Mobility and diet in Neolithic, Bronze Age and Iron Age Germany : evidence from multiple isotope analysis

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Citation

Oelze, V. M. (2012, June 6). *Mobility and diet in Neolithic, Bronze Age and Iron Age Germany : evidence from multiple isotope analysis*. Retrieved from https://hdl.handle.net/1887/19045

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Author: Oelze, Viktoria Martha
Title: Mobility and diet in Neolithic, Bronze Age and Iron Age Germany : evidence from multiple isotope analysis
Issue Date: 2012-06-06

Mobility and Diet in Neolithic, Bronze Age and Iron Age Germany

Evidence from Multiple Isotope Analysis

Proefschrift

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van Rector Magnificus prof. mr. P.F. van der Heijden,
volgens besluit van het College voor Promoties
te verdedigen op woensdag 6 juni 2012
klokke 15.15 uur

door

Viktoria Martha Oelze

geboren te Koblenz
in 1981

Promotiecommissie

Promotors: Prof. Dr. J.-J. Hublin
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Overige Leden: Prof. Dr. H. van der Plicht
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Dit proefschrift is mede mogelijk gemaakt door *Bundesministerium für Bildung und Forschung*, Bondsrepubliek Duitsland, en het *Max Planck Gesellschaft*.

Tiger got to hunt, bird got to fly;
Man got to sit and wonder 'Why, why, why?'

Tiger got to sleep, bird got to land;
Man got to tell himself he understand.

Kurt Vonnegut
Cat's Cradle, 1964

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1. Introduction

1.1. Preface

Exactly 30 years have passed since the first application of stable isotope analysis on European archaeological material (Tauber 1981). Since then, much research has focussed on reconstructing palaeodiet, subsistence and mobility in ancient populations across the continent. However, some prehistoric periods and cultures have been addressed more comprehensively than others, and many temporal and spatial gaps in isotope research yet remain (see chapter 4). The scope of this doctoral thesis is to fill these research gaps in prehistoric Germany with a combination of different isotope systems applied to answer a range of different questions. This thesis consists of four main components:

1) The reconstruction of human diet and animal husbandry in the Early Neolithic (chapter 5)
2) The reconstruction of human mobility and provenance in the Early Bronze Age (chapter 6)
3) The reconstruction of human mobility and provenance in the Early Iron Age (chapter 7)
4) Strontium biosphere mapping in south-western Germany as a basis for reconstructing prehistoric mobility (chapter 6 and 7)

The archaeological sites analysed in this work represent populations in highly transitional and innovative phases of cultural and technological evolution. This includes the earliest sedentary agriculturalists in central Europe, the *Linearbandkeramik* (LBK). Dietary behaviour of these first small scale farmers, as well as their strategies in crop cultivation and animal husbandry, are only fragmentarily documented by means of stable isotope research. Unique skeletal preservation at the LBK sites of Derenburg, Halberstadt and Karsdorf in Central Germany allowed biochemical analysis in individuals with determined age and sex. Moreover, the presence of faunal remains enabled the first evaluation of possible herding strategies in this part of Europe during the LBK. The aim of this study is to gain novel information on the influence of age, sex and social status on the human diet. Furthermore, weaning ages and dietary differences or similarities between neighbouring communities are explored. The work presented in this thesis is the first comprehensive palaeodietary reconstruction of LBK populations. This research is part of an on-going project on the lifeways of Neolithic people in Central Germany, conducted by the Institute for Anthropology, Mainz University, Germany.

The study of the human remains from the Early Bronze site of Singen and the Early Iron Age site of Magdalenenberg were part of an interdisciplinary project between the Max Planck Institute for Evolutionary Anthropology (MPI-EVA) and the Department of Pre- and Protohistory at Leipzig University[1]. Both sites can be assigned to the transitional period between small scale farming societies and the rise of major centres of power and influence; both are suggested to have participated in the inception of bronze and iron metallurgy in Germany. Certainly, the development of metallurgy in the Early Bronze and Iron Ages had implications for socioeconomic organization of society and also the transfer networks between distant groups (Wells 2008). Thus, the study of these populations' material cultures and human life history is particularly interesting for archaeology and archaeological sciences.

The rich grave good assemblage recovered from the site of Singen (Hohentwiel) in Baden-Württemberg, near Lake Constance, has become an important reference collection for bronze artefact typology for the north alpine Bronze Age. The copper alloys found at Singen are widely distributed within the European '*Blechkreis*' and extend into the western Alps, the Baltic Sea and the Carpathian Basin (Krause 1988; Krause 2003). However, it has remained poorly understood how these far reaching metal transfer networks were socialized and maintained. It has been proposed that the Singen community may have integrated foreign individuals for this purpose, a hypothesis which has never been tested biochemically. A similar situation applies to the Early Iron Age necropolis of Magdalenenberg, near Villingen in the Black Forest. The monumental burial mount, assigned to the Hallstatt culture, included a central prince grave and numerous inhumations. According to the abundant and partly exotic grave inventories found at the Magdalenenberg tumulus site, the graves were assumed to represent the social elite with a high number of immigrant individuals. Furthermore, it remains unclear whether the majority of the burial community lived locally or if individuals of high status were brought to the Magdalenenberg for an 'appropriate' burial next to the prince (Spindler 2004). The aim of the biochemical analysis presented in this thesis is to reconstruct individual human residence and mobility patterns. By applying different complementary isotope systems, individuals with a non-

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[1] under direction of Prof. Sabine Rieckhoff and generously funded by the Federal Ministry for Education and Science, Federal Republic of Germany (BMBF), 2008 to 2012, *Förderkennzeichen* 01UA0811.

local origin can be identified and potential regions of provenance can be assigned. By reconstructing individual life history, initial conclusions on the maintenance of socioeconomic networks in the Bronze and Iron Ages of Germany can be drawn.

While the comprehensive biochemical study on the human and faunal remains was conducted at the MPI-EVA, an archaeologist from the Chair of Prehistory at Leipzig University studied the typology of the artefact assemblages for gender and age related connection to ‘foreign’ or ‘exotic’ grave inventories. This on-going work by Julia Koch at the Department of Pre- and Protohistory at Leipzig University will include the scientific evidence presented in this thesis and establish a new theoretical framework for the integration of ‘foreign’ individuals in prehistoric societies (Koch and Kupke in print). The analysis of stable isotope ratios of carbon and nitrogen for dietary reconstruction was part of a masters thesis at the MPI-EVA by Katharina Kupke (2010) under supervision of Michael Richards. The isotope analysis of sulphur, strontium and oxygen and the synthesis of data were part of this doctoral thesis which started in August 2008. This work included sampling of archaeological material in different museums and institutions as well as the labour intensive wet chemical sample pre-treatment in the sample preparation and ultra-clean laboratories at the MPI-EVA. Moreover, large parts of Baden-Württemberg were visited in a field trip in 2009 in order to collect environmental samples for strontium isotope mapping in the geological landscape which surrounds the sites of Singen and Magdalenenberg. The data from this strontium biosphere mapping were not only necessary for data interpretation in this thesis, but provide a valuable reference for future studies using strontium isotopes in this region.

1.2. Isotopic evidence revealed from skeletal remains - a brief science history

In the late 1970’s stable isotope analysis was established as a powerful tool for investigating past human diets from their skeletal remains (Vogel and van der Merwe 1977; DeNiro and Epstein 1978; Van Der Merwe and Vogel 1978). The first measures of stable carbon isotope ratios ($\delta^{13}C$) were more or less by-products of radiocarbon dating and were used to check for marine reservoir effects that altered the dating results in fossil tissues. Hence, the first stable isotope studies in Europe derived from radiocarbon laboratories and compared $\delta^{13}C$ values from different archaeological periods. One of the first dietary studies using $\delta^{13}C$ was done on archaeological human remains from Denmark, including a few Iron Age specimens. For the first time, Tauber (1981) demonstrated that the dependence on marine foods had significantly changed through time. A few years later, biochemical research discovered the potential of a combined approach of using $\delta^{13}C$ parallel to nitrogen stable isotopes ($\delta^{15}N$) to classify the dietary background of an organism (DeNiro and Epstein 1981; Schoeninger *et al.* 1983). In European archaeology, this was first applied in 1988 to Iron Age material from Slovenia, resulting in unique evidence for millet consumption in prehistoric Europe. Parallel to this development, a method known from the field of paleoclimatology came into use in archaeology. Longinelli (1984) found that stable oxygen isotope ratios ($\delta^{18}O$) measured in fossil tissue correlated to local meteoric water sources. Thus, drinking water sources of ancient humans could be reconstructed. Simultaneously, the strontium isotope ratio ($^{87}Sr/^{86}Sr$) geochemistry method was first applied to archaeological material to trace human 'residence catchments' and locality (Ericson 1985). The lead isotope ($^{207}Pb/^{206}Pb$, $^{208}Pb/^{206}Pb$) method, previously used to determine the source of archaeological metal ores (Brill 1970), was applied to human skeletal remains to describe human provenance and mobility (Ghazi 1994). However, this approach is still problematic due to the ubiquity of anthropogenic lead in the modern environment, which makes the utility of modern references problematic (Rummel *et al.* 2007). Finally, sulphur stable isotope ($\delta^{34}S$) analysis has recently been introduced and can detect differences between marine, freshwater and terrestrial food sources and in providing information on the geological background of food resources (Richards *et al.* 2001). While the identification of chemical contamination and alteration in fossil tissue (Ambrose 1990; Iacumin *et al.* 1996; Budd *et al.* 2000; Chiaradia *et al.* 2003) and the isotopic characterization of the term 'local' should turn out to be critical for future isotope research in archaeology (Bentley *et al.* 2004; Evans *et al.* 2010), the combination of the various isotope systems has demonstrated the potential to gain direct insights into the life histories of ancient human populations.

2. Human diet

"Tell me what you eat and I will tell you what you are"

Anthelme Brillat-Savarin (1826)
Physiologie du Gout, ou Meditations de Gastronomie Transcendante

An archaeological site can provide various lines of evidence on how prehistoric humans utilized their environment. Archaeobotanical analysis of charred plant remains or pollen grains allows a better understanding of which plants were gathered or cultivated, and calculations on the timing and efficiency of ancient cropping systems can be made (Jones and Colledge 2001; Bogaard 2004). On the other hand, archaeozoological studies of faunal assemblages can provide information on which animal species were selected for hunting or domestication (Lyman 1994). The mortality profile in domestic species may indicate whether animals were raised for meat or secondary products like milk (Halstead 1998). Artefacts may also indicate what ancient people ate; the best examples of which are fish hooks and so called milk strainers (Hedges 2009). Also, residue analysis of fats and proteins on potsherds indicates which types of food were produced or stored (Craig 2002; Evershed *et al.* 2008). While these approaches make the presence or absence of food items evident, they may not provide a full picture on ancient human dietary choice and behaviour, which may also be affected by age, sex or dietary taboos. Here, direct measures of the consumer's body tissue can determine which primary food sources were utilized by the individual. What remains of a human individual in the archaeological context is, in the best case, a buried skeleton. Depending on the burial conditions and environment, skeletal remains have the potential to persist over millennia and retain a lifetime dietary signal which is preserved in the bones' chemical components. In archaeological science this individual dietary signal is traced with the stable isotope ratios of carbon, nitrogen and sulphur. Following the basic principle of "you are what you eat", the isotopic compositions of food sources are incorporated into body tissues and are preserved in the organic fraction of bone or more specifically the bone collagen (Ambrose 1993; Kohn 1999). On the basis of modern collagen, several reliable criteria have been identified to test the chemical integrity of archaeological bone (DeNiro 1985; Ambrose 1990; van Klinken 1999; Nehlich and Richards 2009). Measures of collagen stable isotope ratios are therefore regarded to truly reflect the *in vivo* dietary signature. As each isotope system is driven by different chemical and ecological mechanisms, different types of food may have different ranges of isotope values. This forms the basis of palaeodietary reconstruction.

2.1. Carbon & Nitrogen

Carbon stable isotopes are expressed as the ratios between the heavy (^{13}C) and the light (^{12}C) isotope of the element carbon as $\delta^{13}C$, and are measured in ‰ units relative to the international standard Pee Dee Belemnite (PDB), a carbonate rock in South Carolina, USA. In terrestrial ecosystems, variation in $\delta^{13}C$ is mainly a result of different photosynthetic carbon reduction pathways (C_3, C_4 or CAM) in green plants. The underlying mechanism is the fractionation in isotope ratio which occurs during chemical processes, e.g. within a plant or animal tissue and is due to the slightly different chemical properties of the two isotopes (Peterson and Fry 1987; Ambrose 1993). C_4-plants produce significantly higher $\delta^{13}C$ values than C_3-plants, providing a useful method to trace the domestication and production of C_4-plants; one example is maize from the New World (Vogel and van der Merwe 1977). While temperate Europe is clearly dominated by C_3-plants, solely the C_4-plant millet (*Panicum miliaceum)* has been introduced with Neolithic expansion. According to $\delta^{13}C$ data, millet was an important staple food in the Bronze and Iron Ages in some parts of Europe (Murray and Schoeninger 1988; Tafuri *et al.* 2009). Apart from plants, $\delta^{13}C$ values correspond to certain positions in the food web, as a specific isotope fractionation (+1-2‰) occurs with every step in the food chain (DeNiro and Epstein 1978). Moreover, variation in $\delta^{13}C$ within terrestrial C_3-dominated ecosystems can correspond to the density and position within a forest canopy (Tieszen 1991; van der Merwe and Medina 1991) or can be affected by latitude and altitude (Körner *et al.* 1991). The $\delta^{13}C$ values of marine ecosystems are relatively uniform and mainly determined by atmospheric carbon, planktonic photosynthesis and respiration as well as by the underlying sedimentation. The $\delta^{13}C$ ratios in freshwater systems can vary largely due to the various potential sources of carbon (Boutton 1991). Measurements of $\delta^{13}C$ in archaeological bone collagen reflect the carbon fraction from the dietary protein component, but do not encompass the main component of dietary carbon, the carbohydrates and fats. While the analysis of the mineral phase of bone (apatite) does represent these components (Ambrose and Norr 1993; Kellner and Schoeninger 2007), its validity remains controversial due to largely unsolved contamination and alteration issues (Koch *et al.* 1997).

