Multi-Isotopic Analysis Reveals Individual Mobility and Diet at the Early Iron Age Monumental Tumulus of Magdalenenberg, Germany

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KEY WORDS strontium; oxygen; sulfur; carbon; nitrogen

ABSTRACT For the Early Iron Age western Hallstatt culture, which includes the site of Magdalenenberg in southwest Germany, it has been proposed that people were mobile and maintained far reaching social and trading networks throughout Europe. We tested this hypothesis by analyzing multiple isotopes (strontium, oxygen, sulfur, carbon, and nitrogen) of the preserved skeletons from the Magdalenenberg elite cemetery to determine diets and to look for evidence of mobility. The analysis of carbon, nitrogen, and sulfur isotope ratios in collagen of humans (n = 50) and associated domestic fauna (n = 10) indicates a terrestrial-based diet. There was a heterogeneous range of isotope values in both strontium (0.70725 to 0.71923, n = 76) and oxygen (13.4‰ to 18.5‰, n = 78) measured in tooth enamel. Although many of the individuals had values consistent with being from Hallstatt culture sites within southwest Germany, some individuals likely originated from further afield. Possible areas include the Alps of Switzerland and Austria or even locations in Italy. Our study strongly supports the assumption of far reaching social and economic networks in the western Hallstatt culture. Am J Phys Anthropol 148:406–421, 2012.

The Early Iron Age on the central European continent is dominated by the Hallstatt Culture, which dates from approximately 800 to 450 BC and is commonly divided into a western and an eastern group (Wells, 2002, 2008). Numerous well-known burial mounds and "princely sites" (Fürstensitze) of the western Hallstatt culture can be found in the region between present-day eastern France and Austria. Prominent examples are the tomb of the "Princess of Vix" and her princely site of Mont Lassois (Burgundy, France), as well as the cemetery and salt mine of Hallstatt in Austria (mapped on Fig. 1A). These sites are not only good examples of the economic wealth of these communities but also of far reaching connections with other cultures and industries. These connections are demonstrated by the presence of exotic objects like Mediterranean pottery and the enormous bronze vessel at Vix or the Baltic amber and African ivory found at Hallstatt (Wells, 2008). Generally, the prominent cemeteries in the Late Hallstatt period (Ha D) also indicate a socially stratified society, with a presumed social elite being buried besides wealthy grave goods within the "princely" cemetery. One example for such an elite burial community is the Magdalenenberg tumulus, located south of the town Villingen-Schwenningen at the eastern edge of the Black Forest of southwest Germany. This monumental tumulus, which is ~100 m wide, contained a central wooden chamber with a "princely burial" (Grave 1) which was first excavated in 1890. A complete excavation was subsequently conducted in the 1970s by Konrad Spindler and his team. During this intensive campaign, a total of 126 secondary graves were recovered from the tumulus, containing 144 burials (Fig. 2). The burials were concentrically organized around the central grave. It is likely that some high status graves close to the center were destroyed due to erosion, historic grave robbing, and the excavations in the late 19th century (Spindler, 2004). Also noteworthy was that the burial orientation with the skull toward southeast, separating the mound into two distinct spheres (Fig. 2). Although the soil composition of the mound and the specific water logged conditions within the tumulus led to the poor preservation of many of the human skeletons, the preservation of other organic material is excel-

Grant sponsor: Federal Ministry for Education and Science, Germany (BMBF), Förderkennzeichen 01UA0811B. Grant sponsor: Max Planck Society.

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Received 4 October 2011; accepted 24 February 2012

DOI 10.1002/ajpa.22063
Published online 3 May 2012 in Wiley Online Library (wileyonlinelibrary.com).

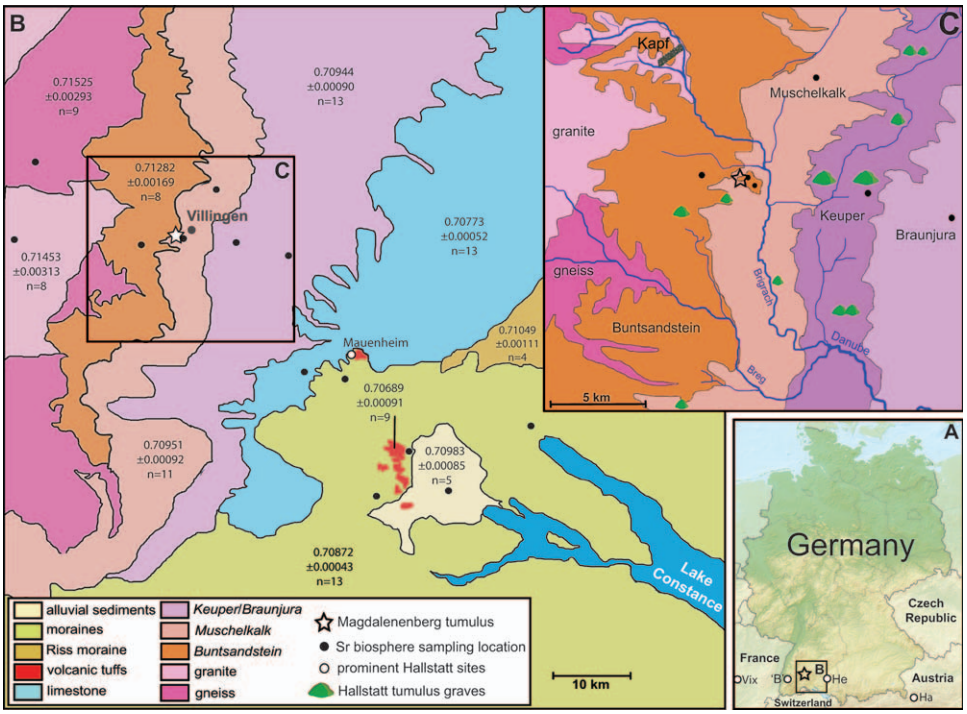

Fig. 1. **A:** Map of Germany and bordering countries ("B" = "Bürgle," He =Heuneburg, Ha = Hallstatt). **B:** Simplified geological map of the study region between Lake Constance (SW) and the Black Forest (NE). Sampling sites and mean values for bioavailable $^{87}Sr/^{86}Sr$ are mapped. **C:** Detailed geological map containing the study site, surrounding Hallstatt cemeteries and the "Kapf" hillfort.

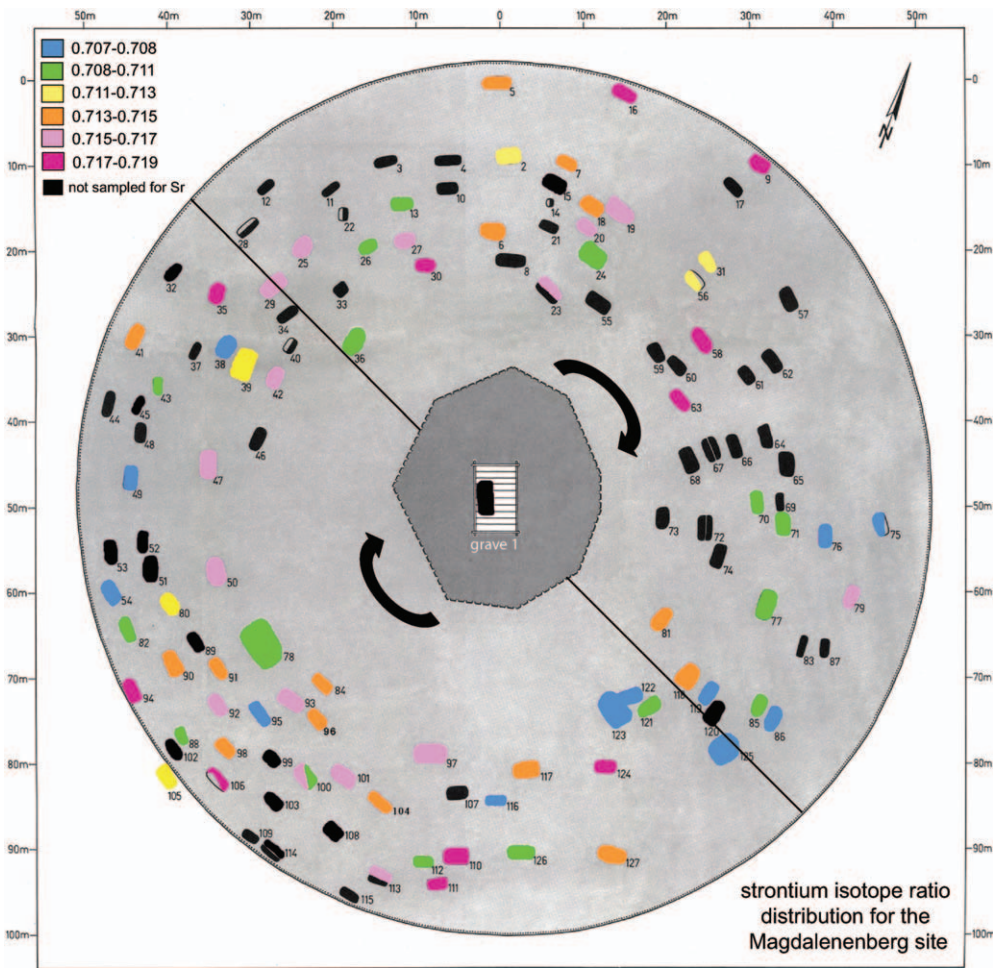

Fig. 2. The Magdalenenberg tumulus with individual grave numbers (modified after Spindler, 2004) and the strontium isotope range highlighted for each sampled grave. The arrows and black line within the cemetery specify the two distinct hemispheres (clockwise and counter-clockwise) of burial orientation around the central prince grave.

lent at the Magdalenenberg site. Wooden construction planks, wagon wheels, furniture, woven baskets, and even hazelnuts and scraps of fur from the prince's grave inventory are preserved. The exact construction date of the central chamber in 616 BC was determined through dendrochronological analysis and falls within the proposed relative chronology of Ha D1 (Billamboz and Neyes, 1999; Rieckhoff, 2001).

