In: West- und Süddeutscher Verband für Altertumsforschung e.V., Generaldirektion Kulturelles Erbe Rheinland-Pfalz, Direktion Archäologie, Speyer Museum der Stadt Worms in Andreasstift, Präsidium der Deutschen Verbände für Archäologie e.V. (eds) Archäologie zwischen Donnersberg und Worms: Ausflüge in ein altes Kulturland. Schnell und Steiner, Regensburg, pp 97–105

Bickle P, Whittle A (2013) The first farmers of Central Europe: diversity in LBK lifeways. Oxbow Books, Oakville

Bowen GJ, Wilkinson B (2002) Spatial distribution of δ^{18}O in meteoric precipitation. Geology 30:315–318

Brather S (2004) Ethnische Interpretationen in der frühgeschichtlichen Archäologie. Geschichte, Grundlagen und Alternativen. Ergänzungsband zum Reallexikon der Germanischen Altertumskunde 42. Walter de Gruyter, Berlin/New York

Brettell R, Evans J, Marzinzik S, Lamb A, Montgomery J (2012a) 'Impious easterners', can oxygen and strontium isotopes serve as indicators of provenance in early medieval European cemetery populations? Eur J Archaeol 15:117–145

Brettell R, Montgomery J, Evans J (2012b) Brewing and stewing: the effect of culturally mediated behaviour on the oxygen isotope composition of ingested fluids and the implications for human provenance studies. J Anal At Spectrom 27:778–785. https://doi.org/10.1039/C2JA10335D

Bryant DJ, Froelich PN (1995) A model of oxygen isotope fractionation in body water of large mammals. Geochim Cosmochim Acta 59: 4523–4537. https://doi.org/10.1016/0016-7037(95)00250-4

Budd P, Montgomery J, Barreiro B, Thomas RG (2000) Differential diagenesis of strontium in archaeological human dental tissues. Appl Geochem 15:687–694

Capo RC, Stewart BW, Chadwick OA (1998) Strontium isotopes as tracers of ecosystem processes: theory and methods. Geoderma 82:197–225

Chenery C, Eckardt H, Müldner G (2011) Cosmopolitan Catterick? Isotopic evidence for population mobility on Rome's northern frontier. J Archaeol Sci 38:1525–1536. https://doi.org/10.1016/j.jas.2011.02.018

Chenery C, Müldner G, Evans J, Eckardt H, Lewis M (2010) Strontium and stable isotope evidence for diet and mobility in Roman Gloucester, UK. J Archaeol Sci 37:150–163. https://doi.org/10.1016/j.jas.2009.09.025

Chiaradia M, Gallay A, Todt W (2003) Different contamination styles of prehistoric human teeth at a Swiss necropolis (Sion, Valais) inferred from lead and strontium isotopes. Appl Geochem 18:353–370

Cleary SE (2013) The Roman West, AD 200–500: an archaeological study. Cambridge University Press, Cambridge

Dansgaard W (1964) Stable isotopes in precipitation. Tellus 16:436–468. https://doi.org/10.1111/j.2153-3490.1964.tb00181.x

Daux V, Lécuyer C, Héran M-A, Amiot R, Simon L, Fourel F, Martineau F, Lynnerup N, Reychler H, Escarguel G (2008) Oxygen isotope fractionation between human phosphate and water revisited. J Hum Evol 55:1138–1147. https://doi.org/10.1016/j.jhevol.2008.06.006

Dupras TL, Tocheri MW (2007) Reconstructing infant weaning histories at Roman period Kellis, Egypt using stable isotope analysis of dentition. Am J Phys Anthropol 134:63–74. https://doi.org/10.1002/ajpa.20639

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

Engels C (2005) Das merowingerzeitliche Gräberfeld Eppstein, Stadt Frankenthal (Pfalz): Eine lokale Studie zu den archäologischen Kulturmodellen von F. Siegmund. Germania 83:309–335