The stable isotope ratio of nitrogen ($\delta^{15}N$) is expressed as the ratio between the heavy (^{15}N) and the light (^{14}N) isotope and is described in ‰ units in relation to the standard value of atmospheric air (AIR), which is ~0‰. In terrestrial ecosystems, nitrogen enters the biosphere from the atmosphere mainly via nitrogen fixing soil bacteria which is then utilized by plants. In terrestrial plants, variation in $\delta^{15}N$ is mainly driven by climate, temperature, precipitation and salinity (Heaton *et al.* 1986; van Klinken *et al.* 2000). On the other hand, variation in $\delta^{15}N$ of consumers is dominated by the trophic level effect. Similar to carbon, $\delta^{15}N$ fractionates in every step in the food chain within the tissue of an organism, leading to an enrichment of approximately 2-5‰ in each trophic level (DeNiro and Epstein 1981; Minagawa and Wada 1984; Hedges and Reynard 2007). As aquatic environments have enriched plant baseline values and exhibit more complex and nested food webs, $\delta^{15}N$ values in marine and freshwater animals are significantly higher than in terrestrial species (Schoeninger and DeNiro 1984). The combination of both isotope systems allows for characterizing herbivorous, omnivorous and carnivorous diets and differentiating between aquatic and terrestrial food sources. As nitrogen is most abundant in the protein fraction (amino acids) of body tissues, data obtained from bone collagen mainly reflects the isotopic composition of dietary protein (Ambrose 1993). Hence, the relative dietary contribution from plant or animal protein, or a mixture of both, can be detected in archaeological bone samples. In humans, differences in the levels of animal protein consumption can be correlated to social status, assuming that meat and milk can be considered desirable foods (Le Huray *et al.* 2006). It is important to note that due to similar trophic levels of meat and milk (and milk-products), these two types of protein cannot be differentiated using stable isotopes. However, this fact is particularly useful in studying breastfeeding and weaning behaviour in ancient humans and animals. Infants living on their mother's milk are isotopically enriched compared to the nursing female, and their dietary signal appears as carnivorous (Fuller *et al.* 2006). The presence or absence of such a nursing signal can provide information on the nursing and weaning age in prehistoric populations (Katzenberg and Pfeiffer 1995; Schurr 1998).

2.2. Sulphur

Stable sulphur isotope analysis in bone collagen has been shown to be a promising new tool for dietary reconstructions. The ratio of the heavy (^{34}S) versus the light (^{32}S) isotope of sulphur is expressed as $\delta^{34}S$ and measured in ‰ units relative to the meteorite standard Canyon Diablo Troilite (CDT). While it had been difficult to analyse sulphur in archaeological samples due to technical constraints, recent improvements allow for smaller samples sizes and lower measurement errors (Giesemann *et al.* 1994; Morrison *et al.* 2000). Furthermore, this new analytical approach was strengthened by the introduction of quantity controls for bone collagen to assure the integrity of $\delta^{34}S$ ratios in collagen (Nehlich and Richards 2009). The main application of $\delta^{34}S$ in archaeological material is to differentiate between marine, freshwater and terrestrial dietary sources (Craig *et al.* 2006; Nehlich *et al.* 2010; Nehlich and Wahl 2011). Within different ecosystems, anaerobic bacteria fractionate sulphur isotopes (Canfield 2001) and cause strong variations in $\delta^{34}S$ values in freshwater, marine and terrestrial ecosystems, ranging from -22‰ to +20‰. Organisms living in marine ecosystems have $\delta^{34}S$ values close to +20‰, whereas purely terrestrial animals have values lower than +10‰, typically between +2‰ and +6‰ (Peterson and Fry 1987; Richards *et al.* 2003). Freshwater values may fall between these two extremes, depending on the conditions for sulphur cycling in the respective aquatic biotope. The first studies on prehistoric populations consuming freshwater fish have shown the reliability of this method in detecting aquatic resource utilization (Nehlich *et al.* 2010; Nehlich and Wahl 2011).

3. Mobility, migration and provenance

“Are you suggesting that coconuts migrate?”

Monty Python (1974)
Monty Python and the Holy Grail

The perception of prehistoric migration and mobility within sedentary societies has fundamentally changed in the last decades. While migration had been a “lazy person’s explanation for culture change” in archaeology (comment by Anthony in Burmeister 2000: 554), the theoretical framework has been intensively discussed (Anthony 1990; Anthony 1992), and scientific methods to trace human movement have been developed (Ericson 1985; White *et al.* 1998). In theory, migration is defined as the spatial movement of people, which is expected to leave traces in the social and physical milieu (Albrecht 1972). In the archaeological record, these people will mainly appear as foreign or exotic due to their foreign material culture. However, it remains difficult to differentiate between the presence of immigrants and cultural diffusion or trade (Burmeister 2000). Also the underlying mechanism of cultural diffusion is most likely human mobility, not necessarily migration. The presence of exotic grave goods at the sites of Magdalenenberg and Singen suggest the presence of ‘foreign’ or at least highly mobile individuals at the sites. Metal objects and raw materials could be associated with distant regions like the Atlantic coast, the Baltic Sea or the Hungarian Plain. But did the transfer of these exotic goods and objects require long distant mobility or even replacement of single individuals, or even groups of people? Or could objects ‘migrate’ via exchange and trade without the necessity of single humans actually migrating from one group to the other? As only the destination and not the journey of artefacts can be identified in the archaeological record, this question remains largely unanswered. While chemical analysis of metal can detect the origin of certain metal ores (Rehren and Pernicka 2008), comparable techniques are also available for human tissues. The analysis of strontium and oxygen isotopes in teeth, and of sulphur in bone collagen, can provide information of not only exotic objects, but also if ‘exotic people’ are present within a burial community.

3.1. Strontium

The analysis of strontium isotopes ($^{87}Sr/^{86}Sr$) in skeletal tissues allow the tracing of human mobility, as each location has a characteristic $^{87}Sr/^{86}Sr$ signature, depending on its geology and formation history (Price *et al.* 2004; Bentley 2006). The $^{87}Sr/^{86}Sr$ signature of a given location is determined by the age and rubidium (Rb) content of the underlying bedrock, as the radiogenic isotope ^{87}Sr forms through radioactive decay of ^{87}Rb. Older geological formations like granite and gneiss have more radiogenic $^{87}Sr/^{86}Sr$ values than e.g. younger volcanic rocks. Unlike many other isotope systems, strontium enters the biosphere without fractionation and is incorporated by plants and animals (Faure and Powell 1972; Graustein 1989). In areas with a heterogeneous geological substrate, the analysis of the $^{87}Sr/^{86}Sr$ ratios in skeletal material can provide information whether an individual lived locally or derived from a different geological context. As different geological formation of similar age may produce similar values, $^{87}Sr/^{86}Sr$ analysis is most reliably applied in combination with other isotope systems like oxygen, sulphur or lead. The sample material of choice for $^{87}Sr/^{86}Sr$ analysis is tooth enamel due to its highly mineralized structure which reliably locks the *in vivo* $^{87}Sr/^{86}Sr$ signal while the tooth is formed (Budd *et al.* 2000; Hoppe *et al.* 2003). As strontium has chemical properties similar to calcium, it is mainly ingested as a trace element in calcium rich foodstuffs like plants and is deposited in the mineral fraction of body tissues including bones and teeth (Bentley 2006). In humans, tooth enamel forms and matures in the first years of life and does not change its composition once mineralized (Humphrey *et al.* 2008). Therefore, dietary signatures of $^{87}Sr/^{86}Sr$ in enamel represent the geological background of an individual's diet during tooth formation in early life history. Depending on the position of the tooth in the dentition, this can record adolescence (third molars), early infancy (anterior dentition) or even the mother's diet (i.e. *in utero* development of the child's deciduous teeth). On the other hand, the porous structures of bone and tooth dentine are more prone to chemical alteration from soil derived strontium (Budd *et al.* 2000). Therefore, $^{87}Sr/^{86}Sr$ data obtained from bone or dentine may be used as a proxy for the soil derived strontium to determine the specific $^{87}Sr/^{86}Sr$ ratios of the burial site. While concerns regarding diagenesis are largely resolved for the analysis of $^{87}Sr/^{86}Sr$ ratios in enamel (Chiaradia *et al.* 2003; Hoppe *et al.* 2003), the main challenge in strontium biogeochemistry is determining which signatures can be considered local and non-local.

3.1.1. Local or non-local? Solving the resolution problem by biosphere $^{86}Sr/^{87}Sr$ mapping

Numerous geochemical studies on strontium isotopes in bedrock and sediments of different ages and formation histories are available in the literature and can provide initial estimates of the local ^{87}Sr/^{86}Sr signature. However, these direct measures of geological substrates are not necessarily representative of what actually enters the biosphere and the food chain due to leaching and weathering (Bentley *et al.* 2004; Evans *et al.* 2010). Therefore, reference data from archaeological or modern materials are needed to serve as a proxy for the soluble and therefore bioavailable strontium fraction at a given location. Some scholars have used a 2σ standard deviation from the mean ^{87}Sr/^{86}Sr recovery in archaeological samples to define the local ^{87}Sr/^{86}Sr signature (Price *et al.* 1994; Grupe *et al.* 1997). However, this approach does not account for the specific geological conditions at a given location and its surroundings.

Today, most researchers studying ^{87}Sr/^{86}Sr ratios in archaeological remains follow the recommendations by Bentley, Price and colleagues (Price *et al.* 2002; Bentley *et al.* 2004) by analysing modern environmental samples (plants and animals) or tooth enamel of contemporary domestics and presumably local fauna. However, acquiring reference material with either method has shown to have both advantages and pitfalls. Modern environmental samples should be collected from plants which grow on the targeted geological substrate, which requires detailed geological background information. More importantly, these plants should not be exposed to modern pollutants and fertilizers from traffic, industry or agriculture to avoid biasing with modern strontium. Collections of modern faunal reference materials should be limited to animals which live relatively exclusively on the targeted geological unit e.g. due to small body size and low levels of mobility (snails, rodents). Conveniently, these animals should provide strontium rich mineralized body tissues sufficient for analysis (teeth, bone, shell), and should be easy to catch or collect in a field survey (snail shells). Strontium reference data from archaeological fauna has the disadvantage that either teeth of locally living animals are simply not available at a site or the reference fauna is less local then expected; this has been documented for prehistoric pigs and other domestics (Bentley and Knipper 2005; Stephan 2009). In summary, the sampling strategy to assess the bioavailability of ^{87}Sr/^{86}Sr in a given location or region largely depends on the material available at the archaeological site and the environmental and geological conditions of its surroundings.

No suitable animal teeth were available to be used as a reference for the local $^{87}Sr/^{86}Sr$ values at the Bronze Age and Iron Age sites used for this thesis. Therefore, modern plants and snails (n=96) were collected in unfertilized forest patches between Lake Constance and the Black Forest in southwest Germany during the summer 2009. A total of 14 sites in the federal state of Baden-Württemberg were visited for sampling. Each site corresponds to a predominant geological unit in the landscape around the archaeological sites of Singen and Magdalenenberg. By mapping the local variability in bioavailable $^{87}Sr/^{86}Sr$, the geological terrains surrounding the sites were characterized by means of strontium isotopes. The complete dataset is made available including GPS coordinates to provide a high degree of reproducibility in future isotope studies in this region.

Other problems arise with the analysis of lead isotopes in archaeological tissue, which is not outlined in detail in this chapter. While the *in vivo* lead isotope signature may be recorded in tooth enamel (Chiaradia *et al.* 2003), it is difficult to find references for lead isotope variation in the modern environment which is imperative if no archaeological faunal specimens are available. Since industrialization and the emission of lead from fossil fuels, modern lead isotope ratios are abundant in nature (Rummel *et al.* 2007). As reference data from archaeological tooth enamel is not available for localizing authentic geological signatures in southern Germany, this methodological approach was considered, but finally not applied in the work of this thesis.

3.2. Oxygen

Complementary to strontium isotopes, stable oxygen isotopes ($\delta^{18}O$) can be used as a geographic indicator that reflects geographical and climatic parameters (White *et al.* 1998). $\delta^{18}O$ is the ratio between light and heavy oxygen isotopes ($^{18}O/^{16}O$) and can be standardized to the values of standard mean ocean water (SMOW) or PDB (see 2.1). While strontium and sulphur are ingested mainly with food, the $\delta^{18}O$ ratio of body water and skeletal tissue relates to the $\delta^{18}O$ ratios 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). Any isotopic input through rainwater is thereby related to temperature, altitude and the distance to the coastline. This generates a gradient of signatures which is reflected in local groundwater, lakes and streams (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). As in strontium isotope analysis, δ^{18}O ratios are most reliably measured in tooth enamel, which is largely resistant to diagenesis and isotopic contamination in the burial environment (Kohn *et al.* 1999). However, for the analysis of δ^{18}O, differences in tooth formation times have to be taken into account, as a significant fractionation of δ^{18}O can be observed during breastfeeding (Wright and Schwarcz 1998). While the measures of strontium and sulphur isotopes are fairly comparable between laboratories, the comparison of δ^{18}O values obtained with different methods (extraction from phosphate or carbonate) and scaled against different international standards (SMOW or PDB) is prone to miscalculation. By means of reproducibility, it has been suggested to convert enamel δ^{18}O values to drinking water δ^{18}O values. However, despite the linear relationship between drinking water and human body tissue, calculations of drinking water δ^{18}O values from tooth enamel may vary depending on the equations used (Daux *et al.* 2008; Chenery *et al.* 2010; Pollard *et al.* 2011). Keeping these limitations in mind, geographical attributions should not be estimated solely using δ^{18}O ratios, but supported by other isotopic evidence, e.g. more robust strontium isotope data (Pollard *et al.* 2011).

3.3. Sulphur

The analysis of δ^{34}S in bone does not only have the potential to detect dietary signals from aquatic ecosystems, but can also provide information on the geological or geographical background of terrestrial foods. In terrestrial ecosystems, the isotopic composition of sulphur in a given locality is mainly determined by the geological substrate and its formation history (Sakai 1957). Due to the fact that fractionation (<1‰) of sulphur in the biosphere is negligibly low, δ^{34}S values of food sources directly correspond to the local signal and are reflected in body tissues like bone collagen (Richards *et al.* 2001). Furthermore, coastal environments are dominated by marine sulphur isotope ratios due to sea spray effects, which are detectable several kilometres inland (O'Dowd *et al.* 1997). δ^{34}S ratios therefore provide information if ancient food sources derive from coastal environments (Craig *et al.* 2006). Although the application of sulphur isotopes in mobility studies is still in its infancy, an initial study has illustrated the potential in identifying immigrant individuals (Vika 2009). The analysis of δ^{34}S in bone collagen is especially useful where teeth (enamel) cannot be sampled for ^{87}Sr/^{86}Sr and δ^{18}O measurements.

Moreover, the combination of isotope analysis in collagen and tooth enamel can provide information on different episodes in an individual's life history. Bone collagen is a living tissue which remodels constantly during life and different bones appear to remodel variably. Therefore, depending on the particular skeletal element, complete turnover of its isotopic composition may never occur (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 when the tooth is formed (Humphrey et al. 2008). Combining the analysis of both tissues holds the potential to explore the approximate timing of mobility and migratory events.

