7. Multi-isotopic analysis reveals individual mobility and diet at the Early Iron Age monumental tumulus of Magdalenenberg, Germany

Vicky M. Oelze[1], Julia K. Koch[2], Katharina Kupke[2], Olaf Nehlich[1], Steve Zäuner[3], Joachim Wahl[3,4], Stephan M. Weise[5], Sabine Rieckhoff[2], Michael P. Richards[1,6]

[1] Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology, D-04103 Leipzig, Germany
[2] Department of Pre- and Protohistory, Leipzig University, D-04109 Leipzig, Germany
[3] Department of Early Prehistory and Quaternary Ecology, Work Group Paleoanthropology, Tuebingen University, D-72070 Tuebingen, Germany
[4] State Office for Cultural Heritage Management Baden-Wuerttemberg, Osteology, D-78467 Constance, Germany
[5] Department of Catchment Hydrology, Helmholtz Center for Environmental Research (UFZ), Halle, D-06120 Halle, Germany
[6] Department of Anthropology, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

American Journal of Physical Anthropology, accepted manuscript (5th December 2011)

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, 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 sulphur 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. While 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.

7.1.Introduction

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; Wells 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 Figure 7.1A). 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 approximately 100m 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 (Figure 7.2). 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 (Figure 7.2). While 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 excellent 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).

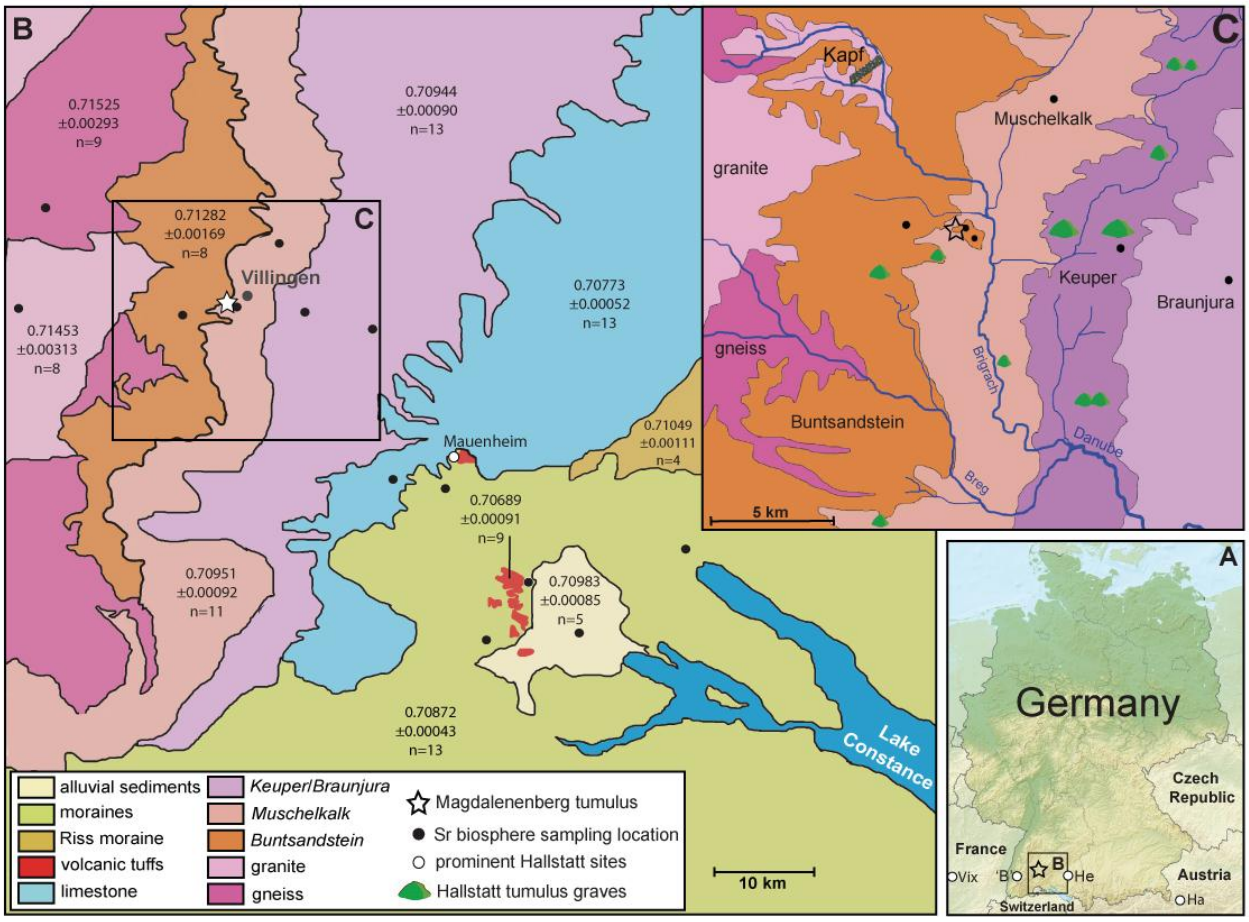

Figure 7.1: **A** map of Germany and bordering countries ('B' = 'Bürgle', He = Heuneburg, Ha = Hallstatt) **B** simplified geological map of the study region between Lake Constance (SW) and the Black Forest (NE), and sampling sites (black dots) and mean values for bioavailable $^{87}Sr/^{86}Sr$ are mapped (after Oelze et al. 2011a). **C** Detailed geological map containing the study site, surrounding Hallstatt cemeteries and the 'Kapf' hillfort.

While 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 approximately 5km northwest of Magdalenenberg. The hillfort encompassed an area of approximately 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 to 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 Figure 7.1C) 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 the question of the origin of their wealth and for the source and sphere of influence and power of the 'prince' himself.