Engels C (2008) Die merowingischen Grabfunde von Mainz-Finthen. Mainzer Archäologische Schriften 8. Generaldirektion Kulturelles Erbe Rheinland-Pfalz, Mainz

Engels C (2012) Das merowingische Gräberfeld Eppstein, Stadt Frankenthal (Pfalz). Internationale Archäologie 121. Verlag Marie Leidorf, Rahden/Westfalen

Ericson JE (1985) Strontium isotope characterization in the study of prehistoric human ecology. J Hum Evol 14:503–514. https://doi.org/10.1016/S0047-2484(85)80029-4

Evans JA, Chenery CA, Montgomery J (2012) A summary of strontium and oxygen isotope variation in archaeological human tooth enamel excavated from Britain. J Anal At Spectrom 27:754–764. https://doi.org/10.1039/C2JA10362A

Ewig E (2012) Die Merowinger und das Frankenreich. Kohlhammer, Stuttgart

Farquhar GD, Ehleringer JR, Hubick KT (1989) Carbon isotope discrimination and photosynthesis. Annu Rev Plant Physiol Plant Mol Biol 40:503–537. https://doi.org/10.1146/annurev.pp.40.060189.002443

Faure G, Mensing TM (2005) Isotopes: principles and applications. Wiley, New York

Fehr H (2015) The transformation into the Early Middle Ages (fourth to eighth Centuries). In: James S, Krmnicek S (eds) The oxford handbook of the archaeology of Roman Germany. https://doi.org/10.1093/oxfordhb/9780199665730.013.19

Fehr H (2008) Germanische Einwanderung oder kulturelle Neuorientierung. Zu den Anfängen des Reihengräberhorizontes. In: Brather S (ed) Zwischen Spätantike und Frühmittelalter. Archäologie des 4. bis 7. Jahrhunderts im Westen. Ergänzungsband zum Reallexikon der Germanischen Altertumskunde 57. Walter de Gruyter, Berlin/New York, pp 67–102

Fehr H (2010) Germanen und Romanen im Merowingerreich. Frühgeschichtliche Archäologie zwischen Wissenschaft und Zeitgeschehen. Ergänzungsband zum Reallexikon der Germanischen Altertumskunde 68. Walter de Gruyter, Berlin/New York

Förstel H, Hützen H (1983) Oxygen isotope ratios in German groundwater. Nature 304:614–616. https://doi.org/10.1038/304614a0

Gat JR (1996) Oxygen and hydrogen isotopes in the hydrologic cycle. Annu Rev Earth Planet Sci 24:225–262. https://doi.org/10.1146/annurev.earth.24.1.225

Gillmaier N, Kronseder C, Grupe G, von Carnap-Bornheim C, Söllner F, Schweissing M (2009) The strontium isotope project of the International Sachsensymposion. In: Bencke N (ed) Beiträge zur Archäozoologie und Prähistorischen Anthropologie VII. Beier und Beran, Langenweißbach, pp 133–142

Graustein WC (1989) ^{87}Sr/^{86}Sr ratios measure the sources and flow of strontium in terrestrial ecosystems. In: Rundel PW, Ehleringer JR, Nagy KA (eds) Stable isotopes in ecological research. Springer, Berlin/Heidelberg, pp 491–512

Gross U (1999) Funde von Keramik aus dem Nordseeküstenraum im fränkischen Reich. In: Both F, Aouni H (eds) Über allen Fronten. Nordwestdeutschland zwischen Augustus und Karl dem Großen. Archäologische Mitteilungen aus Nordwestdeutschland. Beiheft 26. Isensee, Oldenburg, pp 91–112

Grünewald M, Hahn E (2006) Zwischen Varusschlacht und Völkerwanderung. Kunstverlag Fink, Lindenberg/Allgäu