4. Applications to prehistoric Germany

4.1. The Neolithic

The Neolithic transition in Europe is marked by the spread of agricultural societies from the Near East to the European continent, introducing a sedentary way of life as well as domestic crops and animals. This new lifeway included settlements with communal houses and the use of ceramic pottery which allowed for the storage of foods year round (Price 2000; Whittle and Cummings 2007). The first fully agricultural population in central Germany is the *Linearbandkeramik* (LBK), arriving around 5500 BC. In the last two decades, archaeological sciences have improved our understanding of Neolithic subsistence strategies and mobility. Research from an increasing number of laboratories using mass spectrometry on skeletal material has led to an output of numerous isotope studies covering most regions of Europe. The first study on Neolithic human material was conducted on the Mesolithic-Neolithic transition in Portugal (Lubell *et al.* 1994). In the last decade, research has made progress and Neolithic isotope studies cover nearly the entire European continent including France (Le Bras-Goude *et al.* 2006; Herrscher and Le Bras-Goude 2010), Belgium (Bocherens *et al.* 2007), the Netherlands (Smits *et al.* 2010), Scandinavia (Richards *et al.* 2003; Liden *et al.* 2004; Fischer *et al.* 2007; Fornander *et al.* 2008) and Britain (Montgomery *et al.* 2000; Schulting and Richards 2002; Richards *et al.* 2003; Hedges *et al.* 2008), as well as Slovenia (Ogrinc and Budja 2005), Ukraine (Lillie and Richards 2000; Lillie *et al.* 2011), Greece (Papathanasiou 2003), the Balkans (Bonsall *et al.* 2004; Borić *et al.* 2004; Nehlich *et al.* 2010) and Turkey (Richards *et al.* 2003; Lösch *et al.* 2006). Moreover, Neolithic strategies of animal husbandry have been reconstructed by using isotope techniques, e.g. in the contexts of herding strategies and weaning ages (Balasse and Tresset 2002; Noe-Nygaard *et al.* 2005; Balasse *et al.* 2006; Pearson *et al.* 2007).

Table 4.1: Isotope research on Neolithic skeletons from Germany

site	chronology	isotopes	humans	fauna	reference
32 sites, Bavaria	Early-Late Neolithic	C, N	96	#	Asam et al. 2006
Pestenacker	Late Neolithic	C, N, O	1	120	Bösl et al. 2006
Ostorf	3300 BC	C, N	15	10	Olsen et al. 2010
Benzingerode	Bernburger culture	C, N	20	6	Meyer et al. 2007
Trebur	Grossgartach culture	C, N	20	4	Dürrwächter et al. 2003, 2006
Trebur	Hinkelstein cultur	C, N	20	20	Dürrwächter et al. 2003, 2006

Westerhausen	Late Neolithic	C, N, Sr	2	2	Nehlich et al. 2009a
Nieder-Mörlen	LBK	Sr, C, N	17	9	Nehlich et al. 2009b
Herxheim	LBK	C, N	20	14	Dürrwächter et al. 2003, 2006
Derenburg	**LBK**	**C, N**	**39**	**7**	**Oelze et al. 2011a**
Halberstadt	**LBK**	**C, N**	**36**	**6**	**Oelze et al. 2011a**
Kardsorf	**LBK**	**C, N**	**22**	**32**	**Oelze et al. 2011a**
Flomborn	LBK (Early)	Sr	11	#	Bentley et al. 2002
Schwetzingen	LBK (Middle)	Sr	39	#	Bentley et al. 2002
Dillingen	LBK (Middle-Late)	Sr	17	#	Bentley et al. 2002
Talheim	LBK	Sr	28	#	Price et al. 2006
Stuttgart-Mühlhausen	LBK	Sr	53	#	Price et al. 2003
Vaihingen	LBK	Sr	11	36	Bentley & Knipper 2005, Bentley et al. 2004
Altdorf	Bell Beaker	Sr	2	#	Price et al. 2004
Augsburg	Bell Beaker	Sr	17	#	Price et al. 2004
Irlbach	Bell Beaker	Sr	12	#	Price et al. 2004
Künzing-Bruck	Bell Beaker	Sr	6	#	Price et al. 2004
Landau	Bell Beaker	Sr	6	#	Price et al. 2004
Manching	Bell Beaker	Sr	3	#	Price et al. 2004
Osterhofen	Bell Beaker	Sr	8	#	Price et al. 2004
Pommelsbrunn	Bell Beaker	Sr	1	#	Price et al. 2004
Straubingen-Öberau	Bell Beaker	Sr	1	#	Price et al. 2004
Weichering	Bell Beaker	Sr	9	#	Price et al. 2004

The spread of Neolithic cultures throughout Central Europe is a particularly challenging question in human mobility research. Strontium isotope analysis has been applied to several LBK sites in south-western Germany (Fig. 4.1, Tab. 4.1). At most sites, non-local individuals were identified and females were commonly shown to be the dispersed sex. At the LBK sites of Flomborn and Dillingen, over half of the sampled individuals were identified as non-local and at Schwetzingen it was at least one quarter of the population (Bentley *et al.* 2002). Within the earlier phase of the LBK cemetery of Stuttgart-Mühlhausen, one third of the sampled individuals were immigrants, whereas the later phase was almost completely represented by local individuals (Price *et al.* 2003). Additionally, one third of the sampled humans at the site of Vaihingen and one quarter of the adults at the site of Talheim were non-local (Bentley *et al.* 2003; Price *et al.* 2006). This generally high degree of mobility is a good explanation for the rapid expansion of the Neolithic throughout Europe. However, LBK farmers settled almost exclusively on highly productive loess soils which are known to have relatively consistent strontium isotope signatures across Europe with values of 0.708 - 0.710 and possibly 0.711 (Price *et al.* 2003; Nehlich *et al.* 2009). Looking at the summarized data from the previously mentioned LBK sites (Bentley 2006), apparently most data fall within this range. If an LBK individual actually migrated from one settlement to the other, this may not be detectable with this method if they moved from one loess soil to another loess soil with similar isotope ratios. An isotope study at the LBK settlement of Niedermörlen had significantly more radiogenic $^{87}Sr/^{86}Sr$ signatures in most individuals due to different provenances, although the settlement was located on loess soil as well. Only one individual was considered local. The variability of the remaining human $^{87}Sr/^{86}Sr$ values indicated different origins, which was consistent with the finding of various pottery styles at the site (Nehlich *et al.* 2009). Apart from the extensive studies on LBK mobility, human remains from several Bell Beaker sites have been studied in southern Germany (Fig. 4.1). Price and Grupe started their work in the early 1990s and studied samples from ten sites in Bavaria (Price *et al.* 1994; Grupe *et al.* 1997). As the Bell Beaker people dominated large parts of Europe in the late Neolithic and Early Bronze Age, it has been suggested that high levels of mobility or even migration were the cause of the rapid expansion of this culture. The $^{87}Sr/^{86}Sr$ data obtained from enamel and bones of 65 individuals indicated that most had migrated during their lifetimes. The only exception was the site of Irlbach, were only two out of twelve individuals were non-local. Moreover, migrants were evenly distributed between males and females, as well as among the age classes (Price *et al.* 2004). Contrary to the isotopic evidence on LBK and Bell Beaker mobility, we know much less about diet in Neolithic Germany. Only two studies on the diet of LBK farmers have been published. While the diet of the LBK people from the site of Herxheim (n=20) was similar to the later Neolithic populations from Trebur, the data suggested that some (n=3) individuals consumed freshwater fish and that animal protein was an important component of the diet. However, the high number of secondary inhumations at Herxheim makes it likely that the dataset does not encompass a settlement community (Dürrwächter *et al.* 2006). At the site of Niedermörlen (n=15), humans had a terrestrial C_3-plant based diet. Yet, the data from the LBK individuals were difficult to interpret, as the associated herbivore fauna was highly variable in $\delta^{15}N$ and $\delta^{13}C$, indicating that young (suckling) animals and domesticates from different pasture conditions were included in the baseline sample (Nehlich *et al.* 2009).

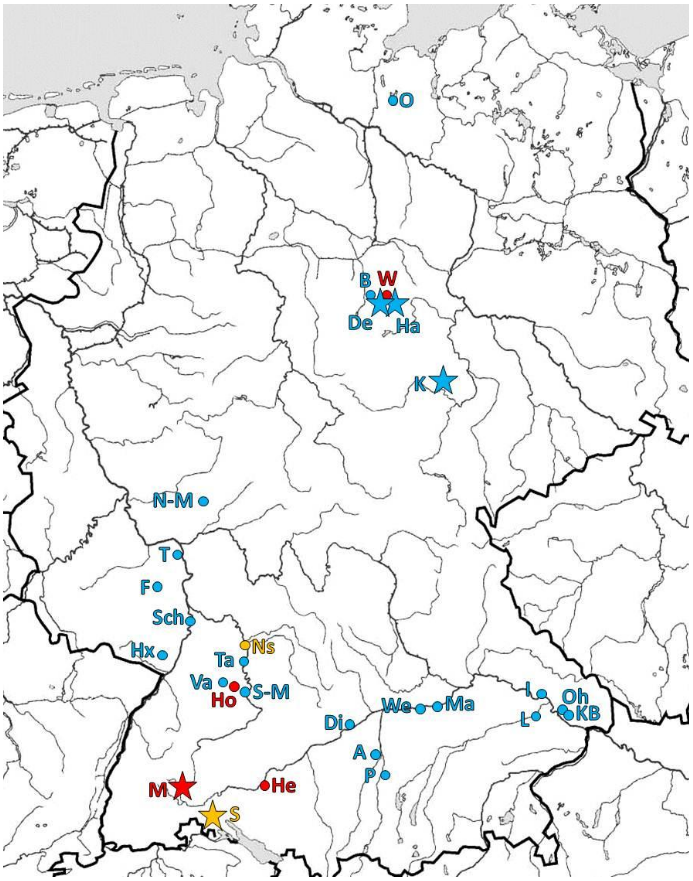

Figure 4.1: Map of Germany including all archaeological sites (n>=2) listed in Tables 4.1, 4.2 and 4.3 (blue symbols = Neolithic, yellow = Bronze Age, red= Iron Age).
The asterisks mark the case study sites Derenburg, Halberstadt, Karsdorf, Magdalenenberg and Singen.

Only a few sites from later Neolithic periods have been studied and most datasets only present small sample sizes or individuals from different sites were compiled in a single study without faunal baseline information (see Tab. 4.1). While these studies could show that Neolithic people were eating C_3-plant based diet and depended on their domestic animals, we know very little about the diet of whole living populations or even neighbouring groups. In chapter 5, I present the first comprehensive stable isotope study on three Neolithic populations representing several generations of LBK communities in central Germany, including children, women and men and their domestic animals.

4.2. The Bronze Age

The Bronze Age in Central Europe dates from 2200 to 1500 cal BC and refers to sedentary societies that utilized copper alloys as the primary material for the production of tools, ornamentation and weaponry. However, copper also predates the Early Bronze Age and bronze remained an important material throughout the Iron Age. The Bronze Age is also characterized by the spread of literacy and the rise of large palace-based societies in the Mediterranean. It appears likely that these significant changes in social and economic life in the Aegean area also affected the people in the Central European hinterland. Accordingly, movements of prestige goods and metals over considerable distances are known from this time period, including ‘barbarian’ Europe. By the middle Bronze Age, metallurgical skills for the production of bronze, raw material, alloys and objects were required and became common. Moreover, the abundance of metal objects as ‘commodities’ and exchange goods gained social meaning as they could be used to demonstrate social division and hierarchy (Harding 2000). Contrary to these socioeconomic developments, the subsistence strategy did not significantly change in the Bronze Age. However, it has been shown that Bronze Age farmers moved their cultivation to marginal soil, possibly due to climatic changes in this time period (Champion *et al.* 1984). The Bronze Age in Germany ended with the introduction of Iron after the Urnfield culture (800 BC) and the rise of the Hallstatt culture with their chiefly seats and princely burials (Harding 2002). Here, I present a brief summary of isotope research on Bronze Age Germany.

Table 4.2: Isotope research on Bronze Age sites from Germany.

site	chronology	isotopes	humans	fauna	reference
Neckarsulm	Urnfield culture	C, N, S	47	5	Nehlich & Wahl 2011
Singen	**Early Bronze Age**	**C, N, S, Sr , O**	**25**	**0**	**Kupke 2010, Oelze et al 2011b**

Apart from the site of Singen presented in this dissertation and the masters thesis of Kupke (2010), only one Bronze Age site has been studied by means of stable isotopes (Fig. 4.1, Tab 4.2). Nehlich and Wahl (2011) presented isotope data from a remarkable Bronze Age site in southwest Germany. The Early Urnfield culture necropolis of Neckarsulm contained a total of 52 individuals buried in 32 graves. Besides the fact that inhumation of the dead was a rather uncommon burial custom for the Urnfield culture, the necropolis also exclusively contained male individuals buried after puberty. Carbon, nitrogen and sulphur stable isotope data for 47 humans and five animals were presented. The faunal specimens, including cattle, horse and deer had isotope values in the expected range for terrestrial herbivores. The Bronze Age males however did not show a dietary pattern depending solely on these animals and domestic plants. Their elevated carbon and nitrogen isotope values could only be explained by the consumption of isotopically enriched dietary sources, additional to terrestrial animals and plants. The sulphur isotope data obtained from both faunal and humans provided the additional information to verify this interpretation. The herbivores showed a local terrestrial isotope signal with little variation while the $\delta^{34}S$ values measured in humans indicate the influence of another dietary source of sulphur, likely freshwater fish. As no skeletal material of freshwater fish was available for sampling, mixing models could not be applied to further investigate the dietary amounts of fish. However, the combination of three isotope systems provided strong arguments for the consumption of freshwater fish for this population. Due to the low variability in these isotope systems, the authors assume that the males at the necropolis represent a settlement population. Finally, individuals buried within the same grave had similar isotope values, indicating they had similar diets and belonged to the same household. Fortunately, strontium isotope analysis on the male necropolis of Neckarsulm is in progress so that these assumptions will soon be tested (Wahl and Price, cited in Nehlich and Wahl 2011).

Isotope data from the site of Singen shows a different dietary pattern. Kupke reported 25 human bone samples in her unpublished masters thesis. The $\delta^{13}C$ and $\delta^{15}N$ values show no evidence of freshwater fish consumption, although the site is located in proximity to several smaller and larger lakes and streams. The $\delta^{34}S$ values, reported in this doctoral thesis (Chapter 6), confirmed this finding. The diet of this population was terrestrial and was dependent on C_3-plants and domestic animals. Moreover, the diet was quite homogeneous within the group and no significant differences according to sex or grave goods could be found (Kupke 2010; Koch and Kupke in print).

4.3. The Iron Age

In Central Europe, the Iron Age began with the gradual replacement of bronze metallurgy with iron around 800 BC. Although bronze remained an important metal for prestige goods like jewellery, iron became the common raw material for weaponry, ornaments and various household goods (Wells 2002). Iron ores were accessible in many European upland regions, making local production feasible where previously copper and tin had to be imported. Nevertheless, the trade of metal objects and prestige goods such as glass was an important component of cultural life in Iron Age Europe and communities maintained regular contact (Stary 1993; Wells 2008). In Germany, the Iron Age is represented by the Hallstatt (Ha C-D) and La Tène culture. These cultures established prominent centres of production and political influence, the so called ‘princely sites’ or ‘chiefly seats’ (in German *Fürstensitze*), which are commonly characterized by hill forts and massive burial constructions, containing luxury goods from the Mediterranean. They can be considered the first step to urbanism, whereas the sedentary population lived in small scale farmsteads or hamlets. While subsistence in Iron Age Germany was similar to the foregone Neolithic and Bronze Age, the introduction of iron ploughs and scythes allowed for a more efficient cultivation of richer soils, and thus supplying more people with smaller farms (Wells 2002). Moreover, isotope data suggests that millet became an especially important crop at least in parts of Central Europe (Murray and Schoeninger 1988). Although isotope research on Iron Age Germany is limited, I briefly present the previous work below.