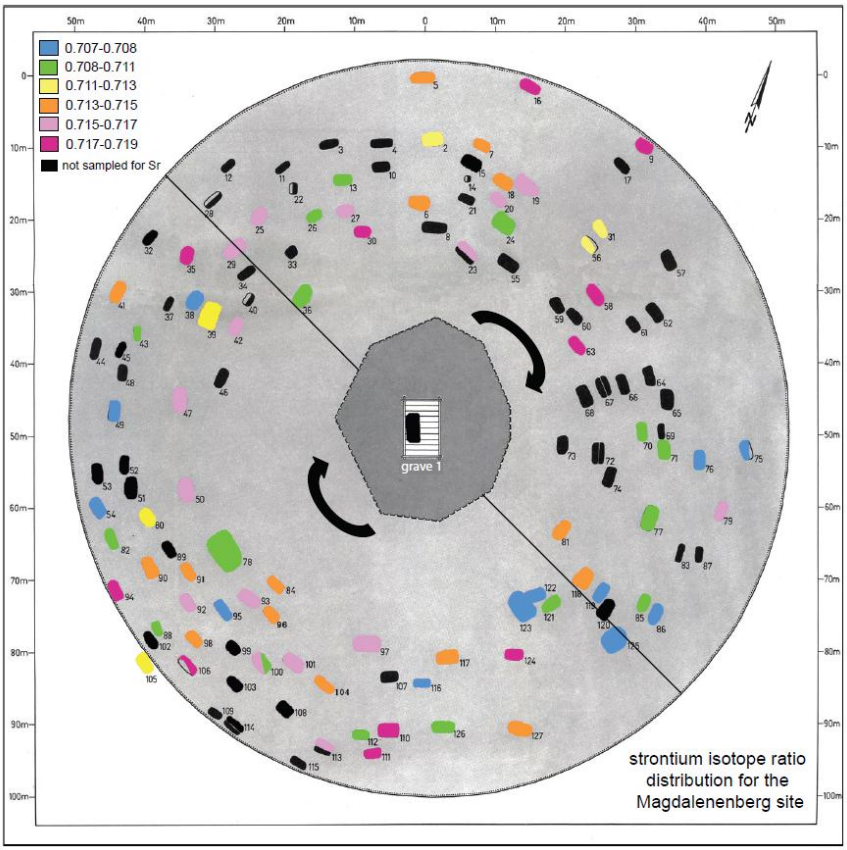

Figure 7.2: The Magdalenenberg tumulus with individual grave numbers (modified after Spindler 2004) and the strontium isotope range highlighted for each sampled grave. The arrows and black line within the cemetery specify the two distinct hemispheres (clockwise and counter-clockwise) of burial orientation around the central prince grave.

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 those 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 to the Early Iron Age human remains. By using various isotope systems (C, N, S, Sr, O), we also seek to constrain the possible region of provenance of any foreign (non-local) individuals to gain insights into the social catchment area of the elite burial population of Magdalenenberg. While the strontium and oxygen isotope ratios in tooth enamel reflect childhood location, the isotopes of sulphur, carbon and nitrogen measured in bone collagen should correspond to the location and diet of later life stages and potentially indicate individuals that 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, sulphur) and mobility/migration (oxygen, strontium, sulphur). 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 utilized since the late 1970s to reconstruct the protein component of archaeological human and animal diets from bone collagen (Lee-Thorp 2008; Vogel and van der Merwe 1977). 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), as the differences in the $\delta^{13}C$ values of plants 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 could be 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, sulphur 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 sulphur 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 sulphur 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. Sulphur 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 analysis 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 sulphur 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 hard tissues of the body as a trace element, substituting for calcium in the tissues (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 (Figure 7.1B) (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 Figure 7.1B). 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). While 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).

7.2.Materials

The ages and biological sex of the human skeletal materials were determined in the 1970s by Gallay (1977). A re-analysis of all human skeletons from the site was conducted by S.Z. and J.W., using more recently developed methods (see the appendix for details of the methodology). Table 7.1 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 probably 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 7.1). 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 sulphur ~1g 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 molars are the first permanent teeth to form at the age of approximately 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 7.1). 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 sulphur isotope ratios (Table 7.2). 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.

7.3. Methods

We extracted collagen from 58 human and ten animal bone samples. The collagen extraction followed the modified Longin method (Brown et al. 1988; Collins and Galley 1998; Longin

1971) and is outlined in detail in the appendix. 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 sulphur 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). 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^{TM} MC-ICP-MS instrument (Thermo Fisher Scientific Inc., Dreieich, Germany).

For the analysis of oxygen isotopes, we extracted phosphates (PO_4) from enamel bioapatite by applying the modified silver phosphate precipitation method (Dettmann et al. 2001; O'Neil et al. 1994, see appendix 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 (Thermo-Finnigan®, Bremen, Germany). Measurement precision was determined using a NBS 120c standard sample for each analytical run, as well as several internal laboratory standards.

7.4. Results

Collagen was extracted from 58 bones and the carbon and nitrogen isotope ratios were measured (Table 7.1 and 7.2). 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 ten animal bone samples, the collagen integrity was questionable. Although the collagen yield may be lower than 1% due to the use of ultra filters (30kDa), all other collagen samples met the recommended quality criteria for isotope analysis (atomic C:N ratio, %carbon and %nitrogen (Ambrose 1990; DeNiro 1985; van Klinken 1999). The 50 human samples with good collagen had a mean δ13C value of -19.7 ± 0.4‰ (1σ), and ranged from -20.9‰ to 18.8‰, and a

mean δ15N value of 9.6 ± 0.8‰ (1σ), with a range of 7.6‰ to 10.9‰. Ten faunal collagen samples yielded a mean δ13C value of -21.1 ± 0.6‰ (1σ) and ranged from -21.9‰ to -20.1‰, and a mean δ15N 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 δ13C and δ15N.

We extracted sufficient collagen (~10mg) for sulphur isotope analysis from 40 human and ten animal bones (Table 7.1 and 7.2). With the exception of the prince burial, all collagen samples met the recommended quality criteria for sulphur isotope ratio analysis (weight %S, atomic C:S and N:S ratios) as outlined by Nehlich and Richards (2009). The δ34S 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 sulphur isotope measurements.

The repeated 87Sr/86Sr 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 (Johnson et al. 1990; Terakado et al. 1988). The total procedural blanks, one for each batch of 13 samples, were negligible. We successfully measured 87Sr/86Sr ratios in 76 enamel and five dentin samples (Table 7.1 and 7.3). The enamel samples have a mean strontium isotope value of 0.71296 ± 0.00333 (1σ) and range from 0.70725 to 0.71923. The 87Sr/86Sr 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 SMOW (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 δ18O ratios in 78 human enamel samples, with a mean δ18O value of 15.9 ± 0.9‰ (1σ) and a range from 13.9‰ to 19.0‰ (Table 7.1). Enamel phosphate values were converted to drinking water δ18O values (δ18Odw) 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 7.1).

Table 7.1: Results of anthropological and isotopic analysis for all human individuals from the Magdalenenberg site, sorted by grave number (infans I = 0-5 years; infans II = 6-12 years; mature = >50years; m = male (m) = probable male; m? = insecure male; f= female; (f) = probable female, f? = unsecure female; ? = sex undetermined; # = measurement error). 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‰.

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	~~6.5~~	~~0.4~~	~~273~~	~~83~~					
2		adolecent-adult	f?											molar	0.71261	105	15.9	-10.6
5	skull	adolecent-adult	(f)	-19.9	9.7	41.0	15.4	3.1	1.5	2.6	0.2	517	167	incisivi	0.71411	43	15.3	-11.9
6		infans 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		infans 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		adolecent-adult	?											premolar	0.71345	48	16.4	-9.6
19		adolecent-adult	f?											M2	0.71561	56	16.1	-10.1
20		adolecent-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		adolecent-adult	f?											molar	0.71579	53	16.2	-9.9
26		infans I	?											M2	0.70970	22	15.7	-11.0
27		infans II	m?											premolar	0.71527	38	16.1	-10.3
29		adult	f											M2	0.71517	45	14.9	-12.7
30		adolecent-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		infans 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		infans 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	infans 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		adolecent	(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)	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~	~~0.01~~					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		infans II	?											M3	0.71531	45	16.3	-9.9