Grünewald M, Koch U (2009) Zwischen Römerzeit und Karl dem Großen. Band I-II. Die frühmittelalterlichen Grabfunde aus Worms und Rheinhessen im Museum der Stadt Worms im Andreasstift. Kunstverlag Fink, Lindenberg/Allgäu

Grünewald M, Wieczorek A (2012) Unter dem Pflaster von Worms: Archäologie in der Stadt. Kunstverlag Fink, Lindenberg/Allgäu

Haak W, Brandt G, de Jong HN, Meyer C, Ganslmeier R, Heyd V, Hawkesworth C, Pike AWG, Meller H, Alt KW (2008) Ancient DNA, strontium isotopes, and osteological analyses shed light on social and kinship organization of the later stone age. Proc Natl Acad Sci 105:18226–18231. https://doi.org/10.1073/pnas.0807592105

Hakenbeck S, McManus E, Geisler H, Grupe G, O'Connell T (2010) Diet and mobility in early medieval Bavaria: a study of carbon and nitrogen stable isotopes. Am J Phys Anthropol 143:235–249. https://doi.org/10.1002/ajpa.21309

Halsall G (1995) Early medieval cemeteries: an introduction to burial archaeology in the post-Roman west. Cruithne Press, Glasgow

Halsall G (2007) Barbarian migrations and the Roman west, 376–568. Cambridge University Press, Cambridge

Heather P (2010) Empires and barbarians: the fall of Rome and the birth of Europe. Oxford University Press

Heaton THE (1999) Spatial, species, and temporal variations in the ^{13}C/^{12}C ratios of C_3 plants: implications for Palaeodiet studies. J Archaeol Sci 26:637–649. https://doi.org/10.1006/jasc.1998.0381

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

Horton TW, Defliese WF, Tripati AK, Oze C (2016) Evaporation induced ^{18}O and ^{13}C enrichment in lake systems: a global perspective on hydrologic balance effects. Quat Sci Rev 131:365–379. https://doi.org/10.1016/j.quascirev.2015.06.030

IAEA/WMO (2018). Global network of isotopes in precipitation. The GNIP database. Accessible at: http://www.iaea.org/water. Accessed 26 March 2018

James E (1988) The franks. Blackwell, Oxford

James E (2009) Europe's barbarians AD 200–600. Routledge, New York

Jim S, Ambrose SH, Evershed RP (2004) Stable carbon isotopic evidence for differences in the dietary origin of bone cholesterol, collagen and apatite: implications for their use in palaeodietary reconstruction. Geochim Cosmochim Acta 68:61–72. https://doi.org/10.1016/S0016-7037(03)00216-3

Knipper C, Maurer A-F, Peters D, Meyer C, Brauns M, Galer SJG, von Freeden U, Schöne B, Meller H, Alt KW (2012) Mobility in Thuringia or mobile Thuringians: a strontium isotope study from early medieval Central Germany. In: Kaiser E, Burger J, Schier W (eds) Population dynamics in prehistory and early history. New approaches using stable isotopes and genetics. Walter de Gruyter, Berlin/Boston, pp 287–310

Knöchlein R (2011) Ad urbem, quam Mogontiacum veteres appellarunt. Vom Legionslager Mainz zu den Anfängen der Stadt des Mittelalters. In: Konrad M, Witschel C (eds) Römische Legionslager in den Rhein- und Donauprovinzen - Nuclei spätantik-frühmittelalterlichen Lebens? Abhandlungen der Bayerischen Akademie der Wissenschaften N.F.138, Verlag C.H.Beck, München, pp 231–261

Knudson KJ, Williams HM, Buikstra JE, Tomczak PD, Gordon GW, Anbar AD (2010) Introducing $\delta^{88/86}$Sr analysis in archaeology: a demonstration of the utility of strontium isotope fractionation in paleodietary studies. J Archaeol Sci 37:2352–2364. https://doi.org/10.1016/j.jas.2010.04.009