Only two studies have been published so far (Fig. 4.1, Tab. 4.3). At the site of Westerhausen, 14 (pre-Roman) Iron Age individuals were sampled for carbon, nitrogen and strontium isotopes. The dietary signal suggested a terrestrial-based omnivorous diet. The $\delta^{13}C$ values were enriched compared to a small sample of Neolithic specimens, indicating that possibly also the C_4-crop millet was cultivated and consumed, as it has been shown for other Iron Age populations in central Europe (Murray and Schoeninger 1988; Le Huray *et al.* 2006). However, the authors hypothesised that the enriched $\delta^{13}C$ values were attributed to a possible deforestation of the region or changing climatic conditions. In order to categorize the local $^{87}Sr/^{86}Sr$ range, the isotope data measured in human enamel were compared to dentine from the same teeth. While eleven individuals originated locally from the foothills of the Harz Mountains, two adult individuals had significantly more radiogenic $^{87}Sr/^{86}Sr$ ratios, suggesting they grew up within the Harz Mountains (Nehlich *et al.* 2009).

Table 4.3: Isotope research on Iron Age sites from Germany.

site	chronology	isotopes	humans	fauna	reference
Hochdorf & Heuneburg	Hallstatt-La Tène	Sr	#	65	Stephan 2009
Westerhausen	(pre-Roman) Iron Age	C, N, Sr	14	0	Nehlich et al. 2009a
Magdalenenberg	**Hallstatt**	**C, N, S, Sr, O**	**78**	**10**	**Oelze et al. in print** **Kupke 2010**

Stephan (2009) conducted strontium isotope analysis on faunal remains from the chiefly seats of the Hallstatt culture in southwest Germany. She analysed teeth of domestic fauna (horse, cattle, goat/sheep and pig) from the hillfort sites *Heuneburg-Vorburg* (Ha D1 and Ha D3, n=37) and *Eberdingen-Hochdorf* (Early La Tène period, n=28). By analysing the $^{87}Sr/^{86}Sr$ ratios in different teeth of the same individual (M1, M2, M3/P4) as well as different parts of the enamel crown (cusp tip, ‘middle’ and cervical area), she intended to track the mobility of individual animals during tooth formation. The differences observed within a single individual and between animal species agree with the general perception of Iron Age animal husbandry by archaeologists: animals were mainly kept in direct proximity of the hillforts, and the various species grazed on different pastures according to their feeding demands. Larger variation in $^{87}Sr/^{86}Sr$ values of cattle, sheep/goat and pigs were related to higher degrees of mobility or even trade of these domestics between different Hallstatt communities in the region. As will be demonstrated, this study is chronologically and spatially relevant for the site of Magdalenenberg (chapter 7).

5. Early Neolithic Diet and Animal Husbandry: Stable Isotope Evidence from three Linearbandkeramik (LBK) Sites in Central Germany

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Journal of Archaeological Science 38 (2): 270-279, accepted 29 August 2010, available online 3 September 2010, published February 2011.

Abstract

The first appearance of the Neolithic Linearbandkeramik (LBK) in Central Germany occurred during the 6th millennium BC. However, though LBK sites are abundant in the German loess areas, there are only a few studies that reconstruct the diet of these first farmers using biochemical methods. Here we present the largest study undertaken to date on LBK material using stable isotope analysis of carbon and nitrogen to reconstruct human diet and animal husbandry strategies. We analysed the bone collagen of 97 human individuals and 45 associated animals from the sites of Derenburg, Halberstadt and Karsdorf in the Middle Elbe-Saale region of Central Germany. Mean adult human values are -19.9 ±0.4 ‰ for $\delta^{13}C$ and 8.7 ±0.8‰ for $\delta^{15}N$. The $\delta^{13}C$ values are typical for terrestrial, temperate European regions, whereas the $\delta^{15}N$ values fall within an expected range for farming societies with a mixed diet consisting of products from domestic animals and plants. The consumption of unfermented dairy products is unlikely as there is direct palaeogenetic evidence of lactose intolerance available for one of the sites. There are no clear indications for dietary differences in sex. Young children under three years of age are enriched in $\delta^{15}N$ due to breastfeeding indicating that weaning likely occurred around the age of three years. The fauna exhibit mean $\delta^{13}C$ values of -20.9 ±0.8‰ and mean $\delta^{15}N$ values of 7.0 ±0.9‰ respectively. Variation in the $\delta^{13}C$ and $\delta^{15}N$ in the domestic animals is probably caused by different livestock managements.

5.1. Introduction

The Neolithic transition can be viewed as one of the most dramatic and significant changes in modern human economic, social and cultural life. Originating in the Near East approximately 10,000 years ago food production by farming spread quickly throughout the rest of Eurasia. This transition from hunter-gatherer subsistence to sedentary agriculture involved not only the domestication of animals and plants but also the invention of processing and storing objects in the form of grinding stones and pottery and the change to more sedentary lifeways (Price, 2000). These economic and cultural innovations arriving simultaneously during the Neolithic expansion in Europe is referred to as the 'Neolithic package' (Çilingiroĝlu, 2005; Jochim, 2000). Although there are some examples for earlier appearances of Neolithic innovations (Jochim, 2000), the complete 'package' arrives in Central Europe with the Linear Pottery Culture (*Linearbandkeramik* or LBK) that originated in western Hungary between 5,550 and 5,400 BC and spread into middle and western Europe (Bánffy, 2004; Price, 2000; Price et al., 2001; Zvelebil, 2004). The LBK expansion appears to have been a rapid process that lasted only several centuries which required a high level of mobility for the people living in LBK communities. In this context human remains from LBK sites have been analyzed in several biochemical studies using strontium isotopes (Bentley, 2007; Bentley and Knipper, 2005; Bentley et al., 2004; Price et al., 2001). The isotopic data show that at some LBK sites up to 60% of the group consisted of non-local individuals, and predominantly females tend to have migrated from other geological areas (Bentley et al., 2002; Price et al., 2001). Bioarchaeological methods have therefore become a powerful tool to reveal information on LBK mobility, marriage systems and individual life histories.

As the most striking feature of the Neolithic is the invention and spread of agriculture, analysing the human dietary habits of this time period is of significant interest. The analysis of carbon and nitrogen stable isotope composition in human and animal bone or dentine collagen allows the reconstruction of human palaeodiets (Ambrose, 1993; Schwarcz and Schoeninger, 1991) as well as early animal husbandry strategies (Balasse et al., 2002; Balasse and Tresset, 2002; Noe-Nygaard et al., 2005). The method is based on the fact that the stable isotopes of carbon and nitrogen are fractionated during many biochemical reactions due to differences in atomic mass. This results in specific isotope ratios depending on the type of ecosystem (e.g. marine versus terrestrial), position in the food chain and climate conditions (Ambrose, 1993; Lee-Thorp and Sponheimer, 2007; Sealy, 2001).

The largest variations in the stable isotope ratios of carbon ($\delta^{13}C$) in terrestrial ecosystems are a result of different photosynthetic carbon reduction pathways (C_3, C_4 or CAM plants). C_4 plants produce significantly higher $\delta^{13}C$ values than C_3 plants, providing a useful method to trace the domestication and production of important C_4 plants like maize in the New World (Katzenberg et al., 1995; Vogel and Van der Merwe, 1977). As the cultivation of C_4 plants plays only a minor role in European prehistory, consumers of the temperate vegetation zone mostly feature $\delta^{13}C$ values between -18‰ and -23‰ (Richards and van Klinken, 1997). Subtle variation in $\delta^{13}C$ within terrestrial C_3-dominated ecosystems can correspond to the density and position within a forest canopy (Drucker et al., 2008; Tieszen, 1991; van der Merwe and Medina, 1991) or can be affected by latitude and altitude (Körner et al., 1988; Körner et al., 1991).

The stable isotopes of nitrogen ($\delta^{15}N$) enter the biosphere from the atmosphere mainly via N-fixing soil bacteria and are then utilized by plants. Throughout different terrestrial environments variation in $\delta^{15}N$ can be largely affected by climate, temperature, precipitation, and coastal effects (Britton et al., 2008; Heaton et al., 1986; van Klinken et al., 2000), making the analysis of faunal samples so crucial to understand the local isotopic baseline. However, in temperate terrestrial ecosystems the fractionation of $\delta^{15}N$ is dominated by a trophic level effect. This effect leads to an enrichment in $\delta^{15}N$ from diet to body tissue by 2-5‰, on an average 3‰, whereas $\delta^{13}C$ only shows modest enrichment of ~1‰ for each step in the food chain (Ambrose, 1991; DeNiro and Epstein, 1981; Hedges and Reynard, 2007; Minagawa and Wada, 1984). In terrestrial carnivores we measure higher $\delta^{15}N$ values (typically around 10-12‰), lower values of around 4-6‰ in herbivores and intermediate values for omnivorous species (Fizet et al., 1995). As nitrogen is most abundant in the protein fraction of body tissues in the form of amino acids, measures of bone collagen mainly reflect the isotopic composition of dietary protein intake (Ambrose, 1993). Carbon isotope ratios in collagen also reflect the protein component of diet, whereas measures of carbon isotope ratios in apatite potentially provide information on dietary energy (carbohydrates and lipids) intake (Ambrose and Norr, 1993; Kellner and Schoeninger, 2007). However, analysing bone apatite remains controversial in terms of contamination and alteration (Koch et al., 1997).

For Central Europe, dietary studies on Neolithic human populations using stable isotopes are only available for Germany (Asam et al., 2006; Dürrwächter et al., 2006; Meyer et al., 2007; Nehlich et al., 2009a; Nehlich et al., 2009b) and Slovenia (Ogrinc and Budja, 2005), and there are few case studies for the earliest periods of the Neolithic. For the LBK, the only data published are from the sites of Herxheim (n=21) and Nieder-Mörlen (n=12) (Dürrwächter et al., 2006; Nehlich et al., 2009b). Dürrwächter et al. (2006) found the same terrestrial-based omnivorous diet for individuals from Herxheim as for the two middle Neolithic populations in their study. Yet three individuals were enriched in $\delta^{15}N$ probably due to freshwater fish consumption. The heterogeneous values from Herxheim support the assumption that the sampled human remains derive from different spatially dispersed LBK communities. Nehlich et al. (2009b) also describe a terrestrial omnivore diet for Nieder-Mörlen. They could find slight differences in $\delta^{15}N$ between the LBK and the earlier phase Flomborn, yet sample size is small. A third dataset from different LBK sites in Bavaria (total n=24) unfortunately lacked isotopic information from associated fauna (Asam et al., 2006), which are imperative for interpreting human isotope data.

For a better understanding of early Neolithic subsistence more data on these first European farmers are required. Here we present the most extensive palaeodietary reconstruction applying stable isotopes to the remains of human LBK individuals and associated fauna from three recently excavated sites in Central Germany. The human remains were found in association with settlements and represent several generations of three living LBK communities.

5.2. Archaeological sites and material

The material of this study derives from three LBK sites, Derenburg Meerenstieg II, Halberstadt Sonntagsfeld and Karsdorf, which are located in the loess regions of present day Saxony-Anhalt. The sites date from the earlier to the later phases of the LBK (Meier-Arendt, 1966), though a more detailed chronology of the LBK is still not available for this region. AMS radiocarbon dates are available for Derenburg and Halberstadt and range from 5200 cal BC to 4800 cal BC (Fritsch et al., in press), whereas dating of material from Karsdorf is in progress. Yet calibrations of radiocarbon dates in this time period are known to be problematic (Strien and Gronenborn, 2005).

Though Derenburg and Halberstadt (Landkreis Harz, Saxony-Anhalt) are located in close proximity to each other (‹10km) in the foothills of the Harz Mountains, the spatial organization of the settlements and burials is very different. At Derenburg the settlement consists of eleven longhouses of at least three occupancy phases, flanked by the typical pits for clay extraction. The houses are located separately from an almost circularly constructed cemetery with a diameter of 25-30m, containing 44 burials (Müller, 2002). In contrast, in Halberstadt longhouses and burials are directly connected with each other. The grave groups of six to eight individuals mostly cluster around one of the four houses of the settlement (Autze, 2005). This gives the impression that each grave group could actually represent a nuclear family or members of a single household. At both sites, with few exceptions, all individuals are buried in east-west orientation in a left side crouched posture. Most, yet not all graves contained the typical linear decorated pottery as well as flint and animal remains. Some graves contained ornaments made of *Spondylus* or oyster shells; two burials were spread with red ochre (Autze, 2005; Müller, 2002).

The LBK settlement of Karsdorf (Burgenlandkreis, Saxony-Anhalt) is located approximately 100km south of Derenburg and Halberstadt, on the river Unstrut, and was occupied between 5240 and 5000 BC (Behnke, 2007). The Neolithic buildings (n=24) of three settlement stages are dated to the early and middle LBK (after Meier-Arendt 1966). Except for four graves, all of the 30 burials are associated in groups next to houses in the centre of the settlement, similar to the site of Halberstadt. The individuals are buried in house-flanking pit graves at the western side of the houses and mostly arranged in north-east or north-west orientation. Grave goods are sparse; few graves contained more than one pot or a shell or horn pendant. Associated with every house group we can identify a person with outstanding grave inventory, who may represent a founding generation.

Residential groups of the LBK of Central Germany typically settled in small farmsteads, consisting of several long houses standing in some distance to each other (Bogucki, 2000; Lüning, 2000). Domestic animals and staple crops were mainly brought from the Near East; there is minimal evidence for autochthonous domestication of animals in Europe (Edwards et al., 2007; Larson et al., 2007). The domestic animal species bred by LBK farmers are mainly cattle, followed by pig, sheep and goat. It should be mentioned here that sheep and goat will be subsumed hereafter because they can hardly be distinguished in the archaeological record (Benecke, 1994). Hunting of wild animals is only of small relevance in the LBK of the study region. Bones of wild species appear with frequencies of less than 5% at LBK sites in the Middle Elbe-Saale region (Döhle, 1997). Crop cultivation in the loess region around the Harz is dominated by barley, emmer and einkorn wheat with additional legumes like peas and lentils, and to a lesser degree flax seed and millet (Kreuz, 1990). Because cultivable acreage was scarce, the agricultural production is assumed to have been small scale but intensive (Bogaard, 2004). At LKB sites in the western Harz foothills, hazel (50-75%) and oak (20-30%), both light-demanding plants, are represented in high frequencies. Furthermore the proportion of non-arboreal pollen rises during the Neolithic, indicating that the woodlands were replaced by more open habitats (Beug, 1992; Kreuz, 1990). These semi-open woodlands could have been used to feed the domestic animals throughout the year, by using meadow or forest pastures in summer and leaf foddering in winter.

The total sample of the present study contains 39 humans and seven animals from Derenburg, 36 humans and six animals from Halberstadt and 22 humans and 32 animals from Karsdorf. The bone preservation of the human remains was excellent and allowed detailed anthropological examination in most cases.

5.3. Methods

Prior to isotope analysis, age and sex determinations were conducted at the osteological laboratory of the Institute for Anthropology, Mainz, Germany and are listed in Table 5.1. Both sexes and all age classes could be identified in the sample using different morphological and metric methods (Brooks and Suchey, 1990; Ferembach et al., 1980; Knußmann, 1988; Lovejoy, 1985; Lovejoy et al., 1985; Meindl and Lovejoy, 1985; Murail et al., 2005; Phenice, 1969; Ubelaker, 1989).