80	longbone	adult	m	~~-20.5~~	~~9.9~~	~~20.3~~	~~6.5~~	~~3.7~~	~~0.22~~					M3	0.71225	42	14.9	-12.7
81		mature?	m?											premolar	0.71454	33	16.2	-9.9
82	longbone	mature	f	~~-21.1~~	~~11.9~~	~~7.2~~	~~1.9~~	~~4.4~~	~~0.13~~					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	infans II	?	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~	~~2.28~~					M1	0.71312	16	16.3	-9.9
99	longbone	infans I	?	-20.1	10.2	42.6	15.6	3.2	4.1	4.7	0.2	605	190					
100/I	longbone	adult	m	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~					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	?	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~					M2	0.71506	21	15.8	-10.8
102	longbone	infans 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)	~~-20.8~~	~~11.5~~	~~10.1~~	~~2.7~~	~~4.4~~	~~0.16~~					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		adolecent-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	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~	~~0.0~~					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

Table 7.1: continued

Table 7.2: The results of the stable isotope analysis in the faunal remains from the site of Magdalenenberg.

find no.	species	date	context	bone	$\delta^{13}C$‰	$\delta^{15}N$‰	%C	%N	C:N	%coll.	$\delta^{34}S$‰	%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	~~-21.9~~	~~6.7~~	~~49.6~~	~~13.9~~	~~4.2~~	~~4.11~~	~~3.8~~	~~0.4~~	~~349~~	~~84~~
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	ulna le.	-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

Table 7.3: 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

7.5. Discussion

7.5.1. Diet

The mean δ13C value for the herbivorous species from Magdalenenberg is -21.5 ± 0.3‰ and the mean δ15N value is 6.0 ± 0.5‰, which is comparable to other prehistoric agricultural populations in Germany (Nehlich and Wahl 2011; Oelze et al. 2011b). The carnivores had an average δ13C and δ15N value of -20.3 ± 0.3‰ and 8.1 ± 2.0‰, respectively. The average δ34S 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 δ13C and δ15N values. Most humans from Magdalenenberg have high δ13C values (mean δ13C value = -19.7 ± 0.4‰; mean δ15N value = 9.6 ± 0.8‰), suggesting that significant amounts of domestic animal protein (milk, meat, etc.) were consumed. Alternatively, elevated δ15N 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).

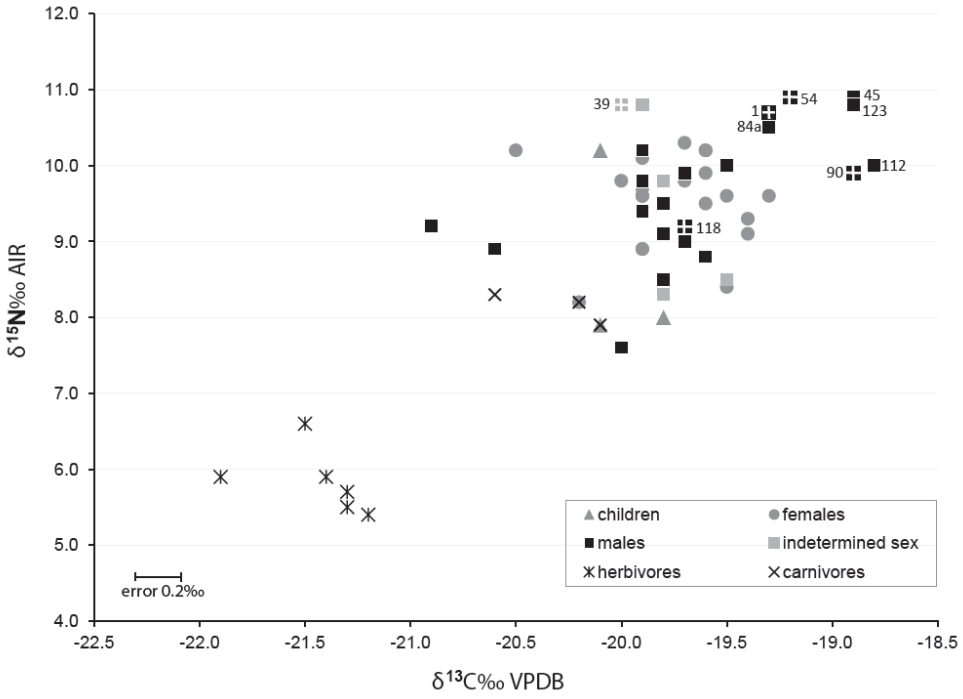

Figure 7.3: Carbon and nitrogen stable isotopes for the fauna and humans from the Magdalenenberg site. The 'prince' burial and 'warriors' buried with daggers are marked with a white cross. The analytical error in $\delta^{13}C$ is shown; the error in $\delta^{15}N$ is smaller than the symbols.

There is no observable difference in δ15N 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 δ13C values was found in the group of adult males, ranging from -20.9‰ to -18.8‰ (range 2.1‰) compared to the females (range 1.2‰) (Figure 7.3). It seems apparent that some males depended on slightly different food sources. The most positive δ13C values were found within one group of males, which also had the highest δ15N values. Compared to the herbivores, their δ15N values are elevated by ~4.5‰ and their δ13C values by ~1.5‰, which leads to the suggestion that 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 δ34S value (3.5 ±1.5‰, 1σ, n=39) is very similar to the mean δ34S value of the fauna (2.6 ± 3.4‰) and shows no input of any aquatic resources.

Moreover, the δ34S values within this group of males are randomly distributed, ranging from -1.9‰ (grave 123) to 5.0‰ (grave 90). While the consumption of aquatic resources is generally uncommon during the Iron Age (Jay and Richards 2007), elevated values in δ13C have been related to the consumption of millet in several Hallstatt and La Tène populations of central Europe. But 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 (grave 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).

7.5.2. 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 to the $^{87}Sr/^{86}Sr$ signatures from (a) the *Buntsandstein* surrounding the Magdalenenberg site, (b) the Hegau region towards the Lake Constance and (c) the bedrock of the Black Forest. Even without the exclusion of outliers, the differences in $^{87}Sr/^{86}Sr$ between 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) (Figure 7.1B). This finding strongly contrasts 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 it is more likely that the individuals with these high values were from closer proximity to the site than these more far-reaching 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 (Figure 7.1B), there is a more latitudinal gradient in the $\delta^{18}O$ values of meteoric water, with the lowest values measured in the southern edge of Germany and the northern Alps (Figure 7.4). Equations to convert enamel phosphate $\delta^{18}O$ values to drinking water $\delta^{18}O$ 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 $\delta^{18}O$ data in comparison with archaeological enamel data, if available, but also revert to $\delta^{18}O_{dw}$ conversions to compare to 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‰.