Koch U (2000) Der Beginn fränkischer Besiedlung im Rhein-Neckar-Raum: Gräber von Mannheim-Vogelstang und Mannheim-Straßenheim. In: Gesellschaft der Freunde Mannheims (ed) Mannheimer Geschichtsblätter N.F. 7, Thorbecke Verlag, Sigmaringen, pp 57–106

Koch U (2001) Das alamannisch-fränkische Gräberfeld bei Pleidelsheim. Theiss, Stuttgart

Koch U (2013) Wer lag neben wem? Eine Analyse des Gräberfeldplanes von Mainz-Hechtsheim. In: Ludowici B (ed) Individual and Individuality? Approaches towards an Archaeology of Personhood in the First Millennium AD. Neu Studien zur Sachsenforschung 4. Theiss, Stuttgart, pp 123–136

Kohn MJ (1996) Predicting animal δ^{18}O: accounting for diet and physiological adaptation. Geochim Cosmochim Acta 60:4811–4829. https://doi.org/10.1016/S0016-7037(96)00240-2

Konrad M, Witschel C (eds) (2011) Römische Legionslager in den Rhein- und Donauprovinzen - Nuclei spätantik-frühmittelalterlichen Lebens? Abhandlungen der Bayerischen Akademie der Wissenschaften N.F.138, Verlag C.H.Beck, München

Kootker LM, van Lanen RJ, Kars H, Davies GR (2016) Strontium isoscapes in the Netherlands. Spatial variations in ^{87}Sr/^{86}Sr as a proxy for palaeomobility. J Archaeol Sci Rep 6:1–13. https://doi.org/10.1016/j.jasrep.2016.01.015

Krueger HW, Sullivan CH (1984) Models for carbon isotope fractionation between diet and bone. In: Turnland JF Johnson PE (eds) Stable Isotopes in Nutrition, ACS Symposium Series 258, American Chemical Society, Washington D.C., pp. 205-222

Laffoon JE, Rojas RV, Hofman CL (2013) Oxygen and carbon isotope analysis of human dental enamel from the Caribbean: implications for investigating individual origins. Archaeometry 55:742–765. https://doi.org/10.1111/j.1475-4754.2012.00698.x

Landesamt für Geologie und Bergbau (2005) Geologie von Rheinland-Pfalz. Schweizerbart, Stuttgart

Lange M (2004) Das fränkische Gräberfeld von Flomborn in Rheinhessen. Kunstverlag Fink, Lindenberg/Allgäu

Lee-Thorp JA, Sealy JC, van der Merwe NJ (1989) Stable carbon isotope ratio differences between bone collagen and bone apatite, and their relationship to diet. J Archaeol Sci 16:585–599. https://doi.org/10.1016/0305-4403(89)90024-1

Leithäuser U (2011) Das merowingerzeitliche Gräberfeld Dirmstein, Kreis Bad Dürkheim. Habelt, Bonn

Lewis J, Pike AWG, Coath CD, Evershed RP (2017) Strontium concentration, radiogenic (^{87}Sr/^{86}Sr) and stable (δ^{88}Sr) strontium isotope systematics in a controlled feeding study. STAR Sci Technol Archaeol Res 3:53–65. https://doi.org/10.1080/20548923.2017.1303124

Lightfoot E, O'Connell TC (2016) On the use of biomineral oxygen isotope data to identify human migrants in the archaeological record: intra-sample variation, statistical methods and geographical considerations. PLoS One 11:e0153850. https://doi.org/10.1371/journal.pone.0153850

Lin GP, Rau YH, Chen YF et al (2003) Measurements of δD and δ^{18}O stable isotope ratios in milk. J Food Sci 68:2192–2195. https://doi.org/10.1111/j.1365-2621.2003.tb05745.x

Longinelli A (1984) Oxygen isotopes in mammal bone phosphate: a new tool for paleohydrological and paleoclimatological research? Geochim Cosmochim Acta 48:385–390. https://doi.org/10.1016/0016-7037(84)90259-X