Rib bones were preferentially sampled for isotope analysis because they should represent a more recent time frame compared to long bones due to generally higher rates of turnover, whereas the collagen of long bones can comprise isotopic signatures leading back to a differing diet in an individual’s adolescence or even childhood (Hedges et al., 2007). We extracted collagen out of 97 human and 45 animal bone samples. The collagen extraction followed the Longin method (Longin, 1971) modified by Brown et al. (1988) and Collins and Galley (1998). Bone samples were cleaned by air abrasion and then demineralized in 0.5M HCl for several weeks, with acid changes every few days. Demineralized samples were then rinsed three times with de-ionized water and gelatinized at 70°C in a pH3 solution for 48 hours. After filtering the insoluble fraction with a 5µm EZEE© filter, samples were again filtered using Amicon© ultrafilters (cut off of <30kDa). The purified solution was then frozen and freeze dried for another 48 hours. Finally, 0.5mg of dried collagen sample was weighed into tin capsules. The measurement was performed in duplicates 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. $\delta^{13}C$ and $\delta^{15}N$ are reported in 'per mil' (‰) relative to the standards VPDB and AIR. The analytical error, calculated from repeated analysis of internal and international standards, was less than 0.2‰ (1σ) for $\delta^{13}C$ and $\delta^{15}N$.

5.4. Results and Discussion

The mean results for each duplicate measurement are shown for each sample in Tables 5.1 and 5.2. All collagen samples are well preserved and meet the published quality criteria of %C, %N and C/N ratios (Ambrose, 1990; DeNiro, 1985; van Klinken, 1999). Three samples have collagen yield less than 1% due to the generally higher losses of degraded collagen during the ultra filtration step (Jørkov, 2007). These samples were considered acceptable as the other collagen quality criteria were met.

The sampled fauna exhibit mean $\delta^{13}C$ values of -20.9 ±0.8‰ (1σ) and mean $\delta^{15}N$ values 7.0 ±0.9‰ (1σ) respectively (Table. 5.2). These values are similar to those from other Neolithic sites in Germany and reflect terrestrial herbivore diet in temperate climatic regions (Dürrwächter et al., 2006; Meyer et al., 2007; Nehlich et al., 2009a). Animals from Derenburg and Halberstadt show only little variation in both isotopes and sample size is small (Figure 5.1). However, the Karsdorf faunal sample contains cattle (n=12), sheep/goat (n=8), pig (n=8) and wild animals like aurochs (n=3) and deer (n=1), and therefore allows a closer view on animal husbandry practices in the LBK (Figure 5.1). With values of -21.4‰ $\delta^{13}C$ and 5.1‰ $\delta^{15}N$ the deer represents isotope values of wild herbivores that browsed and grazed in semi-open woodlands, as the $\delta^{13}C$ values are less negative than those reported for modern wild deer species feeding in dense deciduous or boreal forests (Drucker et al., 2008) even if fossil fuel effects are taken into account (Friedli et al., 1986). A similar picture derives from the aurochs samples that exhibit slightly less negative mean δ^{13}C values of -20.5‰. Even though the sample size is very small, isotope signatures of the wild taxa might support the picture of relatively open landscapes in LBK environments (Kreuz, 2008).

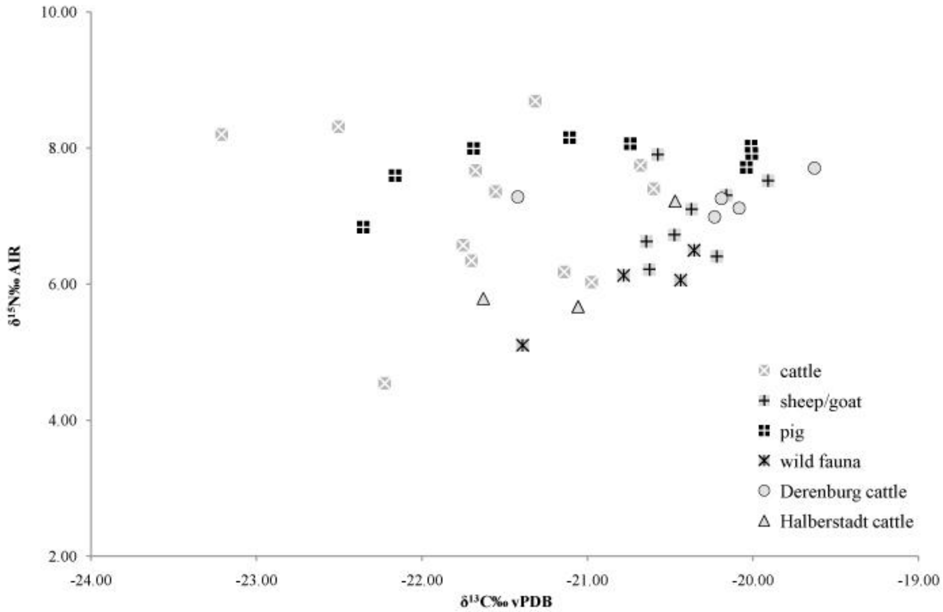

Figure 5.1: Karsdorf faunal sample; scatter blot of δ^{13}C and δ^{15}N data for all domestic and wild animals from the site Karsdorf. By means of comparison the cattle samples from Derenburg and Halberstadt are included.

The domestic animal sample from Karsdorf (Figure 5.1) features mean δ^{13}C values of -21.0 ±0.9‰ (1σ) and mean δ^{15}N values of 7.3 ±0.9‰ (1σ). Variation in the domestic animals might be introduced by varying baseline isotopic signatures due to browsing or grazing in different habitats with distinct isotopic baselines, or by differences in herding and feeding practices. Different patterns can be observed among the domestic animal species. Sheep and goats for instance cluster between 6.4 and 7.9‰ in δ^{15}N and around the mean of -20.4 ±0.3‰ (1σ) in δ^{13}C, suggesting that these animals fed on a very similar diet, as on a similar kind of pasture, although sheep are grazers, whereas goats are habitual mixed feeders (Balasse and Ambrose, 2005; Vera, 2000). Similar to the aurochs, the less negative δ^{13}C values could indicate that pastures were located in open landscapes rather than in dense forests (Drucker et al., 2008). In pigs, mean δ^{15}N values are slightly higher (7.8 ±0.4‰ 1σ) due to more omnivorous diet (Benecke, 1994). Yet, most variation of the pig sample can be observed in δ^{13}C (mean: -21.0 ±1.0‰ 1σ) that ranges

Table 5.1: Human bone collagen samples with archaeological identification and individual data on sex (F= female; M= male; F?= probably female; M?= probably male; ?= sex not known), age (infans I= 0-6 years, infans II= 7-14 years, juvenil= 15-20 years, adult= >20 years) and results of isotopic measurements (mean of duplicate measurement for each samples). $\delta^{13}C$ values are reported relative to standard VPDB; $\delta^{15}N$ values are reported relative to the standard AIR.

site	grave	feature	sex	age class	bone	collagen %	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N
Derenburg	18	565	?	infans I	skull	1.4	-20.5	8.6	32.2	10.8	3.5
Derenburg	20	568?	?	infans I	skull	2.0	-20.0	8.7	35.6	12.5	3.4
Derenburg	23	593	?	infans I	rib	7.0	-19.8	8.9	40.2	14.6	3.2
Derenburg	24	594	?	infans I	rib	3.4	-19.1	11.2	42.5	15.4	3.2
Derenburg	26	595	?	infans I	skull	3.0	-19.2	9.7	37.2	13.4	3.2
Derenburg	27	597	?	infans I	long bone	1.8	-19.5	9.5	42.4	15.5	3.2
Derenburg	47	662 A	?	infans I?	skull	3.9	-19.0	11.5	42.6	15.7	3.2
Derenburg	19	567	?	infans II	rib	4.7	-19.6	8.7	38.9	14.2	3.2
Derenburg	29	604/2	?	infans II	rib	2.9	-19.6	8.6	40.6	14.8	3.2
Derenburg	33	598	?	subadult	rib	5.2	-19.4	8.8	41.0	14.8	3.2
Derenburg	37	606	M?	juvenil	rib	1.9	-20.0	9.0	29.6	10.6	3.3
Derenburg	17	566	M	adult	rib	3.0	-19.4	9.2	38.5	13.9	3.2
Derenburg	31	599	M	adult	rib	4.1	-19.7	8.3	43.0	15.6	3.2
Derenburg	34	596	M	adult	rib	6.6	-19.7	9.2	39.9	14.6	3.2
Derenburg	28	604/1	M	adult	rib	6.1	-19.2	9.2	41.2	15.1	3.2
Derenburg	42	484	M	adult	rib	3.6	-19.8	8.5	42.2	15.3	3.2
Derenburg	46	665	M	adult	rib	6.1	-19.4	8.6	41.6	15.1	3.2
Derenburg	12	486	M	adult	rib	1.9	-20.2	8.3	30.2	10.7	3.3
Derenburg	43	183	M?	juvenil	rib	4.1	-19.7	8.3	41.0	14.8	3.2
Derenburg	9	420	F	adult	rib	7.5	-20.2	8.4	41.9	15.4	3.2
Derenburg	21	591A	F	adult	rib	6.9	-19.8	8.5	41.2	15.2	3.2
Derenburg	30	604/3	F	adult	rib	5.6	-19.4	9.2	40.2	14.7	3.2
Derenburg	38	640	F	adult	femur	1.0	-20.2	10.1	21.7	7.4	3.4
Derenburg	48	643	F	adult	rib	6.9	-19.3	9.1	36.4	13.2	3.2
Derenburg	49	708	F	adult	rib	4.1	-19.6	9.2	43.8	16.3	3.1
Derenburg	32	600	F	adult	rib	4.3	-19.4	8.6	40.4	14.8	3.2
Derenburg	44	644	F	adult	rib	4.0	-19.8	8.4	40.4	14.7	3.2
Derenburg	45	645	F	adult	rib	5.0	-19.8	8.2	40.3	14.9	3.2
Derenburg	16	569	F?	adult	long bone	1.6	-20.6	8.6	18.9	6.3	3.5
Derenburg	35	564	F?	adult	rib	2.5	-20.0	8.4	31.8	11.3	3.3
Derenburg	40	592	F?	adult	rib	5.8	-20.1	8.8	41.3	14.9	3.2
Derenburg	41	649	F?	adult	long bone	1.2	-19.9	8.9	37.1	13.0	3.3
Derenburg	22	590A	F?	adult	long bone	1.0	-20.2	7.9	25.4	8.8	3.4
Derenburg	47	592	F?	adult	long bone	2.0	-20.0	8.7	34.6	12.4	3.2
Derenburg	39	485	F?	adult	rib	3.4	-20.2	8.6	36.5	13.1	3.2
Derenburg	10	421	?	adult	long bone	2.7	-19.5	8.2	36.4	13.0	3.3
Derenburg	11	503	?	adult?	long bone	4.4	-20.5	7.2	32.7	11.9	3.2
Derenburg	21	591B	?	adult?	rib	0.5	-20.2	8.0	33.9	12.1	3.3

Derenburg	52	652	?	?	rib	5.3	-19.8	8.1	40.9	14.9	3.2
Halberstadt	8	322	?	infans I	rib	7.0	-19.0	10.3	39.6	15.5	3.0
Halberstadt	11.2	413	?	infans I	rib	2.8	-19.5	8.7	32.5	11.7	3.2
Halberstadt	17.1	578	?	infans I	rib	6.1	-19.6	10.2	43.6	15.5	3.3
Halberstadt	24	739	?	infans I	rib	1.7	-19.8	8.6	41.2	14.8	3.3
Halberstadt	29	815	?	infans I	rib	4.0	-19.4	10.5	35.8	12.8	3.3
Halberstadt	32	869	?	infans I	long bone	1.6	-19.5	10.0	31.2	11.0	3.3
Halberstadt	33	870	?	infans I	rib	3.7	-19.7	8.9	40.9	14.7	3.2
Halberstadt	37	1076	?	infans I	long bone	2.4	-20.0	9.0	33.8	12.1	3.3
Halberstadt	38	992	?	infans I	rib	3.2	-19.8	7.7	40.3	14.7	3.2
Halberstadt	7	306	?	infans II	rib	1.6	-19.5	9.1	42.3	15.0	3.3
Halberstadt	10.1	343	?	infans II	rib	3.6	-19.2	9.9	41.4	14.7	3.3
Halberstadt	23	741	?	infans II	rib	6.8	-19.7	7.5	39.3	14.5	3.2
Halberstadt	30	859	?	infans II	rib	7.0	-19.8	7.4	40.7	15.0	3.2
Halberstadt	31	860	?	infans II	skull	3.5	-19.9	7.7	35.4	12.9	3.2
Halberstadt	40	1114	?	infans II	rib	8.2	-18.5	9.9	40.9	15.0	3.2
Halberstadt	9	340	?	juvenil	rib	9.4	-20.0	10.5	42.0	15.3	3.2
Halberstadt	28	861	M	adult	rib	4.6	-19.4	9.2	40.6	14.9	3.2
Halberstadt	35	999	M	adult	rib	5.0	-19.7	8.7	39.7	14.5	3.2
Halberstadt	15	430	M	adult	rib	1.9	-19.8	8.4	41.7	15.0	3.3
Halberstadt	2	241	M	adult	rib	1.9	-20.1	8.0	36.5	13.1	3.2
Halberstadt	19.1	613	M	adult	rib	4.3	-19.6	11.7	40.8	14.9	3.2
Halberstadt	27	867	M	adult	rib	5.5	-19.6	9.0	43.0	15.7	3.2
Halberstadt	16	577	M?	juvenil	rib	1.8	-19.8	8.3	37.5	13.4	3.3
Halberstadt	41	1215	M?	juvenil	rib	4.4	-19.6	8.1	33.0	12.1	3.2
Halberstadt	18	536	M?	adult	rib	3.9	-20.1	8.0	37.1	13.3	3.2
Halberstadt	1	139	F	adult	rib	7.7	-19.1	9.1	38.5	14.3	3.2
Halberstadt	17	578	F	adult	rib	3.2	-19.5	8.6	38.0	13.5	3.3
Halberstadt	34	995	F	adult	rib	8.8	-20.2	8.7	40.4	14.8	3.2
Halberstadt	36	1059	F	adult	rib	2.5	-19.9	8.0	39.0	13.9	3.3
Halberstadt	25	804	F	adult	rib	2.2	-19.6	8.2	39.3	14.2	3.2
Halberstadt	42	1324	F	adult	rib	8.2	-19.7	8.2	42.4	15.6	3.2
Halberstadt	22	666	F	adult	rib	4.8	-19.9	8.3	41.9	15.0	3.3
Halberstadt	26	847	F	adult	rib	3.3	-20.2	8.6	33.4	12.0	3.2
Halberstadt	39	1065	F	adult	rib	4.2	-19.7	8.4	41.3	15.2	3.2
Halberstadt	20	662	F?	adult?	long bone	1.8	-20.1	7.4	33.8	11.9	3.3
Halberstadt	10.2	343	?	?	rib	5.5	-20.1	7.6	42.1	15.1	3.3
Karsdorf		115	?	infans I	rib	6.0	-19.9	8.4	38.7	14.0	3.2
Karsdorf		301	?	infans I	rib	4.2	-19.2	12.6	42.4	17.1	2.9
Karsdorf		529	?	infans II	rib	2.8	-20.2	8.1	41.4	13.6	3.6
Karsdorf		305	?	infans I	rib	4.8	-19.7	8.5	39.0	14.2	3.2
Karsdorf		95	?	juvenil	rib	1.0	-20.1	10.8	39.8	13.8	3.4
Karsdorf		509	M	adult	rib	2.1	-20.0	9.1	39.6	14.4	3.2
Karsdorf		537	M	adult	rib	1.4	-19.7	8.9	39.2	14.1	3.2
Karsdorf		611	M	adult	rib	2.0	-20.2	9.1	37.8	14.0	3.2