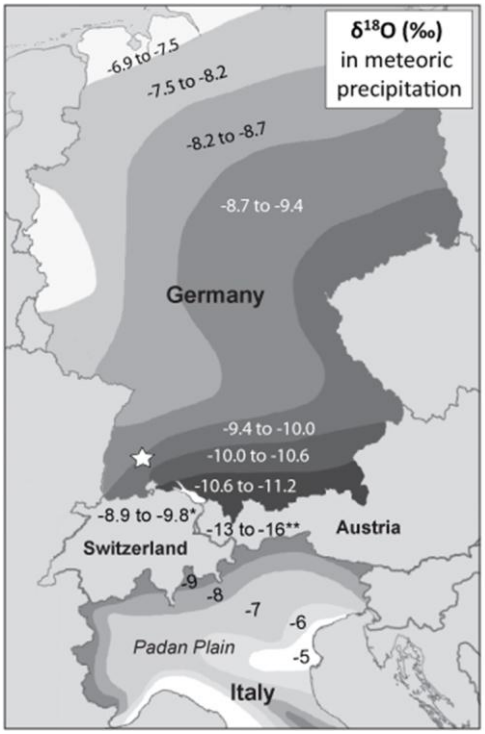

Figure 7.4: Oxygen isotope precipitation map for Germany and Italy (adapted after Tütken et al. 2004 and Longinelli and Selmo 2003) with additional $\delta^{18}O$ data from *faunal remains and **alpine spring water (after Tütken et al. 2008; Müller et al 2003). The site of Magdalenenberg is marked with a star.

Additionally, early forming teeth can potentially be affected by breastfeeding signals. Thus, conclusions drawn solely on behalf of $\delta^{18}O$ evidence should be considered with caution. Here, we only consider the few outliers which have $\delta^{18}O$ values that likely indicate a non-local origin. The $\delta^{18}O$ values of the Magdalenenberg humans range from 13.9‰ to 19.0‰, which suggests different drinking water sources. The $\delta^{18}O$ 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 $\delta^{18}O$ values of meteoric and stream water from the North Sea to the Alps and beyond to the Italian 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 7.1, Figure 7.4) (Buhl et al. 1991; Mayer et al. 1995; Müller et al. 2003; Tütken et al. 2004; Tütken et al. 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 (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 non-local individuals. The observed range of -1.9‰ to 6.7‰, (mean 3.5 ± 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 appear to be randomly distributed in their $^{87}Sr/^{86}Sr$ ratios and $\delta^{18}O$ values (Figure 7.5). Also, there is no association of the orientation of the burials and their organization within the cemetery to the measured isotope values, with the exception of a group west of the tumulus who have lower $^{87}Sr/^{86}Sr$ values (see Figure 7.2). Unfortunately, the skeletal preservation of the 'prince' burial (grave 1) was insufficient to provide information on his mobility, as teeth were not preserved and the sulphur 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 (± 0.00092, 1σ, n=8). Interestingly, the $^{87}Sr/^{86}Sr$ measured in the five human dentin samples (0.71195 ± 0.00245, 1σ) exactly match this range of values (Table 7.3) and thereby likely represent the soluble $^{87}Sr/^{86}Sr$ of the tumulus itself, which was constructed with materials from both geological substrates. While 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 (Figure 7.1C). 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 ± 0.00169 (1σ) and 0.71453 ± 0.00313 (1σ) on granite, which match the variation in geological substrates from the Black Forest measured by Baumann and Hoffmann (1988). A population dwelling on the 'Kapf' and producing foods locally should balance the variation observed between the different local plants and reveal values of around ~0.7130, probably slightly lower if also the *Muschelkalk* between the tumulus and the 'Kapf' site was cultivated, and probably slightly higher if the granite slopes and the metamorphic terrain towards the northwest were used for agriculture as well. A broad range of $^{87}Sr/^{86}Sr$ values between 0.7120 and 0.7145 seem plausible for this scenario, and 17 graves show $^{87}Sr/^{86}Sr$ values within this range (Figure 7.5). 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 (Figure 7.4). 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 appears 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 Km east and south of Magdalenenberg (mapped on Figure 7.1C, 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 (Figure 7.1B 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 (20Km) 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, Figure 7.1B). 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 that are not typically found in southern Germany (Figure 7.4), 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 and colleges (2008) measured archaeological fauna from the Swiss plateau (canton Zurich) and found homogenous values around 0.708, while the oxygen values resembled non-alpine 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.

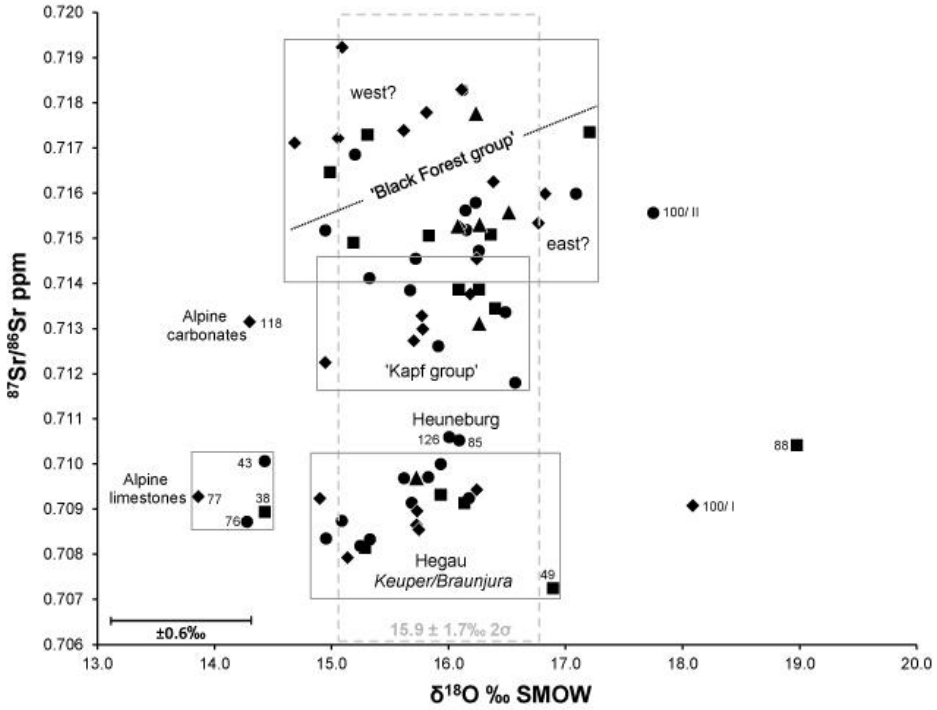

Figure 7.5: Plot of the strontium and oxygen isotope ratios measured in human enamel from the Magdalenenberg site. The analytical error in $\delta^{18}O$ is shown; the error in $^{87}Sr/^{86}Sr$ is smaller than the symbols (squares = males, circles = females, triangles = infants, diamonds = undetermined). The grey dashed box indicated the mean $\delta^{18}O$ value ($\pm 2\sigma$) for all Magdalenenberg human enamel samples.