Although the high social and economic status of the central burial is clear, many questions arose regarding the construction of the mound itself and the people who constructed it. The only nearby Hallstatt settlement is the "Kapf" hillfort, located on a small plateau ~5 km northwest of Magdalenenberg. The hillfort encompassed an area of ~0.04 km^2 and yielded a few Hallstatt settlement artifacts, mainly ceramics. Occupation of the site was short (Ha D1) and it seems unlikely that the prince himself resided on the "Kapf," as it was rather modest compared with the "Mont Lassois" and other "princely" sites (Hübener, 1972). Also, the presence of other less wealthy late Hallstatt culture burial sites close to Magdalenenberg (see Fig. 1C) have led to the assumption that only a "privileged" proportion of the population was allowed to bury their dead next to the prince (Spindler, 1971), raising questions of the origin of their wealth and the source and sphere of influence and power of the "prince" himself.

The Magdalenenberg burial community may have had considerable contact with distant cultures and peoples in other parts of Europe. Exotic grave goods were found in several graves. For example, Grave 65 contained a belt hook of "Acebuchal" type, which is typically found in the Iron Age cemeteries in northern Spain (Spindler, 1972). Another example is Grave 81, where an elderly man was buried with a drago fibula, a fibula style typically found in northern Italy and the eastern Hallstatt culture range (Schmid-Sikimić, 2002). In Grave 96, a lanzett-shaped belt hook was found, which is usually associated with the Golasecca culture in southern Switzerland and northern Italy. An elderly female in Grave 97 was wearing an impressive amber bead necklace (Spindler, 1976), with the source of raw material being the Baltic Sea and the artifact's style similar to that found in northern Italy. In Grave 122, pieces of coral from the Adriatic Sea were recovered (Schmid-Sikimić, 2002). Besides indicating individual status, these various exotic artifacts led to speculations on the presence of immigrant individuals bringing their traditional clothing and material culture to Magdalenenberg. Another explanation could be far reaching exchange networks throughout the western Hallstatt culture and beyond, possibly including individual mobility by trading or "diplomatic presentation" (Wells, 2002).

The aim of this study was to test the hypothesis of mobility and the assumed presence of immigrants at the Magdalenenberg site through the application of a multiple isotope analysis of the Early Iron Age human remains. By using various isotope systems (C, N, S, Sr, and O), we also seek to constrain the possible region of provenance of any foreign (nonlocal) individuals to gain insights into the social catchment area of the elite burial population of Magdalenenberg. Although the strontium and oxygen isotope ratios in tooth enamel reflect childhood location, the isotopes of sulfur, carbon, and nitrogen measured in bone collagen should correspond to the location and diet of later life stages and potentially indicate individuals who lived near the coast.

Stable and radiogenic isotope analyses are powerful tools in archaeology and are used to infer human life history, particularly diet (carbon, nitrogen, and sulfur), and mobility/migration (oxygen, strontium, and sulfur). Carbon and nitrogen stable isotopes, expressed as the ratio of the heavy versus the light isotopes ($^{13}C/^{12}C = \delta^{13}C$, $^{15}N/^{14}N = \delta^{15}N$), have been used since the late 1970s to reconstruct the protein component of archaeological human and animal diets from bone collagen (Vogel and van der Merwe, 1977; Lee-Thorp, 2008). Carbon and nitrogen isotope ratios fractionate during physiological processes within an organism, resulting in increasing (more positive) values with each step in the food chain (Minagawa and Wada, 1984; Ambrose, 1993; Hedges and Reynard, 2007). The $\delta^{13}C$ system can be used as a biochemical marker for the different photosynthetic pathways (C_3, C_4, and CAM) because the differences in the $\delta^{13}C$ values of plants that use different types of photosynthesis are passed on to the body tissues of the consumer (Farquhar et al., 1989; Tieszen, 1991). The C_3 pathway is dominant in temperate Europe and millet is the only relevant C_4 plant introduced since the Neolithic period (Rösch, 1998). However, the importance of millet in diets has been shown for several Iron Age sites in Central Europe (Murray and Schoeninger, 1988; Le Huray and Schutkowski, 2005; Le Huray et al., 2006). Moreover, the $\delta^{13}C$ system corresponds to forest cover and has the potential to detect differences between species feeding in open versus forested environments (van der Merwe and Medina, 1991; Drucker et al., 2008). Finally, the combination of $\delta^{13}C$ and $\delta^{15}N$ is especially useful in differentiating between terrestrial, freshwater and marine diets (Schoeninger et al., 1983; Schoeninger and DeNiro, 1984). Iron Age human isotope data produced so far indicate that even in coastal sites human diets were largely terrestrial (Jay and Richards, 2007).

Recently, sulfur isotope measurement of bone collagen ($\delta^{34}S$) has demonstrated promise for differentiating marine, freshwater, and terrestrial dietary sources in archaeological material (Giesemann et al., 1994; Craig et al., 2006; Nehlich et al., 2010). Anaerobic bacteria fractionate sulfur isotopes (Hoefs, 1997; Canfield, 2001) and cause strong variations in $\delta^{34}S$ values in freshwater and terrestrial ecosystems, ranging from −22‰ to +20‰ (Peterson and Fry, 1987). Organisms living in marine ecosystems have $\delta^{34}S$ values close to +20‰, whereas purely terrestrial mammals have values lower than +10‰ (Richards et al., 2003). The isotopic composition of sulfur in a given locality is mainly determined by the geological substrate and its formation history (Sakai, 1957). Therefore, the $\delta^{34}S$ values of food sources from different regions may vary and be reflected in consumers' body tissues. Sulfur isotopes should therefore be useful for the study of human mobility (Vika, 2009). The analysis of $\delta^{34}S$ in bone collagen is particularly useful in cases where teeth cannot be sampled for strontium or oxygen isotope analysis. Moreover, the combination of isotope analyses in collagen and tooth enamel can provide information on different episodes in individual life history. Bone collagen is a living tissue which remodels constantly during life and, depending on the anatomical position in the skeleton, may not completely turn over its isotopic composition in a lifetime (Wild et al., 2000; Geyh, 2001). The isotopic ratios of carbon, nitrogen, and sulfur measured in collagen reflect the diet in the last decades of an individual's life, while the strontium and oxygen isotope ratios measured in tooth enamel provide

information on the earliest life stages (infancy to adolescence) when the enamel of the individual teeth is formed (Humphrey et al., 2008). Combining the analysis of both tissues holds the potential to explore the approximate timing of mobility and migration events.

The analysis of strontium isotopes ($^{87}Sr/^{86}Sr$) in skeletal tissue is an established method of detecting mobility and migration in humans and animals (Bentley et al., 2002; Price et al., 2004; Stephan, 2009). The $^{87}Sr/^{86}Sr$ signature of a given location is determined by the age of the underlying bedrock and its Rb content, as the radiogenic isotope ^{87}Sr forms through radioactive decay of ^{87}Rb. Older geological formations like granite and gneiss have higher $^{87}Sr/^{86}Sr$ values than younger volcanic rocks. Unlike other isotope systems, strontium enters the ecosystem without fractionation (Faure and Powell, 1972; Graustein, 1989). Thus, a geologically determined signature is incorporated into the elemental composition of hard tissues of the body, substituting for calcium (Ericson, 1985). The analysis of tooth enamel has shown to be the most reliable approach in archaeology, because enamel is largely resistant to diagenetic alteration in the burial environment (Budd et al., 2000; Hoppe et al., 2003). In areas with a heterogeneous geological substrate, the analysis of the $^{87}Sr/^{86}Sr$ ratio in teeth can provide information on the geological provenance of an individual during enamel formation. Provenance studies using $^{87}Sr/^{86}Sr$ strongly depend on environmental background studies to assess the local bioavailable $^{87}Sr/^{86}Sr$ signature, which may substantially differ from direct measurements of geological material (Price et al., 2002; Evans et al., 2010). To construct an isotopic baseline for this study as well as for a previous study on Bronze Age material, a range of modern plants and snails ($n = 96$) was collected in unfertilized forest patches on the different geological units between Lake Constance and the Black Forest in southwest Germany (Fig. 1B) (Oelze et al., 2011a). From this detailed mapping, as well as from previous analysis of $^{87}Sr/^{86}Sr$ in prehistoric animal teeth (Bentley and Knipper, 2005), we can characterize the terrain surrounding the Magdalenenberg site as geologically diverse. The Magdalenenberg tumulus is situated on a small outcrop of Buntsandstein within an area of Muschelkalk. To the west, the terrain is dominated by Buntsandstein and the metamorphic bedrocks of the Black Forest, which have the highest $^{87}Sr/^{86}Sr$ signatures in the region. To the south-east, the terrain consists of different geological layers with lower $^{87}Sr/^{86}Sr$ signatures, and finally the moraines, tuffs, and alluvial sediments around Lake Constance have the lowest values in the study region (see Fig. 1B). Therefore, the heterogeneous geological conditions around the Magdalenenberg site are ideal for identifying variation in $^{87}Sr/^{86}Sr$ ratios, and thus reconstructing human mobility within that region.

Stable oxygen isotope analysis ($^{18}O/^{16}O = \delta^{18}O$) can also be used as geographic indicators, as oxygen isotope values reflect geographic and climatic parameters during bone and tooth mineral formation (White et al., 1998). Although strontium is ingested mainly through food, the $\delta^{18}O$ ratio of body water and skeletal tissue relates to the $\delta^{18}O$ in drinking water (Longinelli and Peretti Padalino, 1980). The dynamics of $\delta^{18}O$ fractionation are largely driven by the water cycle (e.g., evaporation, condensation, and precipitation). The oxygen isotopic composition of meteoric water is thereby related to temperature, altitude, and the distance to the coastline. This relationship normally results in a geographic gradient, but the oxygen isotopic composition of human material will depend on the source of the water, which may be local (e.g., wells) or distantly sourced (e.g., glacial fed rivers) (Longinelli, 1984). For southwest Germany, proxies for $\delta^{18}O$ variation have been developed using data from modern precipitation and archaeological fauna (Bentley and Knipper, 2005). $\delta^{18}O$ is most reliably measured in tooth enamel, which is largely resistant to diagenesis and isotopic contamination in the burial environment (Iacumin et al., 1996 and references therein). However, for the analysis of $\delta^{18}O$, differences in tooth formation times have to be taken into account, as a significant fractionation of $\delta^{18}O$ can be observed during breastfeeding (Wright and Schwarcz, 1998, White et al., 2000).