Karsdorf	304	M	adult	rib	1.9	-20.3	8.8	40.5	14.7	3.2
Karsdorf	300	M	adult	rib	1.1	-20.0	8.7	40.1	14.2	3.3
Karsdorf	605	M	adult	rib	2.2	-19.8	9.0	39.4	14.3	3.2
Karsdorf	170	M	adult	rib	1.1	-20.0	9.0	39.0	14.0	3.3
Karsdorf	303	M	adult	rib	2.5	-20.5	8.8	40.0	14.4	3.3
Karsdorf	122	M	adult	rib	1.4	-19.9	9.3	41.4	14.3	3.4
Karsdorf	131	M?	adult	rib	3.3	-19.5	9.3	36.1	13.0	3.3
Karsdorf	430	F	adult	rib	1.3	-20.1	8.4	39.2	14.0	3.3
Karsdorf	302	F	adult	rib	1.5	-19.6	10.2	39.5	13.9	3.3
Karsdorf	169	F	adult	rib	2.7	-20.0	9.1	38.4	13.9	3.2
Karsdorf	155	F	adult	rib	3.2	-20.1	9.4	40.5	14.7	3.2
Karsdorf	158	F?	adult	rib	2.5	-20.2	6.3	38.3	13.8	3.2
Karsdorf	299	F?	adult	rib	2.7	-19.6	8.9	40.9	15.0	3.2
Karsdorf	192	?	adult	rib	2.2	-20.4	8.5	28.3	10.2	3.2

Table 5.2: Animal bone collagen samples with archaeological and taxonomic identification and the results of isotopic measurements (mean of duplicate measurement for each samples). $\delta^{13}C$ values are reported relative to standard VPDB; $\delta^{15}N$ values are reported relative to the standard AIR. The tree aurochs samples are tagged with '?' because taxonomic classification is based on metric and not morphological estimations.

site	sample no	species	feature	bone	collagen %	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N
Derenburg	D animal 1	cattle	662	vertebra	4.0	-20.2	7.0	43.3	15.6	3.2
Derenburg	D animal 2	cattle	371	skull	2.8	-20.1	7.1	37.5	13.5	3.2
Derenburg	D animal 4	cattle	371	long bone	2.5	-19.6	7.7	40.5	14.2	3.3
Derenburg	D animal 9	cattle	371	vertebra	1.2	-20.2	7.3	44.2	15.9	3.2
Derenburg	D animal 3	cattle	503	long bone	2.1	-21.4	7.3	41.8	15.1	3.2
Derenburg	D animal 8	goat/sheep	371	long bone	4.9	-20.5	7.0	41.8	15.2	3.2
Derenburg	D animal 7	pig	371	skull	7.7	-20.5	7.2	43.5	15.8	3.2
Halberstadt	H animal 1	cattle	3904 k	long bone	5.8	-20.5	7.2	35.4	12.8	3.2
Halberstadt	H animal 2	cattle	3904 k	rib	6.3	-21.6	5.8	41.5	15.2	3.2
Halberstadt	H animal 4	pig	3904 k	mandible	1.0	-21.4	7.7	35.2	12.0	3.4
Halberstadt	H animal 5	?	4217	long bone	1.5	-20.8	5.9	38.6	13.8	3.3
Halberstadt	H animal 6	?	3904	?	2.6	-20.8	5.8	40.8	14.9	3.2
Halberstadt	H animal 10	cattle	4011g	?	1.2	-21.1	5.7	37.4	13.2	3.3
Karsdorf	K animal 1	cattle	26138v	?	5.4	-20.7	7.7	30.8	11.0	3.3
Karsdorf	K animal 2	cattle	26043c	?	2.8	-21.1	6.2	40.6	14.9	3.2
Karsdorf	K animal 3	cattle	26038b	?	1.2	-21.7	6.3	26.5	9.4	3.3
Karsdorf	K animal 4	cattle	26081h	?	1.7	-21.7	7.7	33.2	11.8	3.3
Karsdorf	K animal 5	cattle	26084n	?	4.6	-22.2	4.5	37.9	13.7	3.2
Karsdorf	K animal 6	cattle	26057h	?	1.9	-23.2	8.2	24.0	8.6	3.3
Karsdorf	K animal 7	cattle	26144k	?	2.9	-21.3	8.7	36.5	13.1	3.2
Karsdorf	K animal 8	cattle	26029n	?	2.0	-21.8	6.6	25.4	9.1	3.2
Karsdorf	K animal 9	cattle	26047c	?	3.0	-21.0	6.0	34.0	12.0	3.3
Karsdorf	K animal 10	goat/sheep	26092f	?	0.6	-20.6	7.9	38.4	13.7	3.3

Karsdorf	K animal 11	sheep	26101h	?	2.9	-20.2	7.3	33.4	11.9	3.3
Karsdorf	K animal 12	goat/sheep	26144k	?	9.6	-20.6	6.2	38.2	14.0	3.2
Karsdorf	K animal 13	goat/sheep	26138u	?	5.3	-20.2	6.4	38.5	14.0	3.2
Karsdorf	K animal 14	pig	26138v	?	2.5	-20.0	7.7	41.2	15.0	3.2
Karsdorf	K animal 15	pig	26084n	?	2.9	-22.2	7.6	40.1	14.6	3.2
Karsdorf	K animal 16	pig	26017b	?	2.2	-22.4	6.8	36.9	13.5	3.2
Karsdorf	K animal 17	pig	26092f	?	3.7	-20.7	8.1	33.4	12.0	3.3
Karsdorf	K animal 18	pig	26113i	?	2.9	-21.7	8.0	27.5	9.9	3.2
Karsdorf	K animal 19	deer	26043c	?	2.3	-21.4	5.1	29.0	10.3	3.3
Karsdorf	K animal 20	aurochs?	26144k	?	1.8	-20.8	6.1	39.8	14.6	3.2
Karsdorf	K animal 21	goat/sheep	04:26029 n	long bone	9.4	-20.6	6.6	44.1	16.1	3.2
Karsdorf	K animal 22	cattle	04:26029 n	pelvis	0.6	-21.6	7.4	38.3	12.4	3.6
Karsdorf	K animal 23	aurochs?	04:26043 c	phalange	2.6	-20.4	6.1	42.1	15.2	3.2
Karsdorf	K animal 24	cattle	04:26057 h	phalange	3.1	-22.5	8.3	41.3	14.7	3.3
Karsdorf	K animal 25	pig	04:26092 f	mandibula	3.4	-20.0	7.9	41.5	14.8	3.3
Karsdorf	K animal 26	goat/sheep	04:26092 f	vertebra	1.4	-20.4	7.1	41.1	14.4	3.3
Karsdorf	K animal 27	aurochs?	04:26092 f	phalange	2.9	-20.4	6.5	41.0	14.5	3.3
Karsdorf	K animal 28	sheep	04:26101 h	skull	2.5	-19.9	7.5	42.2	15.3	3.2
Karsdorf	K animal 29	pig	04:26113 i	scapula	1.6	-21.1	8.2	41.7	14.5	3.4
Karsdorf	K animal 30	goat/sheep	04:26138 v	vertebra	1.6	-20.5	6.7	40.7	14.5	3.3
Karsdorf	K animal 31	cattle	04:26138 v	vertebra	4.1	-20.6	7.4	40.7	14.6	3.3
Karsdorf	K animal 32	pig	04:26138 v	metacarpus	3.0	-20.0	8.0	41.2	14.9	3.2

from -22.4‰ to -20.0‰, suggesting that the pigs may have fed in habitats that are differently affected by canopy effects. Negative δ^{13}C values e.g. could be introduced by feeding in forest areas with denser vegetation.

If only the bovid species in the Karsdorf sample are considered, the differences between domestic and wild cattle are pronounced (see Figure 5.1). Contrary to domestic cattle, the aurochs isotope values are more homogenous. The δ^{13}C values of aurochs are significantly higher (one way ANOVA; *p=0.033*) and mean δ^{15}N values are 0.9‰ lower than in domestic cattle. Hence, aurochs might have grazed on different pastures than those of domestic cattle, but similar to the feeding grounds of the domestic sheep and goats from Karsdorf (see above). Although sample size is very small this finding might support the assumption of palaeogenetic studies that domestic cattle herds were spatially kept separate from wild aurochs and genetic introgression was therefore widely prevented (Edwards et al., 2007).

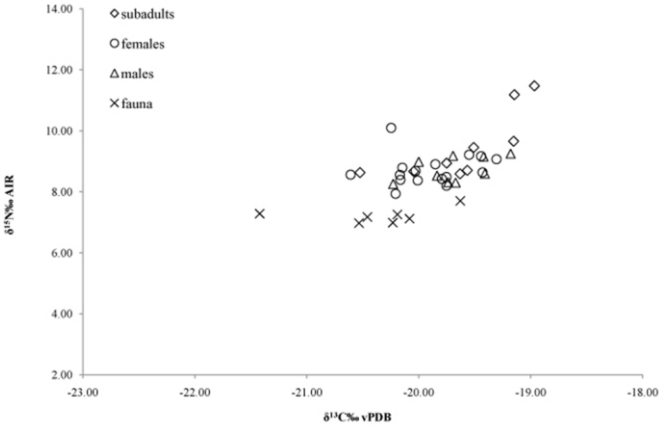

Figure 5.2: Derenburg (Meerenstieg II); scatter blot of $\delta^{13}C$ and $\delta^{15}N$ data for all human and faunal samples.

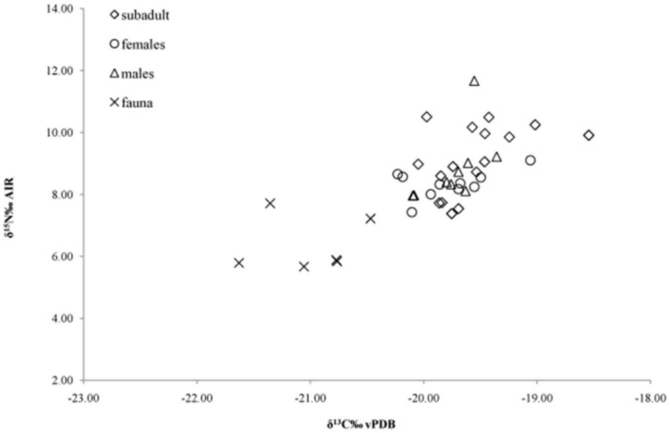

Figure 5.3: Halberstadt (Sonntagsfeld); scatter blot of $\delta^{13}C$ and $\delta^{15}N$ data for all human and faunal samples.

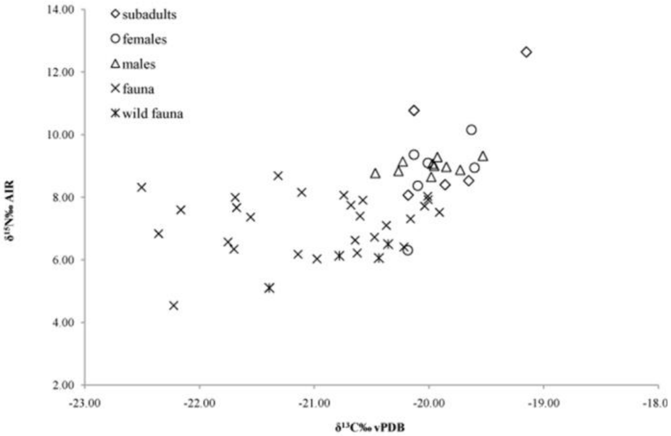

Figure 5.4: Karsdorf; scatter blot of $\delta^{13}C$ and $\delta^{15}N$ data for all human and faunal samples. One cattle specimen (K animal 6) with -23.21‰ $\delta^{13}C$ falls out of the plot area and can be seen in Fig. 1.

The Karsdorf domestic cattle values for $\delta^{13}C$ range from -23.2‰ to -20.6‰ with a mean of -21.6 ±0.8‰ (1σ), and values for $\delta^{15}N$ range from 4.5 to 8.7‰ with a mean of 7.1 ±1.2‰ (1σ). Only one individual, the one with the highest $\delta^{15}N$ value of 8.7‰, is classified as juvenile (K animal 7) by zooarchaeological examination**,** whereas the other animal samples were classified as adults. If the juvenile is removed from the sample the mean $\delta^{13}C$ cattle value remains the same and the mean $\delta^{15}N$ value only decreases to 6.9 ±1.1‰ (1σ). The slightly enriched $\delta^{15}N$ values in some of the cattle can be explained by effects that lead to nitrogen enrichment in the fodder plants, like stocking rate and resulting manuring (Bogaard et al., 2007; Schwertl et al., 2005; van Klinken et al., 2000) or high humidity (Britton et al., 2008). Bogaard et al. (2007) observed an isotopic 'manuring-effect' in crops when fields were intensively cultivated and fertilized with animal manure. This effects ~3‰ higher baseline values, which might be represented by the offset of 2-3‰ in $\delta^{15}N$ between wild and domestic ruminants at the site Karsdorf. In this scenario the $\delta^{13}C$ signatures should rather reflect feeding on open grassland pastures than in dense forests (Benecke, 1994; Drucker et al., 2008). This might be the case for four cattle outliers from Karsdorf (K animals 1, 4, 22, 31).

For salt-marsh fed cattle from the UK, Britton et al. (2008) showed that feeding in boggy and wet pastures leads to significant enrichment in δ^{15}N. Being aware that Britton et al. (2008) deal with pastures under marine influence, we presume that similar effects might cause enrichment in δ^{15}N in freshwater marshes as well. Although freshwater ecosystems are highly variable, δ^{13}C values can be depleted and the complexity of trophic levels leads to enriched δ^{15}N values in freshwater organisms (Dufour et al., 1999; Fry, 1991). It seems plausible that flood plains and meadows that are repeatedly affected by freshwater systems should be enriched in δ^{15}N and could exhibit more negative δ^{13}C values than terrestrial ecosystems. As the site of Karsdorf is located next to the bed of the Unstrut River, it is likely that such wet or damp meadows were easily accessible for the LBK farmers. Based on pollen diagrams, Kreuz (2008) showed that the grassland vegetation in the floodplains of rivers was of special relevance in the LBK as pastures for domestic animals. Additionally there is evidence from wildlife studies that on damp meadows more than twice as many cattle can be fed compared to dry woodland pastures (Nitsche and Nitsche, 1994). Feeding at least some of the livestock on the floodplains seems to be a reasonable scenario for this time period and potentially explains the values of two other cattle outliers that show the highest δ^{15}N values that simultaneously exhibit the lowest δ^{13}C values of the present study (K animal 6 and 24).