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. Here it should be noted that a first molar was sampled which might have led to increased values $\delta^{18}O$ of approximately 0.7± 0.5‰ due to breastfeeding effects during enamel formation (Dupras and Tocheri 2007; White et al. 2000). 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 indicate warmer climate than we find north of the Alps. The German sea coast has the highest meteoric water values in the country (-7‰, Figure 7.4), whereas even higher values of -5‰ and -4‰ can be found at the Italian coast and the Iberian Peninsula (Bowen 2009; Longinelli and Selmo 2003). The $\delta^{34}S$ value of 2.0‰ is a typical terrestrial signature that does not indicate any

measurable input of marine sulphur (+20‰) from marine food consumption or sea spray effects, which can occur up to approximately 20km inland depending on the regional topography (Richards et al. 2001; Wadleigh et al. 1996). 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. Here 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 to the human mean value from the site and resemble $\delta^{18}O$ values measured in archaeological humans in western France (Daux et al. 2005). Calculated values for $\delta^{18}O_{dw}$ lie between -6.6‰ and -5.9‰, which can be found, for example, in Spain, western France or Italy (Figure 7.4). While we did not obtain sulphur 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 utilized 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 (Figure 7.5). 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 Figure 7.1A). The so called 'Bürgle' chariot grave tumulus of March-Buchheim was even larger (ø120m) than the Magdalenenberg mound and although the central 'princely' burial was robbed, the grave architecture and inventories indicate high status (Pare 1992).

7.6.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; Jay and Richards 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 non-local 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.

7.7. Acknowledgements

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 within the BMBF funded 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.

7.8. References

Ambrose SH. 1990. Preparation and characterization of bone and tooth collagen for isotopic analysis. J Arch Sci 17(4):431-451.

Ambrose SH. 1993. Isotopic analysis of palaeodiets: methodological and interpretative considerations. In: Sandford MK, editor. Investigations of ancient human tissue: chemical analyses in anthropology. Langhorne (Pennsylvannia): Gordon and Breach. p 59-130.

Baumann A, and Hofmann R. 1988. Strontium isotope systematics of hydrothermal vein minerals in deposits of West Germany. Geolog Rundschau 77:747-762.

Bentley A. 2006. Kinship and mobility during the prehistoric spread of farming: isotope evidence from the skeletons. General Anthropology 13(1):1-10.

Bentley RA. 2007. Mobility, specialisation and community diversity in the Linearbandkeramik: isotopic evidence from the skeletons. In: Whittle A, and Cummings V, editors. Going over: the Mesolithic-Neolithic transition in north-west Europe. London: British Academy. p 117-140.

Bentley RA, and Knipper C. 2005. Geographical patterns in biologically available strontium, carbon and oxygen isotope signatures in prehistoric SW Germany. Archaeometry 47:629-644.

Bentley RA, Price TD, Luning J, Gronenborn D, Wahl J, and Fullagar PD. 2002. Prehistoric migration in Europe: Strontium isotope analysis of early neolithic skeletons. Curr Anthropol 43(5):799-804.

Billamboz A, and Neyes M. 1999. Das Fürstengrab von Villingen-Magdalenenberg im Jahrringkalender der Hallstattzeit. In: Spindler K, editor. Der Madalenenberg bei Villingen Ein Fürstengrabhügel des 7 vorchristlichen Jahrhunderts Stuttgart: Theiss. p 91-109.

Bowen GJ. 2009. OIPC: The Online Isotopes in Precipitation Calculator (version OIPC2.2). http://wwwwaterisotopesorg. accessed 15th of October, 2011

Brown TA, Nelson DE, Vogel JS, and Southon JR. 1988. Improved collagen extraction by modified Longin method. Radiocarbon 30(2):171-177.

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

Buhl D, Neuser RD, Richter DK, Riedel D, Roberts B, Strauss H, and Veizer J. 1991. Nature and nurture: Environmental isotope story of the River Rhine. Naturwissenschaften 78(8):337-346.

Burton JH, Price TD, and Middleton WD. 1999. Correlation of bone Ba/Ca and Sr/Ca due to biological purification of calcium. J Arch Sci 26:609-616.

Canfield DE. 2001. Biogeochemistry of Sulfur Isotopes. Rev Mineral Geochem 43(1):607-636.

Chenery C, Müldner G, Evans J, Eckardt H, and Lewis M. 2010. Strontium and stable isotope evidence for diet and mobility in Roman Gloucester, UK. J Arch Sci 37(1):150-163.

Collins MJ, and Galley P. 1998. Towards an optimal method of archaeological collagen extraction: the influence of pH and grinding. Ancient Biomolecules 2:209-222.

Craig OE, Ross R, Andersen SH, Milner N, and Bailey GN. 2006. Focus: sulphur isotope variation in archaeological marine fauna from northern Europe. J Arch Sci 33(11):1642-1646.

Czarnetzki A. 1995. Das Kleinkinderdefizit der Merowingerzeit in Südwestdeutschland im Spiegel medizinhistorischer Erkenntnisse. Bull Mém Soc Suisse d'Anthrop 1/2:89–103.

Daux V, LéCuyer C, Adam F, Martineau F, and Vimeux F. 2005. Oxygen Isotope Composition Of Human Teeth And The Record Of Climate Changes In France (Lorraine) During The Last 1700 Years. Climatic Change 70(3):445-464.

Deniel C, and Pin C. 2001. Single-stage method for the simultaneous isolation of lead and strontium from silicate samples for isotopic measurements. Analytica Chimica Acta 426(11):95-103.

DeNiro MJ. 1985. Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. Nature 317:806-809.

Dettmann DL, Kohn MJ, Quade J, Reyerson FJ, Ojah TP, and Hamidullah S. 2001. Seasonal stable isotope evidence for a strong Asian monsoon throughout the past 10.7 Ma. Geology 29:31-34.

Drucker DG, Bridault A, Hobson KA, Szuma E, and Bocherens H. 2008. Can carbon-13 in large herbivores reflect the canopy effect in temperate and boreal ecosystems? Evidence from modern and ancient ungulates. Palaeogeography, Palaeoclimatology, Palaeoecology 266(1-2):69-82.

Dupras TL, and Tocheri MW. 2007. Reconstructing infant weaning histories at Roman period Kellis, Egypt using stable isotope analysis of dentition. Am J Phys Anthropol 134(1):63-74.

Ericson JE. 1985. Strontium Isotope Characterization in the Study of Prehistoric Human Ecology. J Hum Evol 14:503-514.

Evans JA, Montgomery J, Wildman G, and Boulton N. 2010. Spatial variations in biosphere $^{87}Sr/^{86}Sr$ in Britain. Journal of the Geological Society 167(1):1-4.

Farquhar GD, Ehleringer JR, and Hubick KT. 1989. Carbon isotope discrimination and photosynthesis. Annual Review of Plant Physiology and Plant Molecular Biology 40:503-537.

Faure G, and Powell T. 1972. Strontium isotope geology. New York: Springer-Verlag.

Fraser RA, Bogaard A, Heaton T, Charles M, Jones G, Christensen BT, Halstead P, Merbach I, Poulton PR, Sparkes D, Styring AK. 2011. Manuring and stable nitrogen isotope ratios in cereals and pulses: towards a new archaeobotanical approach to the inference of land use and dietary practices. Journal of Archaeological Science 38(10):2790-2804.

Gallay G. 1977. Die Körpergräber aus dem Magdalenenberg bei Villingen. In: Spindler K, editor. Magdalenenberg V, Der hallstattzeitliche Fürstengrabhügel bei Villingen im Schwarzwald, 5 Band. Villingen: Neckar-Verlag. p 69-78.

Fricke HC and O'Neil JR. 1999, The correlation between 18O/16O ratios of meteoric water and surface temperature: Its use in investigating terrestrial climate change over geologic time. Earth Planet Sci Lett 170:181–196.