MATERIALS

The ages and biological sex of the human skeletal materials were determined in the 1970s by Gallay (1977). A reanalysis of all human skeletons from the site was conducted by S.Z. and J.W., using more recently developed methods (see Appendix 1 for details of the methodology). Table 1 presents the results of the physical anthropological analysis of the human remains. Most, but not all, age and sex determinations match the estimations by Gallay (1977), and the remains of five additional individuals were identified. The most interesting characteristic of the sample is the underrepresentation of infants, children, and adolescents. The frequency of adults to subadults is 82.5% to 17.5%, which is not typical for archaeological populations (Langenscheidt, 1985; Czarnetzki, 1995). Hence, it is likely that subadult individuals were buried at a different location or in a different manner. Including the few assessable subadult individuals, we identified 36 males (and probable males) and 38 females (and probable females). The remaining skeletons were indeterminable, due to the lack of diagnostic anatomical parts. The average age of death is 38 years in males and 35 years in females.

For isotope analyses, all individuals from the Magdalenenberg population with preserved skeletal remains were sampled ($n = 90$). The number of individuals with preserved teeth ($n = 80$) was substantially higher than the number of individuals with preserved bones ($n = 58$). For 48 individuals, both a tooth and a bone sample could be obtained (Table 1). In many skeletons, bone and dentine were almost completely degraded and gone, leaving only the often well preserved enamel crown. The poor preservation at the site is the result of the different types of clays, causing an accumulation of moisture in the hill and revealing pH levels of 4.4 to 5.5 (Müller, 1977). The high humidity and low pH levels may have favored the demineralization of the bone mineral fraction and hydrolysis of the organic matter (Grupe, 2007). For the analysis of the stable isotope ratios of carbon, nitrogen, and sulfur, ~1 g of preserved bone was cut from preferentially long bones or ribs. In several cases where there was no, or poor, preservation of these anatomical parts, the skull was sampled. For the analysis of strontium and oxygen, tooth enamel was sampled. As the enamel of different teeth form during different ages in childhood, we preferentially sampled the posterior teeth formed after infancy to avoid effects of breastfeeding on the oxygen isotope values (Wright and Schwarcz, 1998, White et al., 2000). Incisors, canines, and the first

TABLE 1. Results of anthropological and isotopic analysis for all human individuals from the Magdalenenberg site, sorted by grave number (infants I = 0–5 years; infants II = 6–12 years; mature = > 50 years; m = male (m) = probable male; m? = insecure male; f = female; (f) = probable female; f? = unsecure female; ? = sex undetermined; # = measurement error)

Grave	Bone	Age	Sex	$\delta^{13}C$‰	$\delta^{15}N$‰	%C	%N	C:N	%coll	$\delta^{34}S$‰	%S	C:S	N:S	Tooth	Enamel $^{87}Sr/^{86}Sr$	Sr (ppm)	$\delta^{18}O$ SMOW	$\delta^{18}O_{dw}$
1	Longbone	Adult	m	−19.3	10.7	43.9	15.6	3.3	8.4									
2		Adolescent-adult	f?											Molar	0.71261	105	15.9	−10.6
5	Skull	Adolescent-adult	(f)	−19.9	9.7	41.0	15.4	3.1	1.5	2.6	0.2	517	167	Incisive	0.71411	43	15.3	−11.9
6		Infants II	?											M1/M2	0.71558	30	16.5	−9.3
7	Longbone	Adult	?	−19.8	8.3	43.0	15.8	3.2	2.4	4.0	0.2	524	165	M3	0.71490	37	15.2	−12.2
9		Infants I	f?											M1	0.71718	27	#	#
13		Adult-mature	(f)											Canine	0.70971	89	15.8	−10.8
15		Adult	f?											Premolar	#	#	16.2	−9.9
16		Adult	f?											Molar	0.71828	31	16.1	−10.2
18		Adolescent-adult	?											Premolar	0.71345	48	16.4	−9.6
19		Adolescent-adult	f?											M2	0.71561	56	16.1	−10.1
20		Adolescent-adult	?											Molar	0.71508	74	16.4	−9.7
23I		Adult	(f)											M2?	0.71685	68	15.2	−12.2
24		?	f?											Molar	0.71000	89	15.9	−10.6
25		Adolescent-adult	f?											Molar	0.71579	53	16.2	−9.9
26		Infants I	?											M2	0.70970	22	15.7	−11.0
27		Infants II	m?											Premolar	0.71527	38	16.1	−10.3
29		Adult	f											M2	0.71517	45	14.9	−12.7
30		Adolescent-adult	?											M2	0.71735	117	17.2	−7.8
31	Skull	Adult	m?	−20.9	9.2	29.3	9.6	3.6	0.2					M1	0.71299	52	15.8	−10.9
32	Longbone	Adult	f	−19.5	8.4	41.0	15.4	3.1	3.0	4.1	0.2	562	181					
35		Infants I	(m)											M1/M2	0.71777	47	16.2	−9.9
36		Adult/mature	?											Canine	0.70913	86	16.1	−10.1
38		Adult	?											M3	0.70894	47	14.4	−13.8
39	Longbone	Adult	?	−20.0	10.8	32.9	11.2	3.4	0.3					Premolar	0.71197	49	#	#
41		Adult	?											Premolar	0.71387	45	16.3	−9.9
42		Infants II	m?											M2	0.71598	50	16.8	−8.6
43		Adult-mature	f?											M3?	0.71006	51	14.4	−13.8
45	Longbone	Adult	m	−18.9	10.9	43.5	16.5	3.1	6.6	3.5	0.2	545	177					
47	Skull	Adult	(f)	−19.6	9.5	37.5	13.9	3.2	1.2	3.6	0.2	516	164	Premolar	0.71599	23	17.1	−8.1
49		Adult	?											Canine	0.70725	98	16.9	−8.5
50	Longbone	Adult	m?	−19.7	9.9	41.2	15.5	3.1	2.0	3.9	0.2	554	179	M2	0.71525	46	16.1	−10.2
51	Longbone	Mature	m	−19.8	9.5	41.8	14.9	3.3	1.8	1.1	0.2	540	165					
52	Longbone	Infants II	?	−20.1	7.9	43.0	16.1	3.1	5.4	5.1	0.2	498	160	M1	#	#	16.3	−9.8
53	Longbone	Adult	f	−19.4	9.3	42.9	16.1	3.1	4.7	5.8	0.2	536	173					
54	Longbone	Mature	m	−19.2	10.9	42.6	16.1	3.1	5.1	3.5	0.2	563	182	M2	0.70896	44	15.7	−11.0
56	Longbone	Adult	f	−19.9	9.6	40.5	15.1	3.1	0.0					Canine	0.71180	32	16.6	−9.2
58		Adult	?											M2	0.71729	45	15.3	−11.9
63		Adolescent	(m)											M1	0.71778	66	15.8	−10.8
70		Adult	?											M2?	0.70932	96	15.9	−10.6
71		Adult	(f)											Premolar	0.70914	36	15.7	−11.1
75		Adult	?											M1/M2	0.70815	64	15.3	−12.0
76	Skull	Adult	(f)	−19.9	9.6	40.5	15.1	3.1	1.8	5.1	0.2	543	173	Canine	0.70872	41	14.3	−14.2
77	Longbone	Adult	(m)											M2	0.70928	69	13.9	−15.1
78/I	Longbone	Adult	f	−19.5	9.6	35.3	11.8	3.5	0.5					M3	0.70969	55	15.6	−11.3
79		Infants II	?											M3	0.71531	45	16.3	−9.9
80	Longbone	Adult	m											M3	0.71225	42	14.9	−12.7

(continued)

TABLE 1. (Continued)