Table 5.3: Total sample size of each site, mean isotopic values of adult human individuals and animal samples, and isotopic fractionation of δ^{13}C and δ^{15}N between domestic herbivores (pigs and wild fauna excluded) and humans ($\Delta_{\text{herbivore-human}}$).

site	total human samples	adult human means				total animal samples	animal means				$\Delta_{\text{herbivore-human}}$	
		δ^{13}C‰	1σ	δ^{15}N‰	1σ		δ^{13}C‰	1σ	δ^{15}N‰	1σ	Δ^{13}C‰	Δ^{15}N‰
Derenburg	39	-19.8	±0.4	8.8	±0.5	7	-20.4	±0.5	7.2	±0.2	0.5	1.6
Halberstadt	36	-19.8	±0.3	8.4	±0.5	6	-21.0	±0.4	6.4	±0.9	1.1	2.3
Karsdorf	22	-20.0	±0.3	9.0	±0.4	32	-21.0	±0.8	7.1	±1.0	1.1	2.0

In comparison to the animals, the human sample isotope values cluster more tightly, especially in δ^{13}C (see Figure 5.2 - 5.4 and Table. 5.3). The mean human bone collagen isotope ratios for all three sites are for δ^{13}C -19.9 ±0.4‰ (1σ) and 8.7 ±0.8‰ (1σ) for δ^{15}N, when subadults are excluded from the sample. The spectrum of the $\delta^{13}C$ values from -21.3‰ to -19.1‰ clearly reflects a C_3 based diet. The intensive cultivation of C_4 plants like millet can therefore be excluded, although there is archaeobotanical evidence for the introduction of millet in the earliest LBK in the study area (Beug, 1992). The variation in $\delta^{15}N$ of adult human individuals ranges from 6.3‰ to 11.7‰ and represents more than one trophic level. All adult human values are within the expected range for farming societies with a mixed omnivore diet relying on the products of domestic animals and on field crops. The values for the isotope fractionation between the domestic herbivores (only cattle and sheep/goat) and the adult humans ($\Delta_{\text{herbivore-human}}$) are shown in Table 5.3. For Halberstadt and Karsdorf the fractionation factor $\Delta_{\text{herbivore-human}}$ represent one trophic level in $\delta^{13}C$ and between ½ and one trophic level in $\delta^{15}N$ (Ambrose, 1993; Robbins et al., 2005). From this we can conclude that the Halberstadt and Karsdorf populations had significant amounts of domestic herbivore protein in their daily diet. Yet, a different pattern can be observed for the site of Derenburg. Here the $\Delta_{\text{herbivore-human}}$ values are much lower, indicating that the Derenburg population consumed a lower proportion of animal protein in their regular diet.

In the context of animal protein consumption, it is unique that direct evidence on lactose intolerance from ancient DNA is available for individuals in this study. Burger et al. (2007) analysed three LBK individuals from Derenburg (graves 33, grave 21, grave 34) and could prove the absence of the allele (-13,910*T) responsible for the persistence of the lactase enzyme after childhood. According to the calculations of Burger et al. (2007) the frequency of the lactase persistence allele should be less than 0.25 (confidence 99%) in the Neolithic population sampled in their study. As the sites Halberstadt and Karsdorf are spatially and chronologically significantly closer related to Derenburg than the Eastern European sites in their study, we suggest that even less than 25% of the people in our three populations carried the lactase persistence allele. Therefore it appears likely that $\delta^{15}N$ enrichment in humans is a product of meat eating rather than drinking unprocessed ‘raw’ milk. This is of particular interest discussing elevated $\delta^{15}N$ values in the Neolithic, where it usually remains ambiguous if higher proportions of dairy products or actually meat has been consumed (Dürrwächter et al., 2006; Nehlich et al., 2009b). However, we cannot completely exclude the possibility that processed milk products with lower lactose levels were consumed.

The subadults of the three sites have slightly more positive mean δ^{13}C values of 19.6 ±0.4‰ (1σ) and δ^{15}N values of 9.2 ±1.2‰ (1σ) compared to adults. This is most likely due to breastfeeding effects. Breastfeeding results in higher nitrogen isotope values in the infant's tissue compared to the mother's (Fuller et al., 2005; Richards et al., 2002). The maximum nitrogen value of 12.6‰ is a strong nursing signal in a one or two year old child from Karsdorf (feature 301), whereas the lowest values <8‰ are found in several post-weaned children that died in the age of approximately eight years. Values of individuals older than three years are similar to the mean value for adults. At this age, children appear to be fully weaned and mother's milk has been replaced with solid foods similar to the adult diet of the populations. Although sample size is small we assume that children were weaned around the age of three in the LBK of Central Germany.

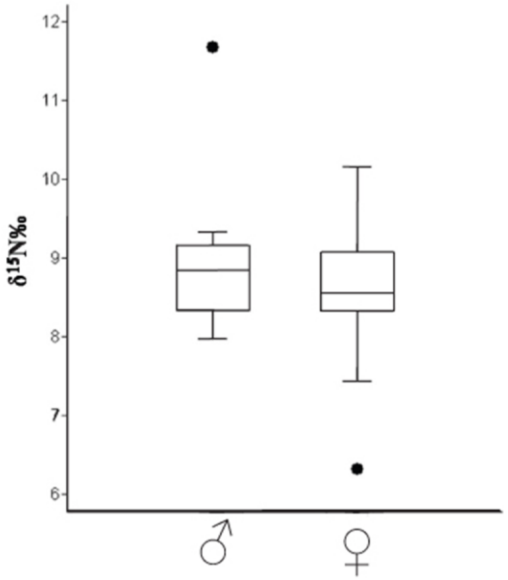

Figure 5.5: Box plot of the mean values, standard deviations and range of δ^{15}N values for adult males (♂) and females (♀) of all three sites. Each dataset has one outlier (males = Halberstadt, grave 19.1; females= Karsdorf, feature 158) that was removed from the analysis (black dots). Both sexes have similar δ^{15}N means, yet females show more variability in their distribution.

In order to investigate potential dietary differences between the sexes**,** the values of all adult females (n=32) and males (n=28) were compared. Two outliers, a male (Halberstadt, grave 19.1) and a female (Karsdorf, feature 158) were excluded from the sample (see Figure 5.5). Differences in δ^{13}C between females with a mean of -19.9 ±0.3‰ (1σ) and males with a mean value of -19.8 ±0.3‰ (1σ) are not significant (*p=0.428*) using a Mann-Whitney U test. The same accounts for δ^{15}N; females with a mean of 8.7 ±0.6‰ (1σ) are not significantly different (*p=0.178*) from the males with mean δ^{15}N values of 8.7 ±0.4‰. Similar results are found if the sexes of each site are compared. However, in Figure 5.5 indicates that females show more variation in δ^{15}N compared to males. This could potentially mean that female's access to animal protein or at least the uptake of enriched δ^{15}N in the bone collagen could vary, possibly in relation to individual social status and maybe even reproductive life history. In direct comparison of the three sites, only slight differences in human diet become visible (see Figure 5.2 - 5.4 and

Table 5.3). As mentioned above we find the lowest $\Delta_{\text{herbivore-human}}$ values at the site of Derenburg, indicating that this community consumed less meat from domestic herbivores than the people from Karsdorf and nearby Halberstadt. In this respect it is interesting that the LBK settlement and burials of Derenburg are also organized in a different way than in the other two sites. This might indicate that although the three sites are contemporary, they reflect two different lifeways. Despite the relative quantities of consumed animal protein the general pattern observed within the three communities is quite similar. At Derenburg adult humans exhibit homogenous δ^{15}N values and only little variation in δ^{13}C (Figure 5.2). One female (grave 38) is slightly enriched in δ^{15}N compared to the rest of the adult population. This 35-45 year old individual was buried with remains of an infant, probably a neonate. In Halberstadt one outlier was excluded from the mean calculation on adult individuals. The resulting mean adult δ^{13}C values for Halberstadt are the same as in the nearby site Derenburg; only the δ^{15}N values are slightly lower. The mentioned outlier is grave 19.1, an elderly male individual (50-65 years), who shows the highest adult δ^{15}N values of 11.7‰ in this study, representing much higher quantities of animal protein in his average diet (Figure 5.3). This male was buried in an extremely crouched posture in some distance to the longhouses or other graves (Autze, 2005).

Finally, the Karsdorf population cluster homogeneously in δ^{13}C around -20‰ and is therefore very similar to the other sites, whereas δ^{15}N is slightly enriched compared to the two other sites, yet there is no archaeological evidence for the exploitation of freshwater protein resources at this site, although the Unstrut River must have been located nearby in prehistoric times. The highest δ^{15}N values for Karsdorf can be observed in one infant with a clear breastfeeding signal (feature 301) and in a 15 to 18 year old individual of unknown sex (feature 95) that is slightly enriched in δ^{15}N, probably due to more meat or milk in its daily diet. In contrast, there is one female individual (feature 158) with the lowest δ^{15}N values in the present study of 6.3‰ that could be classified as a vegan (O'Connell and Hedges, 1999). Her δ^{13}C and δ^{15}N values fall in the range of those of the domestic and wild fauna from Karsdorf (animal mean 7.3 ±0.9‰ 1σ), indicating she might have lived on the similar 'herbivore' diet (see Figure 5.4).

In summary, the general impression of human diet within the three LBK sites is very consistent with little variation, despite a small number of outliers (see Figure 5.6). Dürrwächter et al. (2006) found a different pattern at Herxheim where human δ^{15}N values varied significantly (9.8 ±1.0‰ 1σ), suggesting the burials did not reflect a living community but secondary interments.

Compared to the mean of 10.2 ±0.5‰ (1σ) δ^{15}N values from the adult individuals of LBK site Nieder-Mörlen (n=6), the mean values from Derenburg, Halberstadt and Karsdorf are lower.

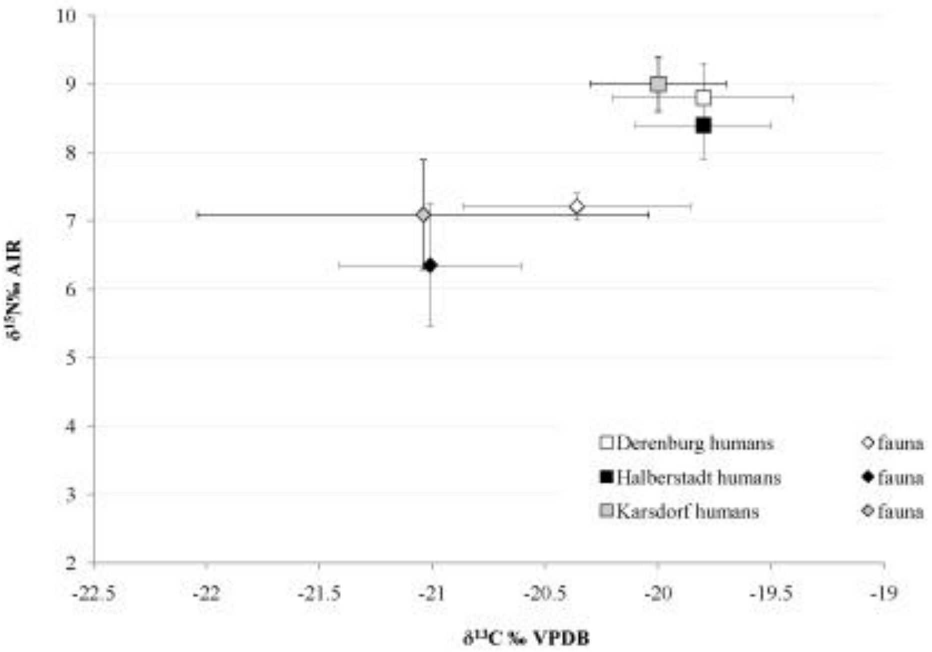

Figure 5.6: Mean values (1σ) for humans and animals of each site.

Nehlich et al. (2009b) suggested that some of the high δ^{15}N values in the domestic animals reflect pre-weaning signals. If this is the case and young animals were culled for meat production at Nieder-Mörlen, this would cause higher δ^{15}N values in the humans. This can be reconstructed by calculating the fractionation factor $\Delta_{\text{herbivore-human}}$ for Nieder-Mörlen (domestic herbivores: n=7; human: n=6, subadults excluded). The values +1.2‰ for $\Delta^{13}C_{\text{herbivore-human}}$ and +2.2‰ for $\Delta^{15}N_{\text{herbivore-human}}$ are remarkably similar to those from Halberstadt and Karsdorf, suggesting that the relative amount of consumed animal protein were almost equal. Yet, the $\Delta_{\text{herbivore-human}}$ factors calculated here for Early Neolithic Germany are not consistent with the Neolithic $\Delta_{\text{fauna-human}}$ values published by Hedges and Reynard (2007) that lie between 3.7‰ and 4.5‰ for $\Delta^{15}N_{\text{fauna-human}}$. Although in that calculation a variety of wild fauna was also taken into account, this may indicate that Neolithic farmers from present day Germany depended less on animal protein compared to the Neolithic people of Britain.

5.5. Conclusion

The human and animal samples from the LBK sites Derenburg, Halberstadt and Karsdorf represent the first farming communities in Central Germany. This sample is the most substantial and detailed dataset on carbon and nitrogen isotopes available for prehistoric Germany and gives insight on different aspects of human subsistence and animal husbandry in the early Neolithic. Although we suggest that the Derenburg population ate less quantities of animal protein than the people in Halberstadt and Karsdorf, the dietary variation within the sites are quite similar. The humans lived on an omnivore diet consisting of C_3 plant crops and animal meat from livestock. The consumption of unfermented dairy products is unlikely as there is direct palaeogenetic evidence of lactose intolerance available for the site Derenburg. There are no significant differences in the access to meat between the sexes. Children in these LBK cultures may have been weaned around the age of three and apparently ate the similar diet as adults after weaning, yet sample size is small. The isotopic signatures of animal bone collagen from Karsdorf reveal that there could have been different strategies of livestock management according to animal species. Comparison of aurochs and domestic cattle indicates that the two species fed in distinct habitats. Both the aspects of human diet and animal husbandry bear direct evidence on early farming subsistence strategy in Central Europe.

5.6. Acknowledgements

This project was funded by the Deutsche Forschungsgemeinschaft (DFG) and by Geocycles, Johannes Gutenberg University, Mainz. The isotope analysis was generously funded by the Max Planck Society. We thank Barbara Fritsch and Robert Ganslmeier from the State Office for Heritage Management and Archaeology, Saxony-Anhalt, for archaeological background information, as well as Hans-Jürgen Döhle for assessing the faunal remains. Furthermore we thank Michael Richards for permission to do isotopic measurements in Leipzig and Stefanie Bösel for technical assistance with the mass spectrometer. Special thanks go to Kate Britton, Olaf Nehlich and to the two anonymous reviewers for the very helpful comments on the manuscript.