Gehlen K, Nielsen H, and Ricke W. 1962. S-Isotopen-Verhältnisse in Baryt und Sulfiden aus hydrothermalen Gängen im Schwarzwald und Jängeren Barytgängen in Süddeutschland und ihre genetische Bedeutung. Geochim Cosmochim Ac 26:1189-1207.

Geyh MA. 2001. Bomb radiocarbon dating of animal tissues and hair. Radiocarbon 43(2B):723-730.

Giesemann AJH, Norman AL, Krouse HR, and Brand WA. 1994. On-line sulfur-isotope determination using an elemental analyzer coupled to a mass spectrometer. Analytical Chemistry 66:2816-2819.

Graustein WC. 1989. 87Sr/86Sr ratios measure the sources and flow of strontium in terrestrial ecosystems. In: Rundel PW, Ehleringer JR, and Nagy KA, editors. Stable isotopes in ecological research. New York: Springer-Verlag. p 491-512.

Grupe G. 2007. Taphonomic and Diagenetic Processes. In: Henke W, and Tattersall I, editors. Handbook of Paeoanthropology. Berlin: Springer. p 241-260.

Hedges REM, and Reynard LM. 2007. Nitrogen isotopes and the trophic level of humans in archaeology. J Arch Sci 34:1240-1251.

Hillson S. 2005. Teeth. Cambridge: Cambridge University Press.

Hoefs J. 1997. Stabel isotope geochemistry. Berlin, Heidelberg: Springer.

Hoppe KA, Koch PL, and Furutani TT. 2003. Assessing the preservation of biogenic strontium in fossil bones and tooth enamel. Int J Osteoarchaeol13:20-28.

Hübener W. 1972. Die hallstattzeitliche Siedlung am Kapf bei Villingen im Schwarzwald. In: Spindler K, editor. Magdalenenberg II, Der hallstattzeitliche Fürstengrabhügel bei Villingen im Schwarzwald, 2 Band. Villingen: Neckar-Verlag. p 51-88.

Humphrey LT, Dean MC, Jeffries TE, and Penn M. 2008. Unlocking evidence of early diet from tooth enamel. P Natl Acad Sci USA 105(19):6834-6839.

Iacumin P, Bocherens H, Mariotti A, and Longinelli A. 1996. Oxygen isotope analyses of co-existing carbonate and phosphate in biogenic apatite: a way to monitor diagenetic alteration of bone phosphate? Earth and Planetary Science Letters 142(1-2):1-6.

Jay M, Fuller BT, Richards MP, Knusel CJ, and King SS. 2008. Iron age breastfeeding practices in Britain: Isotopic evidence from Wetwang Slack, East Yorkshire. Am J Phys Anthropol 136(3):327-337.

Jay M, and Richards MP. 2006. Diet in the iron age cemetery population at Wetwang Slack, East Yorkshire, UK: carbon and nitrogen stable isotope evidence. J Arch Sci 33(5):653-662.

Jay M, and Richards MP. 2007. British Iron Age diet: stable isotopes and other evidence. Proceedings of the Prehistoric Society 73:169-190.

Johnson CM, Lipman PW, and Czamanske GK. 1990. H, O, Sr, Nd, and Pb isotope geochemistry of the Latir volcanic field and cogenetic intrusions, New Mexico, and relations between evolution of a continental magmatic center and modifications of the lithosphere. Contrib Mineral Petr 104(1):99-124.Langenscheidt F. 1985. Methodenkritische Untersuchungen zur Paläodemographie am Beispiel zweier fränkischer Gräberfelder. Materialhefte zur Bevölkerungswissenschaft Sonderheft 2.

Le Huray J, Schutkowski H, and M.P. R. 2006. La Tène dietary variation in Central Europe: a stable isotope study of human skeletal remains from Bohemia. In: Gowland R, and Knüsel C, editors. The social archaeology of funerary remains. Oxford: Oxbow Books. p 155-167.

Le Huray JD, and Schutkowski H. 2005. Diet and social status during the La Tène period in Bohemia: Carbon and nitrogen stable isotope analysis of bone collagen from Kutná Hora-Karlov and Radovesice. Journal of Anthropological Archaeology 24(2):135-147.

Lee-Thorp JA. 2008. On isotopes and old bones. Archaeometry 50:925-950.

Levinson AA, Luz B, and Kolodny Y. 1987. Variations in oxygen isotopic compositions of human teeth and urinary stones. Appl Geochem 2(4):367-371.

Longin R. 1971. New method of collagen extraction for radiocarbon dating. Nature 230:241-242.

Longinelli A. 1984. Oxygen isotopes in mammal bone phosphate: a new tool for paleohydrological and paleoclimatological research? Geochim Cosmochim Ac 48:385-390.

Longinelli A, and Peretti Padalino A. 1980. Oxygen isotopic composition of water from mammal blood: first results. Mass Spectrometry in Biochemical, Medical and Environmental Research 1:135-139.

Longinelli A, and Selmo E. 2003. Isotopic composition of precipitation in Italy: a first overall map. J Hydrol 270(1-2):75-88.

Mayer B, Feger K, Giesemann A, and Jäger H-J. 1995. Interpretation of sulfur cycling in two catchments in the Black Forest (Germany) using stable sulfur and oxygen isotope data. Biogeochemistry 30(1):31-58.

Minagawa M, and Wada E. 1984. Stepwise enrichment of ^{15}N along food chains: further evidence and the relation between ^{15}N and animal age. Geochim Cosmochim Ac 48:1135-1140.

Müller S. 1977. Bodendiagenetische Prozesse im hallstattzeitlichen Grabhügel Magdalenenberg bei Villingen. In: Spindler K, editor. Magdalenenberg V, Der hallstattzeitliche Fürstengrabhügel bei Villingen im Schwarzwald, 5 Band. Villingen: Neckar-Verlag. p 69-78.

Müller W, Fricke H, Halliday A, McCulloch M, and Wartho J. 2003. Origin and migration of the Alpine Iceman. Science 302:862-866.

Murray ML, and Schoeninger MJ. 1988. Diet, status, and complex social structure in Iron Age Central Europe: Some contributions from bone chemistry. In: Gibson DB, and Geselowitz MN, editors. Tribe and Polity in Late Prehistoric Europe: Demography, Production and Exchange in the Evolution of Complex Social Systems. New York: Plenum Press. p 155-176.

Nehlich O, Boric D, Stefanovic S, and Richards MP. 2010. Sulphur isotope evidence for freshwater fish consumption: a case study from the Danube Gorges, SE Europe. J Arch Sci 37(5):1131-1139.

Nehlich O, and Richards MP. 2009. Establishing collagen quality criteria for sulphur isotope analysis of archaeological bone collagen. Archaeological and Anthropological Sciences 1(1):59-75.

Nehlich O, and Wahl J. 2011. Binnengewässer – eine unterschätzte Nahrungsressource –Stabile Kohlenstoff-, Stickstoff- und Schwefelisotope aus dem Kollagen menschlicher und tierischer Knochenreste aus der urnenfelderzeitlichen Nekropole von Neckarsulm. Fundberichte aus Baden-Württemberg 31:97-113.