Luz B, Kolodny Y (1985) Oxygen isotope variations in phosphate of biogenic apatites, IV. Mammal teeth and bones. Earth Planet Sci Lett 75:29–36. https://doi.org/10.1016/0012-821X(85)90047-0

Luz B, Kolodny Y, Horowitz M (1984) Fractionation of oxygen isotopes between mammalian bone-phosphate and environmental drinking water. Geochim Cosmochim Acta 48:1689–1693. https://doi.org/10.1016/0016-7037(84)90338-7

Madgwick R, Lewis J, Grimes V, Guest P (2017) On the hoof: exploring the supply of animals to the Roman legionary fortress at Caerleon using strontium (^{87}Sr/^{86}Sr) isotope analysis. Archaeol Anthropol Sci:1–13. https://doi.org/10.1007/s12520-017-0539-9

Maurer A-F, Galer SJG, Knipper C, Beierlein L, Nunn EV, Peters D, Tütken T, Alt KW, Schöne BR (2012) Bioavailable ^{87}Sr/^{86}Sr in different environmental samples — effects of anthropogenic contamination and implications for isoscapes in past migration studies. Sci Total Environ 433:216–229. https://doi.org/10.1016/j.scitotenv.2012.06.046

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

Montgomery J (2010) Passports from the past: investigating human dispersals using strontium isotope analysis of tooth enamel. Ann Hum Biol 37:325–346. https://doi.org/10.3109/03014461003649297

Montgomery J, Evans JA, Cooper RE (2007) Resolving archaeological populations with Sr-isotope mixing models. Appl Geochem 22:1502–1514

Müldner G, Chenery C, Eckardt H (2011) The 'Headless Romans': multi-isotope investigations of an unusual burial ground from Roman Britain. J Archaeol Sci 38:280–290. https://doi.org/10.1016/j.jas.2010.09.003

Nehlich O, Montgomery J, Evans J, Schade-Lindig S, Pichler SL, Richards MP, Alt KW (2009) Mobility or migration: a case study from the Neolithic settlement of Nieder-Mörlen (Hessen, Germany). J Archaeol Sci 36:1791–1799. https://doi.org/10.1016/j.jas.2009.04.008

Oldenstein J (1992) Kastell Alzey: archäologische Untersuchungen im spätrömischen Lager und Studien zur Grenzverteidigung im Mainzer Dukat. Habilitation dissertation, Universität Mainz

Oelze VM, Koch JK, Kupke K, Nehlich O, Zäuner S, Wahl J, Weise SM, Rieckhoff S, Richards MP (2012) Multi-isotopic analysis reveals individual mobility and diet at the early iron age monumental tumulus of magdalenenberg, Germany. Am J Phys Anthropol 148:406–421. https://doi.org/10.1002/ajpa.22063

Oelze VM, Nehlich O, Richards MP (2011) 'There's no place like home'—no isotopic evidence for mobility at the early bronze age cemetery of Singen, Germany. Archaeometry 54:752–778. https://doi.org/10.1111/j.1475-4754.2011.00644.x

O'Leary MH (1988) Carbon isotopes in photosynthesis. BioScience 38:328–336. https://doi.org/10.2307/1310735

Ortega LA, Guede I, Zuluaga MC, Alonso-Olazabal A, Murelaga X, Niso J, Loza M, Quirós Castillo JA (2013) Strontium isotopes of human remains from the San Martín de Dulantzi graveyard (Alegría-Dulantzi, Álava) and population mobility in the early middle ages. Quat Int 303:54–63. https://doi.org/10.1016/j.quaint.2013.02.008

Passey BH, Robinson TF, Ayliffe LK, Cerling TE, Sponheimer M, Dearing MD, Roeder BL, Ehleringer JR (2005) Carbon isotope fractionation between diet, breath CO_2, and bioapatite in different mammals. J Archaeol Sci 32:1459–1470. https://doi.org/10.1016/j.jas.2005.03.015