Grave	Bone	Age	Sex	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C:N	%coll	$\delta^{34}S‰$	%S	C:S	N:S	Tooth	Enamel $^{87}Sr/^{86}Sr$	Sr (ppm)	$\delta^{18}O$ SMOW	$\delta^{18}O_{dw}$
81		Mature?	m?											Premolar	0.71454	33	16.2	−9.9
82	Longbone	Mature	f											M3	0.70924	51	16.2	−10.1
84a	Longbone	Mature	m	−19.3	10.5	42.2	15.9	3.1	5.6	3.4	0.2	550	178	Canine	0.71376	28	16.2	−10.0
85	Skull	Adult	f	−20.0	9.8	33.7	12.3	3.2	1.4	2.7	0.2	496	155	Canine	0.71053	42	16.1	−10.2
86	Rib	Adult	f	−19.7	9.8	42.7	16.1	3.1	4.8	2.7	0.2	590	191	M3	0.70835	19	15.0	−12.7
88	Longbone	Adult	?	−19.5	8.5	43.9	16.2	3.2	5.2	2.0	0.2	639	202	M1	0.71042	28	19.0	−4.0
89	Longbone	Adult	m	−19.8	9.1	42.2	15.6	3.1	4.5	2.9	0.2	566	179					
90	Longbone	Adult	m?	−18.9	9.9	42.8	15.8	3.2	4.6	5.0	0.2	533	169	M1	0.71328	77	15.8	−10.9
91	Longbone	Adult	f	−19.3	9.6	40.9	15.1	3.2	2.4	3.6	0.2	585	185	Premolar	0.71336	63	16.5	−9.4
92	Longbone	Mature	(m)	−19.9	9.4	39.9	14.7	3.2	1.7	4.2	0.2	520	164	M3	0.71625	35	16.4	−9.6
93	Longbone	Adult	m	−19.9	10.2	40.8	14.8	3.2	1.6	2.8	0.2	537	167	M1	0.71533	40	16.8	−8.8
94	Longbone	Adult	(m)	−20.0	7.6	42.3	15.6	3.2	2.5	5.2	0.2	561	177	Premolar	0.71829	41	16.1	−10.2
95	Longbone	Adult	f	−19.4	9.1	42.7	15.9	3.1	6.2	3.5	0.2	630	201	M3	0.70833	39	15.3	−11.9
96	Longbone	Mature	f?	−19.6	10.2	43.4	16.0	3.2	5.9	3.4	0.2	540	171	M3	0.71455	53	15.7	−11.0
97	Rib	Adult	f?	−19.9	9.6	41.0	15.3	3.1	2.3	3.7	0.2	644	206	M1	0.71518	34	16.2	−10.1
98	Rib	Infants II	?											M1	0.71312	16	16.3	−9.9
99	Longbone	Infants I	?	−20.1	10.2	42.6	15.6	3.2	4.1	4.7	0.2	605	190					
100/I	Longbone	Adult	m											M1	0.70907	21	18.1	−5.9
100/II	Rib	Adult	f	−20.5	10.2	43.1	15.7	3.2	5.3	6.7	0.2	593	185	M1?	0.71556	15	17.7	−6.6
101	Longbone	Adult	?											M2	0.71506	21	15.8	−10.8
102	Longbone	Infants II	?	−19.8	8.0	42.4	15.7	3.2	3.7	4.4	0.2	591	188	M1	#	#	16.7	−8.9
103	Longbone	Adult	(f)	−20.2	8.2	42.3	15.5	3.2	3.5	4.5	0.2	572	180					
104	Skull	Adult	?	−19.9	10.8	32.7	11.1	3.4	0.5					M3?	0.71386	17	16.1	−10.2
105	Longbone	Adult	(m)											Premolar	0.71273	96	15.7	−11.1
106	Longbone	Adult	m?	−19.6	8.8	35.6	12.6	3.3	1.0					M3	0.71721	28	15.1	−12.5
108	Longbone	Mature?	m?	−19.7	9.0	41.9	15.4	3.2	3.2	1.9	0.2	557	176					
110		Adolescent-adult	m?											Premolar	0.71739	56	15.6	−11.3
111		Adult	m?											Canine	0.71711	39	14.7	−13.3
112	Longbone	Adult	m?	−18.8	10.0	42.3	15.4	3.2	3.7	3.1	0.2	595	186	M3	0.70924	52	14.9	−12.8
113/II	Longbone	Adult	?	−19.8	9.8	40.1	14.5	3.2	2.0	2.9	0.2	530	164	M3	0.71647	34	15.0	−12.6
114/I	Longbone	Adult	m	−19.8	8.5	37.3	13.6	3.2	0.3									
116	Skull	Adult	m											M2	0.70855	102	15.7	−11.0
117	Longbone	Adult	f	−19.9	8.9	39.7	14.2	3.3	2.3	5.4	0.2	519	159	Premolar	0.71472	57	16.3	−9.9
118	Longbone	Adult	m?	−19.7	9.2	40.2	14.4	3.3	1.3					M2	0.71315	42	14.3	−14.1
119	Skull	Adult	m	−19.9	9.8	38.8	13.7	3.3	0.6					Premolar	0.70792	44	15.1	−12.3
120	Skull	Adult	(f)	−19.6	9.9	42.5	15.5	3.2	2.7	3.6	0.2	575	180	Canine	#	#	17.5	−7.2
121	Longbone	Adult	m	−19.5	10.0	42.7	15.5	3.2	1.8	0.9	0.2	508	158	M2	0.70943	286	16.2	−9.9
122	Longbone	Adult	f	−19.6	10.2	41.5	14.9	3.2	2.3	3.2	0.2	563	173	M2	0.70874	54	15.1	−12.4
123	Longbone	Adult	(m)	−18.9	10.8	37.1	13.8	3.1	2.0	−1.9	0.2	548	175	M2	0.70865	48	15.7	−11.0
124	Longbone	Adult	m	−20.6	8.9	41.3	14.9	3.2	2.5	4.0	0.2	559	173	M3	0.71923	23	15.1	−12.4
125	Longbone	Adult	(f)	−19.9	8.9	42.7	15.7	3.2	4.4	3.5	0.2	594	187	M3	0.70818	27	15.2	−12.1
126	Longbone	Adult	(f)	−19.9	10.1	28.2	10.0	3.3	1.0					M3	0.71060	113	16.0	−10.4
127	Rib	Adult	f	−19.7	10.3	41.6	15.5	3.1	2.9	2.9	0.2	592	189	M3	0.71385	103	15.7	−11.1

All enamel $\delta^{18}O$ values were corrected to NBS 120c by +0.5‰. $\delta^{18}O_{dw}$ values were calculated from enamel $\delta^{18}O$ values after Levinson et al. (1987), corrected by 1.4‰.

TABLE 2. The results of the stable isotope analysis in the faunal remains from the site of Magdalenenberg

Find no.	Species	Date	Context	Bone	δ^{13}C‰	δ^{15}N‰	%C	%N	C:N	%coll.	δ^{34}S‰	%S	C:S	N:S
?	Cattle	Hallstatt	Stray find	Pelvis	−21.9	5.9	42.7	15.1	3.3	5.5	5.1	0.3	340	103
Vi 70/251	Goat/sheep	Hallstatt	Stray find	Radius	−21.3	5.5	41.2	14.5	3.3	6.54	5.6	0.2	502	151
Vi 70/458	Goat/sheep	Hallstatt	Stray find	Tibia	−21.4	5.9	41.6	14.8	3.3	4.73	6.3	0.2	575	175
Vi 70/251	Ungulate	?	Stray find	Rib	−21.2	5.4	43.6	15.6	3.3	4.9	0.4	0.2	617	189
Vi 70/408	Goat/sheep	Hallstatt	Stray find	Tibia	−21.5	6.6	42.5	14.9	3.3	6.33	−4.3	0.2	520	156
Grave 1	Pig	Hallstatt	Grave good	Humerus										
Vi 70/2	Cattle	Modern?	Intrusive	Skull	−21.3	5.7	41.5	15.3	3.2	8.21	2.6	0.2	572	181
Vi 70/2	Dog	Modern?	Intrusive	Humerus	−20.6	8.3	40.5	14.9	3.2	6.68	2.2	0.2	487	154
Vi 70/2	Dog	Modern?	Intrusive	Ulnale	−20.1	7.9	42.7	15.6	3.2	10.4	#	#	#	#
Vi 70/2	Cat	Modern?	Intrusive	Femur	−20.2	8.2	42	15.3	3.2	6.6	2.8	0.3	404	126

molars are the first permanent teeth to form at the age of ~1 to 4 years (Hillson, 2005). The largest proportion of teeth in this study are second and third molars (n = 36) and premolars (n = 14) (Table 1). Due to the loss of the tooth roots and dentin or heavy dental wear, the exact position in the dentition could not be identified for some molars (n = 8). In cases with no option to sample later forming teeth, we sampled first molars (n = 9), canines (n = 9), and one incisor instead. In three subadult individuals, we sampled the first permanent molar. Additionally, we randomly sampled dentine of five teeth with good preservation to assess the range of local soluble strontium at the archaeological site.

In this project, we sampled all available animal remains (n = 10) from the site for the analysis of carbon, nitrogen, and sulfur isotope ratios (Table 2). The bones of cattle, goat/sheep, and one unidentified ungulate were likely deposited during the construction of the tumulus in the Early Iron Age. A pig skeleton was found in the central chamber as a grave good. Other remains of dog, cat, and cattle are classified as modern intrusive specimens. They may derive from "buried" modern house pets or waste from other historic periods.

METHODS

We extracted collagen from 58 human and 10 animal bone samples. The collagen extraction followed the modified Longin method (Longin, 1971; Brown et al., 1988; Collins and Galley, 1998) and is outlined in detail in Appendix 1. Carbon and nitrogen isotope ratios were measured in duplicate using a Flash EA 2112 coupled to a DeltaXP mass spectrometer (Thermo-Finnigan®, Bremen, Germany). The sulfur isotope measurement was performed on the same collagen material in duplicate using a HekaTech EuroVector coupled to a Delta V Plus mass spectrometer (Thermo-Finnigan®, Bremen, Germany). All measurements were conducted at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany.

Strontium was purified from human and animal tooth enamel and dentine following the ion exchange method after Deniel and Pin (2001) at the clean laboratory and MC-ICP-MS facility at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany (see Appendix 1). Samples were measured parallel to the standards SRM_987 and SRM_1486, as well as one beaker blank per run, in a Thermo Fisher Neptune™ MC-ICP-MS instrument.

For the analysis of oxygen isotopes, we extracted phosphates (PO_4) from enamel bioapatite by applying the modified silver phosphate precipitation method (O'Neil et al., 1994; Dettmann et al., 2001, see Appendix 1 for details). Isotope ratios were measured at the Helmholtz Center for Environmental Research in Halle, Germany, in a Thermo Finnigan ConFlow III coupled to a Thermo Finnigan DeltaXLplus IRMS. Measurement precision was determined using a NBS 120c standard sample for each analytical run, as well as several internal laboratory standards.