O'Neil JR, Roe LJ, Reinhard E, and Blake RE. 1994. A rapid and precise method of oxygen isotope analysis of biogenic phosphate. Israel Journal of Earth Sciences (43):203-212.

Oelze VM, Nehlich O, and Richards MP (2011a). 'There's no place like home' - No isotopic evidence for mobility at the Early Bronze Age cemetery of Singen, Germany. Archaeometry, doi: 10.1111/j.1475-4754.2011.00644.x

Oelze VM, Siebert A, Nicklisch N, Meller H, Dresely V, and Alt KW (2011b). Early Neolithic diet and animal husbandry: stable isotope evidence from three Linearbandkeramik (LBK) sites in Central Germany. J Arch Sci 38 (2):270-279.

Pare C. 1992. Das Bürgle bei March-Buchheim: ein Riesengrabhügel der Späthallstattzeit. Archäologisches Korrespondenzblatt 22:503-514.

Pellegrini M, Donahue RE, Chenery C, Evans J, Lee-Thorp J, Montgomery J, and Mussi M. 2008. Faunal migration in late-glacial central Italy: implications for human resource exploitation. Rapid commun mass sp 22(11):1714-1726.

Peterson BJ, and Fry B. 1987. Stable Isotopes in Ecosystem Studies. Annu Rev Ecol Syst 18:293-320.

Pollard AM, Pellegrini M, and Lee-Thorp JA. 2011. Technical note: Some observations on the conversion of dental enamel $\delta^{18}O_p$ values to $\delta^{18}O_w$ to determine human mobility. Am J Phys Anthroplo 145(3):499-504.

Price TD, Burton JH, and Bentley RA. 2002. The characterization of biological available strontium isotope ratios for the study of prehistoric migration. Archaeometry 44(1):117-135.

Price TD, Knipper C, Grupe G, and Smrcka V. 2004. Strontium Isotopes and Prehistoric Human Migration: The Bell Beaker Period in Central Europe. European Journal of Archaeology 7(1):9-40.

Richards MP, Fuller BT, and Hedges REM. 2001. Sulphur isotopic variation in ancient bone collagen from Europe: implications for human palaeodiet, residence mobility, and modern pollutant studies. Earth Planet Sc Lett 191(3-4):185-190.

Richards MP, Fuller BT, Sponheimer M, Robinson T, and Ayliffe L. 2003. Sulphur isotopes in palaeodietary studies: a review and results from a controlled feeding experiment. Int J Osteoarchaeol13:37-45.

Rieckhoff S. 2001. Die Kelten in Deutschland. Stuttgart: Theiss.

Rösch M. 1998. The history of crops and crop weeds in south-western Germany from the Neolithic period to modern times, as shown by archaeobotanical evidence. Veg Hist Archaeobot 7(2):109-125.

Sakai H. 1957. Fractionation of sulphur isotopes in nature. Geochim Cosmochim Ac 12(1-2):150-169.

Schmid-Sikimić B. 2002. Eisenzeitlicher Bestattungsplatz im Brennpunkt zwischen Nord und Süd. Bonn Habelt.

Schoeninger MJ, and DeNiro MJ. 1984. Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. Geochim Cosmochim Ac 48:625-639.

Schoeninger MJ, DeNiro MJ, and Tauber H. 1983. Stable nitrogen isotope ratios of bone collagen reflect marine and terrestrial components of prehistoric human diet. Science 220:1381-1383.

Spindler K. 1971. Magdalenenberg I, Der hallstattzeitliche Fürstengrabhügel bei Villingen im Schwarzwald, 1. Band. Villingen: Neckar-Verlag.

Spindler K. 1972. Ein Gürtelhaken iberischer Herkunft vom Magdalenenberg bei Villingen im Schwarzwald. Archäologisches Korrespondenzblatt 2:271-277.

Spindler K. 1976. Magdalenenberg IV, Der hallstattzeitliche Fürstengrabhügel bei Villingen im Schwarzwald, 4. Band. Villingen: Neckar-Verlag.

Spindler K. 1980. Magdalenenberg VI, Der hallstattzeitliche Fürstengrabhügel bei Villingen im Schwarzwald, 6. Band. Villingen: Neckar-Verlag.

Spindler K. 2004. Der Magdalenenberg bei Villingen im Schwarzwald - eine Bilanz nach 30 Jahren. In: Hänsel B, editor. Parerga praehistorica. Bonn: Habelt. p 135-160.

Spötl C, and Pak E. 1996. A strontium and sulfur isotopic study of Permo-Triassic evaporites in the Northern Calcareous Alps, Austria. Chemical Geology 131(1-4):219-234.

Stephan E. 2009. Rekonstruktion eisenzeitlicher Weidewirtschaft anhand archäozoologischer und isotopenchemischer Untersuchungen. In: Benecke N, editor. Beiträge zur Archäozoologie und Prähistorischen Anthropologie. Langenweißbach: Beier & Beran. p 65-79.

Terakado Y, Shimizu H, and Masuda A. 1988. Nd and Sr isotopic variations in acidic rocks formed under a peculiar tectonic environment in Miocene Southwest Japan. Contrib Mineral Petr 99 (1):1-10.

Tieszen LL. 1991. Natural variations in the carbon isotope values of plants: implications for archaeology, ecology and paleoecology. J Arch Sci 18:227-248.

Tütken T, Langenegger E, and Wild W. 2008. Native or not? Isotope analysis of a female sl´keleton on the 9th century A.D. from Elsau, Canton Zurich, Switzerland. Anthropol Anzeiger 66:19-50.

Tütken T, Vennemann TW, and Pfretzschner H-U. 2004. Analyse stabiler und radiogener Isotope in archäologischem Skelettmaterial: Herkunftsbestimmung des karolingischen Maultiers von Frankenthal und Vergleich mit spätpleistozänen Großsäugerknochen aus den Rheinablagerungen. Praehistorische Zeitschrift 79(1):89-110.

van der Merwe NJ, and Medina E. 1991. The canopy effect, carbon isotope ratios and foodwebs in Amazonia. J Arch Sci 18:249-259.

van Klinken GJ. 1999. Bone collagen quality indicators for palaeodietary and radiocarbon measurements. J Arch Sci 26:687-695.

Vika E. 2009. Strangers in the grave? Investigating local provenance in a Greek Bronze Age mass burial using $\delta^{34}S$ analysis. J Arch Sci 36(9):2024-2028.

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 Chemistry 118(4):933-940.

Vogel JC, and Merwe NJvd. 1977. Isotopic Evidence for Early Maize Cultivation in New York State. American Antiquity 42(2):238-242.

Wadleigh MA, Schwarcz HP, and Kramer JR. 1996. Isotopic evidence for the origin of sulphate in coastal rain. Tellus B 48(1):44-59.

Warneke T. 1999. Hallstatt- und frühlatènezeitlicher Anhängerschmuck. Rahden: Leidorf.

Wells P. 2008. Trade and Exchange in later Prehistory. In: Jones A, editor. Prehistoric Europe: theory and practice. Oxford: Wiley-Blackwell.