Pohl W (2002) Die Völkerwanderung: Eroberung und Integration. Kohlhammer, Stuttgart

Price TD, Bentley RA, Lüning J, Gronenborn D, Wahl J (2001) Prehistoric human migration in the Linearbandkeramik of Central Europe. Antiquity 75:593–603

Price TD, Meiggs D, Weber M-J, Pike-Tay A (2015) The migration of Late Pleistocene reindeer: isotopic evidence from northern Europe. Archaeol Anthropol Sci 9:1–24. https://doi.org/10.1007/s12520-015-0290-z

Price TD, Wahl J, Knipper C et al (2003) Das bandkeramische Gräberfeld vom "Viesenhäuser Hof" bei Stuttgart-Mühlhausen. Neue Untersuchungsergebnisse zum Migrationsverhalten im frühen Neolithikum. Fundberichte aus Baden-Württ 27:23–58

Prowse TL, Schwarcz HP, Garnsey P, Knyf M, Macchiarelli R, Bondioli L (2007) Isotopic evidence for age-related immigration to imperial Rome. Am J Phys Anthropol 132:510–519. https://doi.org/10.1002/ajpa.20541

Riemer E (2008) Das merowingerzeitliche Gräberfeld von Kleinbockenheim, Bockenheim an der Weinstraße. In: West- und Süddeutscher Verband für Altertumsforschung e.V., Generaldirektion Kulturelles Erbe Rheinland-Pfalz, Direktion Archäologie, Speyer Museum der Stadt Worms in Andreasstift, Präsidium der Deutschen Verbände für Archäologie e.V. (eds) Archäologie zwischen Donnersberg und Worms: Ausflüge in ein altes Kulturland. Schnell und Steiner, Regensburg, pp 151–154

Roberts SB, Coward WA, Ewing G et al (1988) Effect of weaning on accuracy of doubly labeled water method in infants. Am J Phys 254:R622–R627

Rozanski K, Araguás-Araguás L, Gonfiantini R (1993) Isotopic patterns in modern global precipitation. In: Swart PK, Lohmann KC, McKenzie J, Savin S (eds) Continental isotope indicators of climate, Geophysical monograph series 78. American Geophysical Union, Washington, D.C, pp 1–36

Schreg R (2006) Dorfgenese in Südwestdeutschland: das Renninger Becken im Mittelalter. Materialhefte zur Archäologie in Baden-Württemberg 76. Theiss, Stuttgart

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

Schweissing MM, Grupe G (2003) Stable strontium isotopes in human teeth and bone: a key to migration events of the late Roman period in Bavaria. J Archaeol Sci 30:1373–1383. https://doi.org/10.1016/S0305-4403(03)00025-6

Slovak NM, Paytan A (2012) Applications of Sr isotopes in archaeology. In: Baskaran M (ed) Handbook of environmental isotope geochemistry. Springer, Berlin/Heidelberg, pp 743–768

Sponheimer M, Lee-Thorp JA (1999) Oxygen isotopes in enamel carbonate and their ecological significance. J Archaeol Sci 26:723–728. https://doi.org/10.1006/jasc.1998.0388

Stauch E (2017) On the validation of archaeological and physical-anthropological mobility indicators. The migration history of an Early Medieval settlement community. In: Scharl S, Gehlen KS zur PA (eds) Mobility in prehistoric sedentary societies. Verlag Marie Leidorf, Rahden/Westfalen, pp 229–261

Stauch E (2004) Wenigumstadt – Ein Bestattungsplatz der Völkerwanderungszeit und des frühen Mittelalters im nördlichen Odenwaldvorland. Habelt, Bonn