RESULTS

Collagen was extracted from 58 bones, and the carbon and nitrogen isotope ratios were measured (Tables 1 and 2). In eight of these samples, the amount of extracted collagen was not sufficient for measurement (n = 4) or the results indicated poor quality collagen (n = 4). In one of the 10 animal bone samples, the collagen integrity was questionable. Although the collagen yield may be lower than 1% due to the use of ultra filters (30 kDa), all other collagen samples met the recommended quality criteria for isotope analysis (atomic C:N ratio, %carbon and %nitrogen (DeNiro, 1985; Ambrose, 1990; van Klinken, 1999). The 50 human samples with good collagen had a mean δ^{13}C value of −19.7 ± 0.4‰ (1σ), and ranged from −20.9‰ to 18.8‰, and a mean δ^{15}N value of 9.6 ± 0.8‰ (1σ), with a range of 7.6‰ to 10.9‰. Ten faunal collagen samples yielded a mean δ^{13}C value of −21.1 ± 0.6‰ (1σ) and ranged from −21.9‰ to −20.1‰, and a mean δ^{15}N value of 6.4 ± 1.3‰ (1σ) and a range of 4.6‰ to 8.3‰. The analytical precision was better than 0.2‰ (1σ) for all measurements of δ^{13}C and δ^{15}N.

We extracted sufficient collagen (~10 mg) for sulfur isotope analysis from 40 human and 10 animal bones (Tables 1 and 2). With the exception of the prince burial, all collagen samples met the recommended quality criteria for sulfur isotope ratio analysis (weight %S, atomic C:S and N:S ratios) as outlined by Nehlich and Richards (2009). The δ^{34}S ratios for humans at Magdalenenberg had a mean value of 3.5 ± 1.5‰ (1σ) and range from −1.9‰ to 6.7‰; the animal bones had a mean of 2.6 ± 3.2‰ (1σ) and ranged from −4.3‰ to 6.8‰. The measurement error was better than 0.6‰ for all sulfur isotope measurements.

The repeated ^{87}Sr/^{86}Sr measurement of the standard SRM 987 resulted in a mean of 0.710251 ± 0.00004 (1σ, n = 24) and was corrected to the accepted value of 0.710240 ± 0.00004 (Terakado et al., 1988; Johnson et al., 1990). The total procedural blanks, one for each batch of 13 samples, were negligible. We successfully measured ^{87}Sr/^{86}Sr ratios in 76 enamel and five dentin samples (Tables 1 and 3). The enamel samples have a mean strontium isotope value of 0.71296 ± 0.00333 (1σ) and range from 0.70725 to 0.71923. The ^{87}Sr/^{86}Sr ratio measured in human dentine had a mean value of

0.71195 ± 0.00245 (1σ) and ranged from 0.70904 to 0.71416.

Oxygen isotope ratios are reported relative to the international standard standard mean ocean water. Repeated analysis of NBS 120c yielded a mean of 21.2 ± 0.6‰ (1σ, n = 3), which is in the range of what is reported for other laboratories. However, data were corrected by +0.5‰ to meet the international NBS 120c value of −21.7‰ (summarized in Chenery et al., 2010). From this and other internal standard materials, we calculated a measurement error of less than ± 0.6‰. We successfully analyzed the δ^{18}O ratios in 78 human enamel samples, with a mean δ^{18}O value of 15.9 ± 0.9‰ (1σ) and a range from 13.9‰ to 19.0‰ (Table 1). Enamel phosphate values were converted to drinking water δ^{18}O values ($\delta^{18}O_{dw}$) using the formula in Levinson et al. (1987), correcting a method bias of −1.4‰, as recently recommended by Chenery et al. (2010) and resulted in drinking water values of −10.7 ± 3.7‰ (2σ, n = 78) (Table 1).

TABLE 3. Strontium isotope analysis result for enamel and dentin from five randomly sampled human teeth

Grave	Tooth	Enamel $^{87}Sr/^{86}Sr$	Sr (ppm)	Dentin $^{87}Sr/^{86}Sr$	Sr (ppm)
80	M3	0.71225	42	0.70904	91
93	M1	0.71533	40	0.71349	46
54	M2	0.70896	44	0.71352	62
23I	Molar	0.71685	68	0.71416	71
47	Premolar	0.71599	23	0.70953	48
Mean		0.71388	44	0.71195	64
S.d. 1σ		0.00325	16	0.00245	19

DISCUSSION

Diet

The mean δ^{13}C value for the herbivorous species from Magdalenenberg is −21.5 ± 0.3‰ and the mean δ^{15}N value is 6.0 ± 0.5‰, which is comparable with other prehistoric agricultural populations in Germany (Nehlich and Wahl, 2011; Oelze et al., 2011b). The carnivores had an average δ^{13}C and δ^{15}N value of −20.3 ± 0.3‰ and 8.1 ± 2.0‰, respectively. The average δ^{34}S value for the fauna was 2.6 ± 3.4‰, indicating a terrestrial based diet (Richards et al., 2003). Only a few human individuals overlap with the carnivores in their δ^{13}C and δ^{15}N values. Most humans from Magdalenenberg have high δ^{13}C values (mean δ^{13}C value = −19.7 ± 0.4‰; mean δ^{15}N value = 9.6 ± 0.8‰), suggesting that significant amounts of domestic animal protein (milk, meat, etc.) were consumed. Alternatively, elevated δ^{15}N values could also be explained by intensive manuring of crop plants or the consumption of immature animals with persisting nursing signals (Hedges and Reynard, 2007; Fraser et al., 2011).

There is no observable difference in δ^{15}N between males and females, which suggests that there were no gender restrictions in the access to animal proteins (Oneway ANOVA; f = 21, m = 21; P = 0.32). Heterogeneity in δ^{13}C values was found in the group of adult males, ranging from −20.9‰ to −18.8‰ (range 2.1‰) compared with the females (range 1.2‰) (Fig. 3). It seems apparent that some males depended on slightly different food sources. The most positive δ^{13}C values were found within one group of males, who also had the highest δ^{15}N values. Compared with the herbivores, their δ^{15}N values are elevated by ~4.5‰ and their δ^{13}C values by ~1.5‰, which leads to the suggestion that

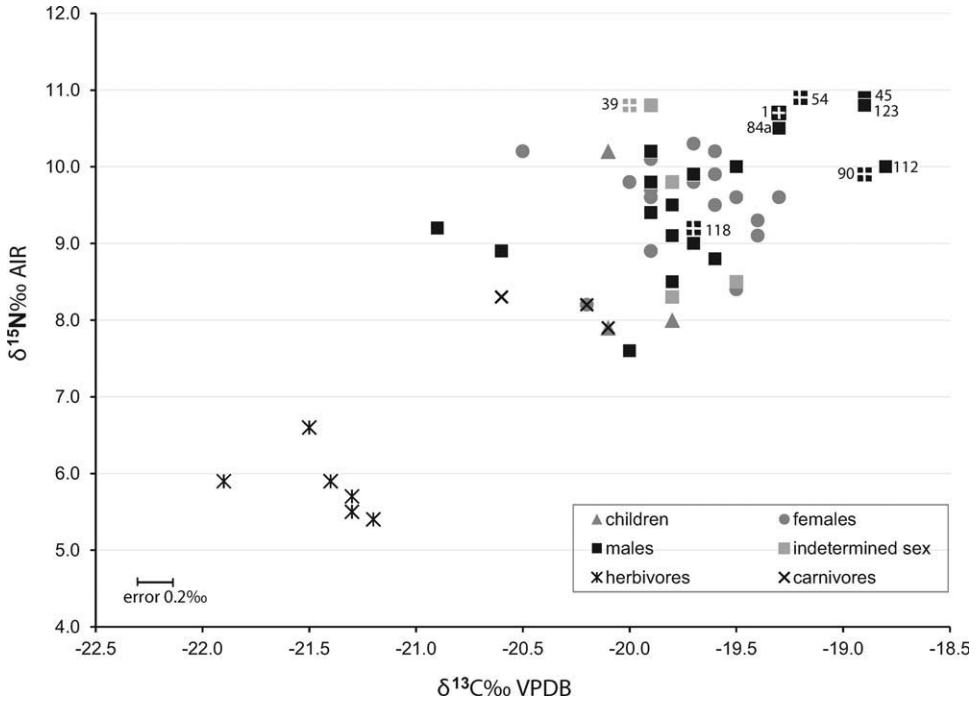

Fig. 3. Carbon and nitrogen stable isotopes for the fauna and humans from the Magdalenenberg site. The "prince" burial (Grave 1) and "warriors" buried with daggers (Graves 39, 54, 90, and 118) are marked with a white cross. The analytical error in δ^{13}C is shown, the error in δ^{15}N is smaller than the symbols.

their dietary protein almost exclusively derived from animal tissues. The consumption of small amounts of fish by some of the individuals would also explain such a pattern, yet the human mean δ^{34}S value (3.5 ± 1.5‰, 1σ, n = 39) is very similar to the mean δ^{34}S value of the fauna (2.6 ± 3.4‰) and shows no input of any aquatic resources. Moreover, the δ^{34}S values within this group of males are randomly distributed, ranging from −1.9‰ (Grave 123) to 5.0‰ (Grave 90). Although the consumption of aquatic resources is generally uncommon during the Iron Age (Jay and Richards 2007), elevated values in δ^{13}C have been related to the consumption of millet in several Hallstatt and La Tène populations of central Europe; however, only values greater than −18‰ are considered to be the result of intensive millet consumption (Le Huray and Schutkowski, 2005; Le Huray et al., 2006). Therefore, we suggest that this group of males lived mainly on an animal protein dominated diet, with minor millet consumption. In summary, their diet was somehow distinct from the rest of the population, either due to different regional dietary habits or social status. Interestingly, this group includes the prince grave (Grave 1) and two males with daggers (Graves 54 and 90), which can be characterized as high status "warrior" graves. This finding is in line with previous studies on later Iron Age populations, where high status "warrior" burials could be correlated with a diet dominated by animal protein (Le Huray and Schutkowski, 2005; Le Huray et al., 2006).