Wells PS. 2002. The Iron Age. In: Milisauskas S, editor. European Prehistory - A Survey. New York: Kluwer Adademic.

White CD, Spence MW, Le Q. Stuart-Williams H, and Schwarcz HP. 1998. Oxygen Isotopes and the Identification of Geographical Origins: The Valley of Oaxaca versus the Valley of Mexico. J Arch Sci 25(7):643-655.

Wild E, Arlamovsky K, Golser R, Kutschera, W., Priller A, Puchegger S, Rom W, Steier P, and Vycudilik W. 2000. 14C dating with the bomb peak. Nucl Instrum Meth B 172:944 - 950.

Wright LE, and Schwarcz HP. 1998. Stable carbon and oxygen isotopes in human tooth enamel: Identifying breastfeeding and weaning in prehistory. Am J Phys Anthropol 106(1):1-18.

White CD, Spence MW, Longstaffe FJ, and Law KR. 2000. Testing the Nature of Teotihuacán Imperialism at Kaminaljuyú Using Phosphate Oxygen-Isotope Ratios. Journal of Anthropological Research 56(4):535-558.

7.9. Appendix methods

Provided as an online supplementary.

7.9.3. 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 (Brown et al. 1988; Collins and Galley 1998; Longin 1971). Bone samples were cleaned using air abrasion and then demineralized in 0.5M HCl for several weeks at 4°C, with acid changes every few days. Completely demineralized samples were rinsed three times with de-ionized water and gelatinized for 48 hours at 70°C in a pH3 solution. The insoluble fraction was first filtered with a 5µm EZEE© filter, and subsequently filtered using Amicon© ultrafilters (cut off of <30kDa). The purified solution was frozen and then freeze dried for 48 hours. Finally, 0.5mg and 10mg of dried collagen sample was weighed into tin capsules for measurement of carbon and 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.

7.9.4. 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 deionised water. Samples were transferred to the clean laboratory, rinsed again in ultrapure acetone and dried overnight. Subsequently ~10-20mg of enamel or dentin was weighed into clean Teflon beakers and digested in 1ml of 14.3M HNO_3 on a hotplate (120°C). The dissolved samples of enamel and dentin were evaporated to dryness and were combined with 1ml of 3M HNO3 before being loaded on clean, pre-conditioned 2ml columns containing cleaned Sr-spec^{TM} resin (EiChrom, Darien, IL, USA). Samples were reloaded three times. Then, after several washes with 3M HNO_3, the strontium was eluted from the resin with ultrapure deionised water into clean Teflon beakers and dried down on a hot plate. The remaining samples, again re-dissolved 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^{TM} MC-ICP-MS instrument (Thermo Fisher Scientific Inc., Dreieich, Germany).

7.9.5. 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 (Dettmann et al. 2001; O'Neil et al. 1994). 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 1ml 2M HF for 24 hours. Then samples were centrifuged and the solution containing the phosphate was transferred into a new tube. Several drops of BTB (Bromothymol blue) was added to subsequently be able to check the pH (<7). Then the HF was buffered with 300µl of NH_4OH. When the sample was neutral, ~700µl 2M AgNO3 was added. Subsequently the silver phosphate crystals precipitated resulting in Ag_3PO4 crystals of light yellow colour. The residue was centrifuged, rinsed with deionised 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 ~700µg Ag_3PO_4 into silver capsules, ~0.5mg of graphite was added as described by Vennemann and colleges (2002). The capsules were then combusted to CO in a HekaTech high-temperature

combustion oven with helium carrier gas at 1450 °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.

7.9.6. Age and sex determination

The commonly anthropological methods for age and sex determination were applied to all human remains from the Magdalenenberg site (Buikstra and Ubelaker 1997; Ferembach et al. 1980). 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 (Iscan 1989; Lovejoy 1985; Lovejoy et al. 1985; Meindl and Lovejoy 1985; 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 (Bruzek 2002; Ditch and Rose 1972; Murail et al. 2005).

7.9.7. References appendix

Brown TA, Nelson DE, Vogel JS, and Southon JR. 1988. Improved collagen extraction by modified Longin method. Radiocarbon 30(2):171-177.

Bruzek J. 2002. A method for visual determination of sex, using the human hip bone. Am J Phys Anthropol 117(2):157-168.

Buikstra JE, and Ubelaker DH. 1997. Standards for Data Collection from Human Skeletal Remains. Arkansas Arch Survey Research Series 44.

Collins MJ, and Galley P. 1998. Towards an optimal method of archaeological collagen extraction: the influence of pH and grinding. Ancient Biomolecules 2:209-222.

Deniel C, and Pin C. 2001. Single-stage method for the simultaneous isolation of lead and strontium from silicate samples for isotopic measurements. Analytica Chimica Acta 426(11):95-103.

Dettmann DL, Kohn MJ, Quade J, Reyerson FJ, Ojah TP, and Hamidullah S. 2001. Seasonal stable isotope evidence for a strong Asian monsoon throughout the past 10.7 Ma. Geology 29:31-34.

Ditch LE, and Rose JC. 1972. A multivariate dental sexing technique. Am J Phys Anthropol 37(1):61-64.

Ferembach D, Schwidetzky I, and Stloukal M. 1980. Recommendations for age and sex diagnoses of skeletons. J Hum Evol 9(7):517-549.

Iscan MY. 1989. Age Markers in the Human Skeleton. Springfield C. C. Thomas.

Longin R. 1971. New method of collagen extraction for radiocarbon dating. Nature 230:241-242.

Lovejoy CO. 1985. Dental wear in Libben population: Its functional pattern and role in the determination of adult skeletal age at death. Am J Phys Anthropol 68:47-56.

Lovejoy CO, Meindl RS, Pryzbeck TR, and Mensforth RP. 1985. Chronological metamorphosis of the auricular surface of the ilium: a new method for the determination of adult skeletal age at death. Am J Phys Anthropol 68:15-28.

Meindl RS, and Lovejoy CO. 1985. Ectocranial suture closure: A revised method for determination of skeletal age at death based on the lateral-anterior sutures. Am J Phys Anthropol 68:57-66.

Murail P, Bruzek J, Houët F, and Cunha E. 2005. DSP: A tool for probabilistic sex diagnosis using worldwide variability in hip-bone measurements. Bulletins et mémoires de la Société d'Anthropologie de Paris 17(3-4):167-176

O'Neil JR, Roe LJ, Reinhard E, and Blake RE. 1994. A rapid and precise method of oxygen isotope analysis of biogenic phosphate. Israel Journal of Earth Sciences (43):203-212.

Richards M, Harvati K, Grimes V, Smith C, Smith T, Hublin JJ, Karkanas P, and Panagopoulou E. 2008. Strontium isotope evidence of Neanderthal mobility at the site of Lakonis, Greece using laser-ablation PIMMS. J Arch Sci 35(5):1251-1256.

Vennemann TW, Fricke HC, Blake RE, O'Neil JR, and Colman A. 2002. Oxygen isotope analysis of phosphates: a comparison of techniques for analysis of Ag_3PO_4. Chemical Geology 185:321-336.

White TD. 2000. Human osteology (2. edition). San Diego: Academic Press.