Stephan E, Knipper C, Schatz K, Price TD, Hegner E (2012) Strontium isotopes in faunal remains: evidence of the strategies for land use at the Iron Age site Eberdingen-Hochdorf (Baden-Württemberg, Germany). In: Kaiser E, Burger J, Schier W (eds) Population dynamics in prehistory and early history. New approaches using stable isotopes and genetics. Walter de Gruyter, Berlin/Boston, pp 265–286

Tieszen LL (1991) Natural variations in the carbon isotope values of plants: implications for archaeology, ecology, and paleoecology. J Archaeol Sci 18:227–248. https://doi.org/10.1016/0305-4403(91)90063-U

Tieszen LL, Fagre T (1993) Effect of diet quality and composition on the isotopic composition of respiratory CO_2, bone collagen, bioapatite, and soft tissues. In: Lambert JB, Grupe G (eds) Prehistoric human bone. Springer, Berlin/Heidelberg, pp 121–155

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

Turck R, Kober B, Kontny J, et al (2012) “Widely travelled people” at Herxheim? Sr isotopes as indicators of mobility. In: Kaiser E, Burger J, Schier W (eds) Population dynamics in prehistory and early history. New approaches using stable isotopes and genetics. Walter de Gruyter, Berlin/Boston, pp 149–163

Viner S, Evans J, Albarella U, Parker Pearson M (2010) Cattle mobility in prehistoric Britain: strontium isotope analysis of cattle teeth from Durrington Walls (Wiltshire, Britain). J Archaeol Sci 37:2812–2820. https://doi.org/10.1016/j.jas.2010.06.017

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

Vohberger M (2011) Lokal oder Eingewandert? Interpretationsmöglichkeiten und Grenzen lokaler Strontium- und Sauerstoffisotopensignaturen am Beispiel einer Altgrabung in Wenigumstadt. Dissertation, Ludwig-Maximilians-Universität München

White CD, Spence MW, Longstaffe FJ, Stuart-Williams H, Law KR (2002) Geographic identities of the sacrificial victims from the feathered serpent pyramid, Teotihuacan: implications for the nature of state power. Lat Am Antiq 13:217–236. https://doi.org/10.2307/971915

White CD, Spence MW, Longstaffe FJ, Law KR (2004) Demography and ethnic continuity in the Tlailotlacan enclave of Teotihuacan: the evidence from stable oxygen isotopes. J Anthropol Archaeol 23: 385–403. https://doi.org/10.1016/j.jaa.2004.08.002

Wieczorek A (1996a) Die Ausbreitung der fränkischen Herrschaft in den Rheinlanden vor und seit Chlodwig I. In: Wieczorek A, Périn P, von Welck K, Menghin W (eds) Die Franken - Wegbereiter Europas. Vor 1500 Jahren: König Chlodwig und seine Erben. Verlag Philipp von Zabern, Mainz, pp 241–260

Wieczorek A (1996b) Identität und Integration - Zur Bevölkerungspolitik der Merowinger nach archäologischen Quellen. In: Wieczorek A, Périn P, von Welck K, Menghin W (eds) Die Franken - Wegbereiter Europas. Vor 1500 Jahren: König Chlodwig und seine Erben. Verlag Philipp von Zabern, Mainz, pp 346–357

Wieczorek A (1989) Mitteldeutsche Siedler bei der fränkischen Landnahme in Rheinhessen. Eine Untersuchung zur handgeformten Keramik Rheinhessens. In: Gerlich A (ed) Das Dorf am Mittelrhein. Fünftes Alzeyer Kolloquium. Geschichtliche Landeskunde 30. Steiner, Wiesbaden, pp 11–101

Wood IN (1994) The Merovingian kingdoms, 450–751. Longman, London

Wright LE, Schwarcz HP (1998) Stable carbon and oxygen isotopes in human tooth enamel: identifying breastfeeding and weaning in prehistory. Am J Phys Anthropol 106:1–18. https://doi.org/10.1002/(SICI)1096-8644(199805)106:1<1::AID-AJPA1>3.0.CO;2-W