Mobility and provenance

The variations observed among the strontium isotope ratios give an impression of a burial population that was somewhat heterogeneous in its origin. We can observe three large groupings of ^{87}Sr/^{86}Sr values, which can be associated with the ^{87}Sr/^{86}Sr signatures from (a) the Buntsandstein surrounding the Magdalenenberg site, (b) the Hegau region toward the Lake Constance, and (c) the bedrock of the Black Forest. Even without the exclusion of outliers, the differences in ^{87}Sr/^{86}Sr among these described groups are statistically highly significant (linear regression analysis, P = 0.000, R^2 = 0.9756). In fact, the strontium data obtained from the human enamel samples (0.70725–0.71923, n = 76) cover nearly the entire spectrum of strontium data measured in modern biosphere samples in southwest Germany (0.70570–0.72190, n = 93) as documented by Oelze et al. (2011a) (Fig. 1B). This finding strongly contrasts with the ^{87}Sr/^{86}Sr data reported in several other studies on Neolithic sites and one Bronze Age cemetery in this part of Germany, which at most ranged between 0.708 and 0.712 (Bentley, 2006; Oelze et al., 2011a). However, all ^{87}Sr/^{86}Sr values reported in this study can potentially also be found in other regions of Europe. Similar high ^{87}Sr/^{86}Sr values are reported from Sweden and Norway, the Alps, Scotland, the Bohemian Massif, and the Central Massif in France (e.g., Evans et al., 2010; Voerkelius et al., 2010). However, we think the most parsimonious explanation for individuals with high values in this study are origins in closer proximity to the site than these more distant locations.

Although we observe a gradient in ^{87}Sr/^{86}Sr ratios following a longitudinal direction with the highest values in the western part of the study region (Fig. 1B), there is a more latitudinal gradient in the δ^{18}O values of meteoric water, with the lowest values measured in the southern edge of Germany and the northern Alps (Fig. 4). Equations to convert enamel phosphate δ^{18}O values to drinking water δ^{18}O values ($\delta^{18}O_{dw}$) can be problematic and prone to calculation errors in some cases (Chenery et al., 2010; Pollard et al., 2011). Below, we directly discuss the human enamel δ^{18}O data in comparison with archaeological enamel data, if available, but also revert to $\delta^{18}O_{dw}$ conversions to compare with rough estimations of meteoric $\delta^{18}O_{dw}$ values. However, one should keep in mind that the data obtained from human enamel phosphate had to be corrected by 0.5‰ and measurement errors are as high as 0.6‰. Additionally, early forming teeth can potentially be affected by breastfeeding signals. Thus, conclusions drawn solely based on δ^{18}O evidence should be considered with caution. Herein, we only consider the few outliers which have δ^{18}O values that likely indicate a nonlocal origin. The δ^{18}O values of the Magdalenenberg humans range from 13.9‰ to 19.0‰, which suggests different drinking water sources. The δ^{18}O values of drinking water ($\delta^{18}O_{dw}$) calculated from human enamel range from −15.1‰ to −4.0‰ (mean −10.7 ± 3.7‰, 2σ, n = 78), and cover the complete range in δ^{18}O values of meteoric and stream water from the North Sea to the Alps and beyond to the Italian

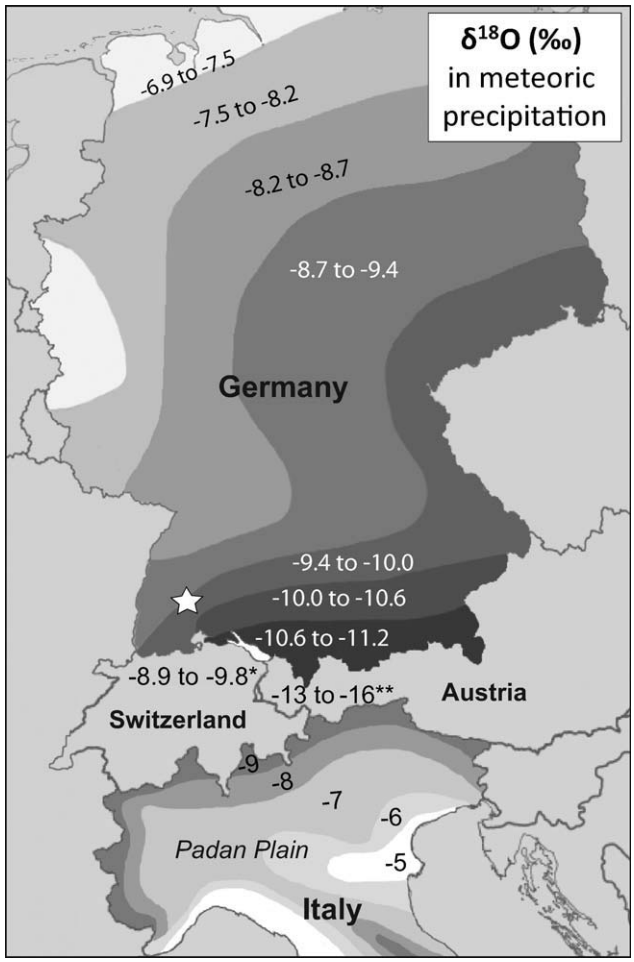

Fig. 4. Oxygen isotope precipitation map for Germany and Italy (adapted after Longinelli and Selmo, 2003; Tütken et al., 2004) with additional δ^{18}O data from *faunal remains and **alpine spring water (after Müller et al., 2003; Tütken et al., 2008). The site of Magdalenenberg is marked with a star.

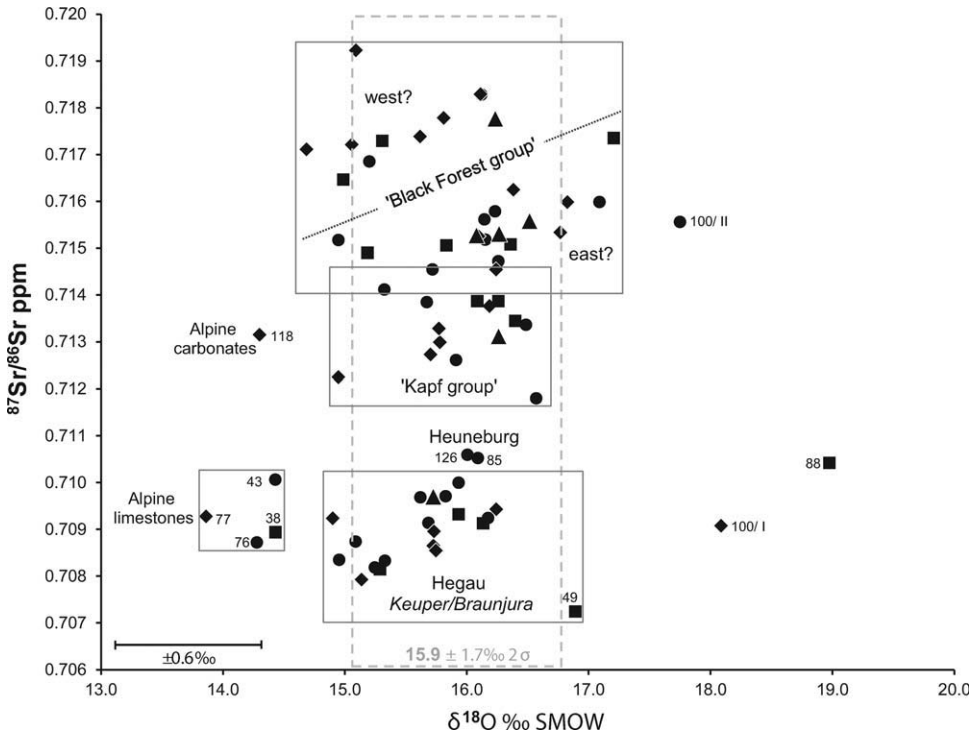

Fig. 5. Plot of the strontium and oxygen isotope ratios measured in human enamel from the Magdalenenberg site. The analytical error in $\delta^{18}O$ is shown; the error in $^{87}Sr/^{86}Sr$ is smaller than the symbols (squares = males, circles = females, triangles = infants, diamonds = undetermined). The gray dashed box indicated the mean $\delta^{18}O$ value ($\pm$ 2σ) for all Magdalenenberg human enamel samples.

coastline. The average $\delta^{18}O_{dw}$ value calculated from the Iron Age teeth is slightly more negative than the $\delta^{18}O$ values obtained from modern local streams, precipitation, or groundwater, which range from $-8.5‰$ to $-10.5‰$ (Table 1, Fig. 4) (Buhl et al., 1991; Mayer et al., 1995; Müller et al., 2003; Tütken et al., 2004, 2008). It seems plausible that either the discussed analytical issues or temporal differences in past and present climate and annual mean temperatures may be the cause of this variation (Fricke and O'Neil, 1999; Daux et al., 2005).

The $\delta^{34}S$ values obtained from the site of Magdalenenberg give no clear indications of nonlocal individuals. The observed range of $-1.9‰$ to 6.7‰, (mean 3.5 $\pm$ 1.5‰, 1σ, n = 39) is potentially local and consistent with geological data from the Black Forest which range from $-3.4‰$ and $+9.8‰$ (Gehlen et al., 1962). However, bone collagen remodels constantly during life, and any exotic $\delta^{34}S$ signature incorporated in early childhood may be completely replaced by the local $\delta^{34}S$ signal in adulthood. Moreover, very similar $\delta^{34}S$ signatures may be found in other regions of Germany and Europe. Nevertheless, both strontium and oxygen isotopes indicate that the individuals from the Magdalenenberg were mobile during their early life stages and originated in different geological and geographical areas. Unlike other time periods (Bentley, 2007), no sex or age-related distribution of either strontium or oxygen isotopic compositions of males, females, and children were found. They seem to be randomly distributed in their $^{87}Sr/^{86}Sr$ ratios and $\delta^{18}O$ values (Fig. 5). Also, there is no association of the orientation of the burials and their organization within the cemetery with the measured isotope values, with the exception of a group west of the tumulus who have lower $^{87}Sr/^{86}Sr$ values (see Fig. 2). Unfortunately, the skeletal preservation of the "prince" burial (Grave 1) was too poor to provide information on his mobility, as teeth were not preserved and the sulfur analysis failed. Also, the associated pig bone from the central chamber was diagenetically altered, possibly due to some unknown preservation treatments applied to the bones from this grave in the past. Environmental samples used to assess the local bio-available $^{87}Sr/^{86}Sr$ signature at the site itself derive from the edge of the tumulus as well as from the small elevated forest patch next to it (Oelze et al., 2011a). They represent the Buntsandstein bedrock and ranged from 0.71143 to 0.71489 (n = 6). The Muschelkalk region surrounding the Magdalenenberg, on the other hand, had a mean of 0.70951 ($\pm$ 0.00092, 1σ, n = 8). Interestingly, the $^{87}Sr/^{86}Sr$ measured in the five human dentin samples (0.71195 $\pm$ 0.00245, 1σ) exactly match this range of values (Table 3) and thereby likely represent the soluble $^{87}Sr/^{86}Sr$ of the tumulus itself, which was constructed with materials from both geological substrates. Although the tumulus was a place for the dead, the "Kapf" has been considered as a potential home of the Magdalenenberg people. The "Kapf" is dominated by Buntsandstein and bordered by granite rocks, which shape the slopes of two small rivers (Fig. 1C). It is likely that food plants, the main source of strontium uptake (Burton et al., 1999), were cultivated on the Buntsandstein plateau and valley instead of on the steep granite slopes. According to data from Oelze et al. (2011a), the mean bioavailable $^{87}Sr/^{86}Sr$ values on Buntsandstein are 0.71282 $\pm$ 0.00169 (1σ) and 0.71453 $\pm$ 0.00313 (1σ) on granite, which match the variation in

geological substrates from the Black Forest measured by Baumann and Hofmann (1988). A population dwelling on the "Kapf" and producing foods locally should balance the variation observed among the different local plants and have values of around ~0.7130, probably slightly lower if also the Muschelkalk between the tumulus and the "Kapf" site were cultivated, and probably slightly higher if the granite slopes and the metamorphic terrain toward the northwest were used for agriculture as well. A broad range of $^{87}Sr/^{86}Sr$ values between 0.7120 and 0.7145 seems plausible for this scenario, and 17 graves show $^{87}Sr/^{86}Sr$ values within this range (Fig. 5). These individuals could be potentially assigned to the "Kapf." Only the adult male from Grave 118 has a low oxygen isotope value of 14.3‰ ($\delta^{18}O_{dw} = -14.1$‰), which could potentially be associated with the northern watershed of the Alps (Fig. 4). In the Alps, a matching $^{87}Sr/^{86}Sr$ value of 0.71315 was found in leaches of Mesozoic carbonates (Müller et al., 2003). Therefore, it seems possible that this individual came from the alpine highlands.

One large cluster of individuals with significantly lower $^{87}Sr/^{86}Sr$ values of between 0.70725 and 0.71060 can probably be associated with geological substrates to the east and south of the Magdalenenberg, with the lowest values characteristic of younger geological units like the Jurassic layers and volcanic tuffs of the Hegau region surrounding Lake Constance (Oelze et al., 2011a). A range of Hallstatt period tumuli with ordinary grave good inventories has been reported for this region, especially in the Keuper and Jurassic Braunjura area only a few kilometer east and south of Magdalenenberg (mapped on Fig. 1C, summarized in Spindler, 1980). These two geological layers are quite uniform in their $^{87}Sr/^{86}Sr$ values, which are 0.70951 ± 0.00092 (1σ, n = 11) and 0.70944 ± 0.00090 (1σ, n = 13). It seems possible that the individuals within this $^{87}Sr/^{86}Sr$ range can be assigned to the nearby Hallstatt tumulus sites on the Keuper and Braunjura soils. Also, people from the contemporary burial site of Mauenheim, situated at the edge of the geologically young Hegau substrates of molasse, limestone, and tuff, could potentially be found within this cluster (Figs. 1B and 5). The adult individual (Grave 49) with the lowest $^{87}Sr/^{86}Sr$ signal in the data set (0.70725) would correspond well to the volcanic tuffs at Mauenheim. His oxygen value of 16.9‰ is similar to what was measured in Bronze Age human enamel (16.6‰) and Neolithic pig enamel (16.6‰) from the nearby (20 km) city of Singen (Oelze et al., 2011a; pig data from Bentley and Knipper, 2005, corrected after Iacumin et al., 1996). It seems possible that this individual grew up within the Mauenheim community. In the same cluster of lower $^{87}Sr/^{86}Sr$ values, two adult females (Graves 85 and 126) had $^{87}Sr/^{86}Sr$ values of 0.71053 and 0.71060 matching exactly what was measured at the contemporary princely site of Heuneburg. The Heuneburg settlement is located on the edge of the Swabian Alps on a plateau of a Riss moraine above the River Danube and various domestic faunal specimens from there had a mean $^{87}Sr/^{86}Sr$ value of 0.7105 (Stephan, 2009). This value is similar to the bioavailable $^{87}Sr/^{86}Sr$ signature measured for the Riss moraine (0.71049 ± 0.00111, 1σ, n = 4, Fig. 1B). It is possible that these two females grew up at the Heuneburg fortress and moved to the Black Forest in later life stages. Interestingly, several animals (cattle and pigs) from the Heuneburg site had high $^{87}Sr/^{86}Sr$ values ranging from 0.7135 to 0.715 and were classified as potential imports from the southern Black Forest (Stephan, 2009). According to our data, they may have been imported from the Magdalenenberg area, most likely the "Kapf," as no other contemporary settlements are known from this geological area. This finding perhaps suggests an economic and social connection between the two spheres of local power.

Among the individuals with the lower $^{87}Sr/^{86}Sr$ values, there are four individuals (Graves 38, 43, 76, and 77), who have $\delta^{18}O$ values lower than the mean $\delta^{18}O$ value ±2σ. Their values range from 13.9‰ to 14.4‰, which convert to $\delta^{18}O_{dw}$ values of between −15.1‰ and −13.8‰. Such values are not typically found in southern Germany (Fig. 4) but are consistent with water from the northern watershed of the Alps (Müller et al., 2003). Regions in the northern alpine region with $^{87}Sr/^{86}Sr$ values matching those of these individuals (from 0.70872 to 0.71006) are, for example, the Swiss plateau and the northern Alps of Austria. Tütken et al. (2008) measured archaeological fauna from the Swiss plateau (canton Zurich) and found homogenous values around 0.708, while the oxygen values resembled nonalpine waters with $\delta^{18}O$ values of around −9.8‰ and −8.9‰. The northern Calcareous Alps, a relatively young limestone formation which includes the Iron Age salt mining community of Hallstatt, should also have low $^{87}Sr/^{86}Sr$ values. Evaporites from Hallstatt ranged from 0.70727 to 0.70977 (Spötl and Pak, 1996). Although other regions in Europe show similar isotope values, a connection to Hallstatt is suggested by various grave goods found at the Magdalenenberg site. Therefore, taking into account the errors in the $\delta^{18}O$ measurements, it is possible that these individuals with alpine $\delta^{18}O$ and low $^{87}Sr/^{86}Sr$ values grew up close to the salt mine of Hallstatt in Austria and moved to Magdalenenberg after childhood.

Another adult individual (Grave 88) has a high $\delta^{18}O$ value of 19.0‰, but with a "local" $^{87}Sr/^{86}Sr$ value of 0.71042. Herein, it should be noted that a first molar was sampled which might have led to increased values $\delta^{18}O$ of ~0.7± 0.5‰ due to breastfeeding effects during enamel formation (White et al., 2000; Dupras and Tocheri, 2007). However, even taking this into account, the $\delta^{18}O$ value is still high and results in a $\delta^{18}O_{dw}$ value between −5‰ and −4‰, which indicates warmer climate than we find north of the Alps. The German sea coast has the highest meteoric water values in the country (−7‰, Fig. 4), whereas even higher values of −5‰ and −4‰ can be found at the Italian coast and the Iberian Peninsula (Longinelli and Selmo, 2003; Bowen, 2009). The $\delta^{34}S$ value of 2.0‰ is a typical terrestrial signature that does not indicate any measurable input of marine sulfur (+20‰) from marine food consumption or sea spray effects, which can occur up to ~20 km inland depending on the regional topography (Wadleigh et al., 1996; Richards et al., 2001). This argues against this individual emigrating from a coastal area in the last decades before death. Bioavailable $^{87}Sr/^{86}Sr$ signatures match the signature of Grave 88 (0.71042) can also be found in Italy, from the Padan Plain to Sicily, and sporadically in more distant Spain (Voerkelius et al., 2010).

Two other individuals with elevated $\delta^{18}O$ values are from Grave 100. Herein, a young adult female (100/II) and a young adult male (100/I) were buried next to each other. Again, first molars were sampled, which may slightly alter the $\delta^{18}O$ values. But even taking this into account, their $\delta^{18}O$ values (17.7‰ and 18.1‰) are elevated compared with the human mean value from the site and resemble $\delta^{18}O$ values measured in archaeological humans in west-

ern France (Daux et al., 2005). Calculated values for $\delta^{18}O_{dw}$ lie between −6.6‰ and −5.9‰, and can be found, for example, in Spain, western France, or Italy (Fig. 4). Although we did not obtain sulfur data from the female, the male has a $\delta^{34}S$ value of 6.7‰, which is the highest human value in this dataset (mean 3.5 ± 1.5‰, 1σ, n = 39); yet still far too low to indicate a coastal dweller. Another indicator for the origin of these individuals could be a bronze pendant buried with the female which suggests a connection to the north Italian Golasecca culture at the edge of the Alps and the Padan plain (Warneke, 1999). Interestingly, while the $\delta^{18}O$ values from Grave 100 are both similarly high, the two $^{87}Sr/^{86}Sr$ signatures are very different (0.71556 and 0.70907), showing this "couple" grew up in distinct geological areas. Nevertheless, both $^{87}Sr/^{86}Sr$ values would be consistent with an origin in northern Italy, where the crystalline bedrocks of the Alps with higher $^{87}Sr/^{86}Sr$ values (Müller et al., 2003) join the younger glacial sediments of the plain. Bioavailable strontium data similar to those found in the male (0.70907) are reported from Central Italy (below 0.7091), but similar values could potentially also be found in the glacial sediments further north (Pellegrini et al., 2008). Therefore, it is possible that these two individuals originated in the Golasecca culture south of the Alps.

Data interpretation is perhaps more straightforward for the larger cluster of humans with $^{87}Sr/^{86}Sr$ values above ~0.7145. We can quite confidently associate these individuals with the metamorphic gneiss (0.71525 ± 0.00293, 1σ, n = 9, range 0.71156–0.72190) and granites (0.71453 ± 0.00313, 1σ, n = 8, range 0.71033–0.71877) of the Black Forest uplands, as the range corresponds to what was measured in modern snails and plants (Oelze et al., 2011a), Neolithic pigs (0.7163, n = 21, Bentley and Knipper, 2005) and various modern geological substrates from the Black Forest (Baumann and Hofmann, 1988). Nevertheless, a clear separation of this group from the "Kapf group" is not possible due to the uncertainty about which geological areas were used for agriculture by Iron Age people in this region. Within the "Black Forest group," a significant separation in both strontium and oxygen can be observed (Oneway ANOVA, $^{87}Sr/^{86}Sr$ P = 0.000, $\delta^{18}O$ P = 0.044), which may be due to origins in the east or west of the Black Forest Mountains where differences in bedrock can be observed. One subgroup ("west?") has higher $^{87}Sr/^{86}Sr$ (above ~0.716) and possibly also slightly lower $\delta^{18}O$ values while the other subgroup ("east?") has lower $^{87}Sr/^{86}Sr$ (below ~0.716) ratios and possible slightly higher $\delta^{18}O$ values (Fig. 5). In fact, the west area of the Black Forest is dominated by gneiss with higher $^{87}Sr/^{86}Sr$ signatures. Moreover, despite the mentioned uncertainties in $\delta^{18}O$ data accuracy, one could suggest that rainwater deriving from the Atlantic Ocean may lead to lower oxygen isotope values in precipitation at the western side of the mountains, similar to what occurs in the northern Alps. According to the $^{87}Sr/^{86}Sr$ and archaeological evidence, we might suggest that perhaps this "western" Black Forest group could be associated with the contemporary monumental tumulus site in March-Buchheim located in the western edge of the Black Forest, where the gneiss bedrock borders the Rhine valley (see Fig. 1A). The so-called "Bürgle" chariot grave tumulus of March-Buchheim was even larger (ø 120 m) than the Magdalenenberg mound and although the central "princely" burial was robbed, the grave architecture and inventories indicate high status (Pare, 1992).

CONCLUSION

We reconstructed the diet and mobility of the burial population from the Magdalenenberg site and found very heterogeneous isotopic patterns indicating different regions of origin. Although there have been several previous isotopic dietary studies on Iron Age populations in eastern Central Europe and Great Britain focused on dietary behavior (Murray and Schoeninger, 1988; Le Huray and Schutkowski, 2005; Le Huray et al., 2006; Jay and Richards, 2006, 2007; Jay et al., 2008), and one using strontium on Iron Age domestic fauna to reconstruct mobility (Stephan, 2009), this is the first comprehensive study of the mobility of Iron Age humans using a combination of different isotope systems. Our findings strongly support the general assumption that Early Iron Age society was highly mobile. Only a fraction of the burial population could be inferred to be local, i.e., likely from the settlement on the nearby "Kapf" hillfort. For the nonlocal people, we found that the isotope data matched well with isotope data from the wider region of southwest Germany, mainly the Black Forest, the Lake Constance area, and Heuneburg, and potentially also beyond to the Alps and northern Italy. One group with high $^{87}Sr/^{86}Sr$ values might have come from the western Black Forest and may have been connected to the "Bürgle" princely site in the western foothills, which would imply a socioeconomic network though the Central Black Forest in the Early Iron Age.

ACKNOWLEDGMENTS

The authors thank Sven Steinbrenner and Annabell Reiner for assistance with sample preparation and the strontium isotope analysis. The associate editor, the two anonymous reviewers, Sandro Corrieri and Kate Britton are gratefully acknowledged for very helpful suggestions on earlier drafts of the article. They thank Dirk Heider for advice on statistics. This research was funded by the BMBF within the project "Life history reconstruction of mobile individuals in sedentary societies" conducted at the Department of Pre- and Protohistory, Leipzig University and the Max Planck Institute for Evolutionary Anthropology, Leipzig.

APPENDIX 1: METHODS

Collagen extraction

To analyze carbon, nitrogen, and sulfur isotope ratios, we extracted collagen from 58 human and 11 animal bone samples. The collagen extraction followed the modified Longin method (Longin, 1971; Brown et al., 1988; Collins and Galley, 1998). Bone samples were cleaned using air abrasion and then demineralized in 0.5 M HCl for several weeks at 4°C, with acid changes every few days. Completely demineralized samples were rinsed three times with deionized water and gelatinized for 48 h at 70°C in a pH 3 solution. The insoluble fraction was first filtered with a 5 μm EZEE© filter, and subsequently filtered using Amicon© ultrafilters (cut off of < 30 kDa). The purified solution was frozen and then freeze dried for 48 h. Finally, 0.5 and 10 mg of dried collagen sample was weighed into tin capsules for measurement of carbon, nitrogen, and sulfur, respectively. Carbon and nitrogen isotope ratios were measured in a Flash EA 2112 coupled to a DeltaXP mass spectrometer

(Thermo-Finnigan®, Bremen, Germany) at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany.

The sulfur isotope measurement was performed in duplicates in a HekaTech EuroVector coupled to a Delta V plus mass spectrometer (Thermo-Finnigan®, Bremen, Germany) at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany.

Strontium

Strontium was purified from human and animal tooth enamel and dentin following the ion exchange method after Deniel and Pin (2001) at the clean laboratory and MC-ICP-MS facility at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany (Richards et al., 2008). First, all tooth samples were manually cleaned with a dental drill to remove superficial contaminations. Samples showing traces of paint or glue were additionally cleaned several times in ultrapure acetone ultrasonic baths. Then, after cutting a chip of the tooth crown, spanning from the cementoenamel junction to the occlusal surface, the enamel was separated from attached dentin under a magnifying lens. The opposite procedure was applied to five dentin samples, where attached enamel was removed. The chunks of enamel and dentin were then cleaned from remaining dust by repeated rinsing and ultrasonic baths with deionized water. Samples were transferred to the clean laboratory, rinsed again in ultrapure acetone, and dried overnight. Subsequently ~10–20 mg of enamel or dentin was weighed into clean Teflon beakers and digested in 1 ml of 14.3 M HNO_3 on a hotplate (120°C). The dissolved samples of enamel and dentin were evaporated to dryness and were combined with 1 ml of 3 M HNO_3 before being loaded on clean, preconditioned 2 ml columns containing cleaned Sr-spec™ resin (EiChrom, Darien, IL). Samples were reloaded three times. Then, after several washes with 3 M HNO_3, the strontium was eluted from the resin with ultrapure deionized water into clean Teflon beakers and dried down on a hot plate. The remaining samples, again redissolved in 3% HNO_3, were then ready for the measurement parallel to the standards SRM_987 and SRM_1486, as well as one beaker blank per run, in a Thermo Fisher Neptune™ MC-ICP-MS instrument (Thermo Fisher Scientific, Dreieich, Germany).

Oxygen

For the analysis of $\delta^{18}O$, we extracted phosphates (PO_4) out of enamel bioapatite by applying the modified silver phosphate precipitation method (O'Neil et al., 1994; Dettmann et al., 2001). First 10–15 mg of tooth enamel, spanning from the cementoenamel junction to the occlusal surface, was cut from the tooth crown, manually cleaned with a dental drill and then ground to fine powder with a clean pastille. Under a fume hood, the sample was then dissolved in 1 ml 2 M HF for 24 h. Then, samples were centrifuged, and the solution containing the phosphate was transferred into a new tube. Several drops of Bromothymol blue was added to subsequently be able to check the pH (< 7). Then the HF was buffered with 300 μl of NH_4OH. When the sample was neutral, ~700 μl 2 M $AgNO_3$ was added. Subsequently, the silver phosphate crystals precipitated resulting in Ag_3PO_4 crystals of light yellow color. The residue was centrifuged, rinsed with deionized water four times, and then dried down in a freeze dryer. The measurement of the Ag_3PO_4 samples was conducted in the Department for Hydrology at the Helmholtz Centre for Environmental Research—UFZ, Halle, Germany. After weighing ~700 μg Ag_3PO_4 into silver capsules, ~0.5 mg of graphite was added as described by Vennemann et al. (2002). The capsules were then combusted to CO in a HekaTech high-temperature combustion oven with helium carrier gas at 1,450°C. The CO was lead via a Thermo Finnigan ConFlow III into a Thermo Finnigan DeltaXLplus IRMS (Thermo-Finnigan®, Bremen, Germany) for isotope analysis. Measurement precision was controlled using a NBS 120c standard sample for each analytical run, as well as several internal laboratory standards.

Age and sex determination

The commonly anthropological methods for age and sex determination were applied to all human remains from the Magdalenenberg site (Ferembach et al., 1980; Buikstra and Ubelaker, 1997). Age was determined after dental status including dental wear, state of closure in the epiphyses, status of the auricular surface, as well as closure of the cranial sutures and the sphenobasilar symphysis and by the presence or absence of age related alterations in the joints (Lovejoy, 1985; Lovejoy et al., 1985; Meindl and Lovejoy, 1985; Íşcan, 1989; White, 2000). The sex was estimated by assessing the morphological characteristics of the skull and pelvis. Also, the shape of the auditory canal, body height, and general postcranial robusticity were taken into account (Ditch and Rose, 1972; Bruzek, 2002; Murail et al., 2005).

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