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6. ‘There’s no place like home’ - No isotopic evidence for mobility at the Early Bronze Age cemetery of Singen, Germany

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Archaeometry, accepted 8 September, 2011, available online since 14 December 2011,
doi: 10.1111/j.1475-4754.2011.00644.x

Abstract

The Early Bronze Age necropolis of Singen (Hohentwiel) located near Lake Constance represents a population from a period of technological transition in south-western Germany. The site contains several graves with metal artefacts which originated in other parts of Central and Western Europe, and therefore these could be interpreted as being the graves of non-local individuals. The purpose of this study was to investigate this possibility through the application of isotopic analysis. The ratios of strontium and oxygen isotopes in human enamel reflect the geological origin of food and drinking water consumed during enamel formation in early life stages. Additionally, the ratio of sulphur isotopes from bone collagen reflects the origin of foods consumed during the last ten to twenty years of life of an adult individual. We used these three isotope systems to attempt to identify local and non-local individuals at the site. We found that the isotope ratios of Sr, O and S of the humans were relatively homogeneous and generally correspond to the isotope signature of the local geology, climate and environment. We conclude that the sampled population is of local origin and does not show patterns of individual mobility, even though there is evidence for long-distance trade and exchange of the metal artefacts at this site.

6.1. Introduction

The Early Bronze Age site of Singen (Hohentwiel) is the largest known Early Bronze Age period (EBA A1) cemetery in southern Germany (Harding, 2000; Krause, 1988). The site is located in the valley next to the Hohentwiel volcano, a prominent landmark within the hilly landscape of the Hegau region, north-west of the Lake Constance. During excavation campaigns in the 1950s a total of 96 graves were discovered, which can be divided into four to five distinct zones (Fig. 6.1) and have been interpreted as kin-related groups. Many graves contained elaborate stone settings, and in some cases the distribution of wedging stones indicated the presence of wooden coffins (Krause, 1988). Radiocarbon dates of seven human bone samples from the site range in age from approximately 2200 to 2000 cal BC (Krause, 1988; Kromer, 1988).The overall preservation of organic material at Singen is poor and only the remains of approximately 30 inhumations could be recovered, some of them only represented by bone and tooth fragments. However, in most cases age and sex could still be estimated. This anthropological evidence supports a sex differentiated burial practice (females oriented south; males oriented north) and sex-specific distribution of grave goods. Females tended to be buried with awls, pins, a neck ring or bracelets, whereas males were buried with bracelets, pins and a dagger at their waist (Sprenger, 1995). The few exceptions to this pattern have brought up speculations whether females buried with daggers could be widows taking over male roles in the family or non-local individuals that entered the community by marriage (Harding, 2000). The well preserved and rich assemblage of metal artefacts at the cemetery has become a reference collection for bronze artefact typology for

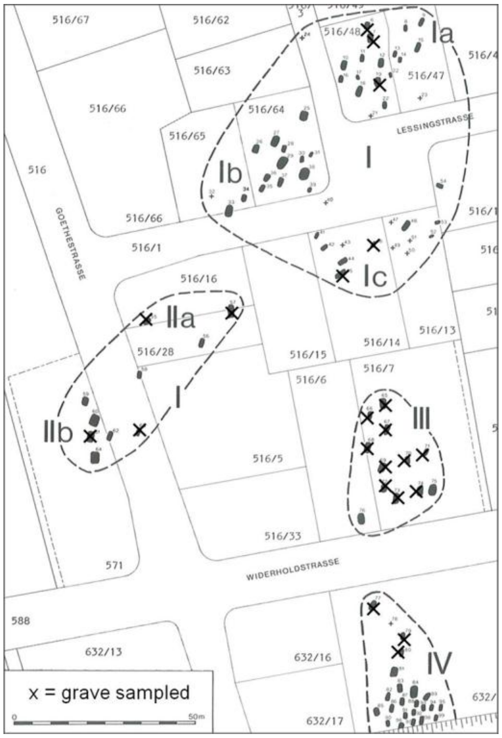

Figure 6.1: Map of the archaeological site of Singen am Hohentwiel and the graves sampled (grave 101 lies outside the mapped area), modified after Krause (1988).

the north alpine Bronze Age. The copper alloys found at Singen revealed high levels of the trace elements antimony, nickel, arsenic and silver, and predates the knowledge of alloying with tin. This ‘Singen metal’ or ‘Singen copper’ is widely distributed within the European ‘*Blechkreis*’ and beyond, from the western Alps to the Baltic Sea and the Carpathian basin (Harding, 2000; Kienlin and Stöllner, 2009; Krause, 2003). Findings of contemporary flanged axes made of ‘Singen copper’ in Swiss sites and around the Lake Constance have led to the hypothesis that the copper was mined in the Alps and the Singen community played an important role in the transfer of this metal, maybe even controlled its’ trading north of the lake (Kienlin and Stöllner, 2009; Krause, 1988). Other specific features at the site of Singen are the four bronze daggers, referred to as so called ‘Atlantic daggers’. Their style and *pointiliè* decoration resembles the Armorico-British style (type A) from the Wessex Culture in Great Britain (Fig. 6.2). The same type of dagger is also well known as the Loucè and Rumèdon type in coastal Brittany, France (Krause, 1988). Chemical metal analysis strongly supports this assumption and reports high levels of tin, typical for the Atlantic region (Christoforidis and Pernika, 1988; Krause, 1988). Additionally the surface of all four Singen daggers was treated with arsenic bronze, a procedure commonly found in contemporary daggers from Brittany (Krause, 1988).

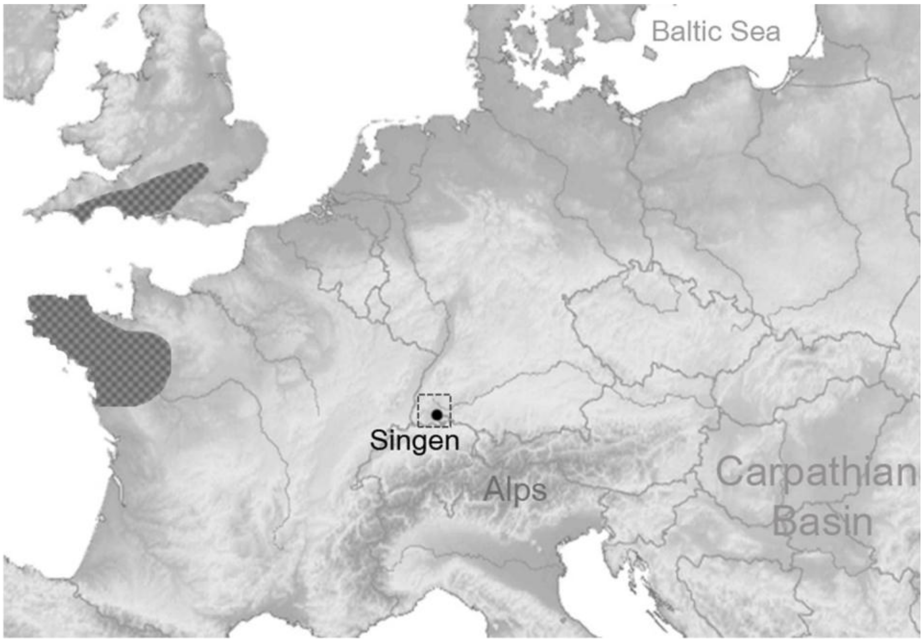

Figure 6.2: Topographic map of Central Europe. The site and map section used in Figures 6.3 and 6.4 are marked with a dashed box. The areas of the ‚Atlantic‘ Early Bronze Age cultures are patterned (after Krause, 1988).

These various lines of evidence have led to the assumption that the Singen community had far reaching connections in southern Germany and possibly even reaching the Atlantic coast or eastern parts of Europe. However, it remained unknown to what extent these connections required actual physical mobility of members of the Singen community. Did the transfer of metal objects or metallurgical expertise require long range movement of group members? Or did trading networks include consolidation and exchange in form of exogamic marriage systems? The aim of this study was to investigate possible mobility or migration by applying biochemical analysis to the human remains of the Singen cemetery. By analysing different complementary isotope systems, we sought to gain novel information on whether individuals originated locally or derived from other geographical and geological regions. Moreover analysing different tissues can provide isotopic information on different stages in life history like childhood and adolescence (tooth enamel), as well as the last ten to twenty years before death (bone). Isotope analysis has been applied in various regions and time periods to reconstruct human mobility and diet (Ambrose, 1993; Bentley, 2007; Price, 1989; Richards et al., 2008; Richards et al., 2000). Many studies have shown the potential of stable isotope analysis of strontium and oxygen to reveal individual mobility during life history (Evans et al., 2006b), or to prove that groups of people migrated due to their lifeways (Price et al., 2004), due to force (Schroeder et al., 2009), or that only a certain portion of a population was mobile, e.g. due to exogamic traditions (Bentley, 2007).

The stable strontium isotope ^{87}Sr forms through radioactive decay of ^{87}Rb in bedrock (Faure and Powell, 1972) and is measured in relation to the lighter isotope ^{86}Sr (^{87}Sr/^{86}Sr). The isotopic signature of a geological formation is determined by the age of the underlying rock, with older geological units having more radiogenic ^{87}Sr/^{86}Sr ratios. The particular ^{87}Sr/^{86}Sr signature of a geological area enters the biosphere by leaching and weathering and is finally absorbed by plants (Graustein, 1989). Animals feeding on these plants will incorporate the ‘local’ ^{87}Sr/^{86}Sr signature in their bones and teeth because of the similar chemical properties of strontium and calcium (Ericson, 1985). Tooth enamel has shown to be the best substance for the analysis of ^{87}Sr/^{86}Sr in archaeology as its compact structure is largely resistant to post-mortem diagenetic alteration and strontium uptake from the burial environment (Budd et al., 2000). The same applies to the analysis of stable oxygen isotopes. The ratio between the heavy and light isotope of oxygen (δ^{18}O) is incorporated in the oxygen bonds of the enamel during formation and reflects the δ^{18}O in the local drinking water. Local $\delta^{18}O$ values in water are determined by the local geography, climate and corresponding meteoric precipitation (Longinelli, 1984). The resulting local $\delta^{18}O$ ratio relates to temperature, coastal proximity, as well as to latitude and altitude (Cuntz et al., 2002; Gat, 1980; Yurtsever, 1975), except if non-local drinking water is largely introduced by rivers or streams. Hence, the combination of $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ signatures allows the reconstruction of human mobility and residential patterns (Bentley and Knipper, 2005). Tooth enamel is an ideal sampling tissue for this purpose, as it does not change its isotopic composition once it is formed (Humphrey et al., 2008). In humans the anterior teeth and the first molar are formed in the first years of life, whereas the premolars and second molars form in childhood, and third molars may not be completely formed until adolescence (Hillson, 1996; Reid and Dean, 2006). Therefore, $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ in enamel reflect the residence of an individual during early life stages (childhood/adolescence) and does not carry information about the area of residence in adulthood.

Similar to strontium, sulphur isotopes in body tissues are also related to the isotopic signature of the local geology. Sulphur isotopes can be measured in bone collagen, which remodels more or less constantly during life (Hedges et al., 2007). Therefore, depending on the sampled bone, sulphur isotopes can be used to trace the provenance of the last years of an individual's life (Richards et al., 2001; Richards et al., 2003). Some bones however may reveal much slower turnover rates than others. Bone of the skull for example may not have completely remodelled after childhood (Geyh, 2001; Wild et al., 2000). Sulphur isotope ratios ($\delta^{34}S$) in bone collagen strongly correspond to dietary protein sources and give particular insight into whether terrestrial, freshwater or marine foods were preferentially consumed (Nehlich et al., 2010; Nehlich et al., submitted; Privat et al., 2007; Richards et al., 2003). Vika (2009) was able to identify immigrants to Bronze Age Thebes by using sulphur isotope analysis. She showed that humans and animals had the same sulphur isotopic signature, but one individual had a significantly more ^{34}S-depleted isotopic composition, which was concluded to result from non-local food sources, therefore this individual immigrated to ancient Thebes.

6.2. Materials

We sampled archaeological human bone, dentine and enamel for isotope analyses. Due to limited skeletal preservation at the site, only 29 individuals could be sampled. However, we could sample individuals from all of the four major grave groups in the cemetery (Fig. 6.1). Unfortunately, three out of four of the burials with the 'Atlantic' daggers (graves 60, 67, 76 and 84) did not contain preserved skeletons for analysis. In total we sampled bone from 29 burials, yet only 22 of these also contained teeth for sampling. In two subadult individuals (grave 6 and 66) we could sample one deciduous and one permanent tooth from the jaw, resulting in a subset of 24 tooth enamel samples in this study. All information on age and sex (Tab. 1) was taken from Gerhardt (1964) with some additions by J. Wahl (Krause, 1988). We were only able to measure the δ^{18}O of nine enamel samples due to sampling, funding and measurement limitations. The aim of δ^{18}O analysis was to find further evidence of local or non-local origin for those individuals which yielded the most heterogenic ^{87}Sr/^{86}Sr signatures in our sample set, in comparison to a number of individuals with presumably very 'local' ^{87}Sr/^{86}Sr signals. For measurement of δ^{18}O we therefore selected those samples which showed the 'highest' (graves 65, 74 and 77) and 'lowest' (graves 55, 73 and 80) ^{87}Sr/^{86}Sr values as well as samples which revealed 'intermediate/local' ^{87}Sr/^{86}Sr values (graves 19, 57 and 70). Unfortunately, animal bones or teeth for comparison were not recovered at the site of Singen. For the analysis of ^{87}Sr/^{86}Sr and δ^{18}O we sampled tooth enamel because enamel reflects biogenic strontium and oxygen incorporated during tooth formation and is resistant to contaminations due to its dense structure (Budd et al., 2000; Hoppe et al., 2003). We also randomly sampled dentine of eight individuals as a proxy of local soluble strontium in the burial environment, as ^{87}Sr/^{86}Sr values in dentine are likely affected by diagenetic uptake of soil derived strontium (Budd et al., 2000). However, stable isotope ratios of associated fauna are a valuable proxy for the bioavailability of strontium, oxygen and sulphur in a given environment (Bentley and Knipper, 2005; Craig et al., 2006; Price et al., 2002). Alternative sampling of animal bones from several other Bronze Age sites in the proximity of Singen was also not possible because material was not accessible in the depots of the State Office for Heritage Management and Archaeology, Konstanz, Germany. To assess the bioavailable strontium isotope ratios of the region between the Lake Constance and southern Black Forest, we collected a variety of modern snail shells and plants in June 2009 (Fig. 6.3).

Snails have a limited range of movement and are therefore an ideal candidate to detect the local variability in bioavailable strontium (Evans et al., 2010; Price et al., 2002). Strontium is deposited in the shell, as it substitutes for calcium, which is the main component of snail shell (Rosenthal et al., 1965). Plant strontium values reflect the mobile strontium in the local soil in different root depths as well as the strontium introduced by rainwater and atmospheric dust (Evans et al., 2009).

During field sampling, the different major geological formations in the region were located using geological mapping information (LGRB maps dGk25s: 7916 Villingen-Schwenningen-West, 8218 Gottmadingen, 8219 Singen (Hohentwiel), by the Landesamt für Geologie, Rohstoffe und Bergbau, Freiburg). In each geological unit we selected elevated forest patches where anthropogenic contaminations (e.g. fertilizers, traffic pollutions) are unlikely. At each sampling

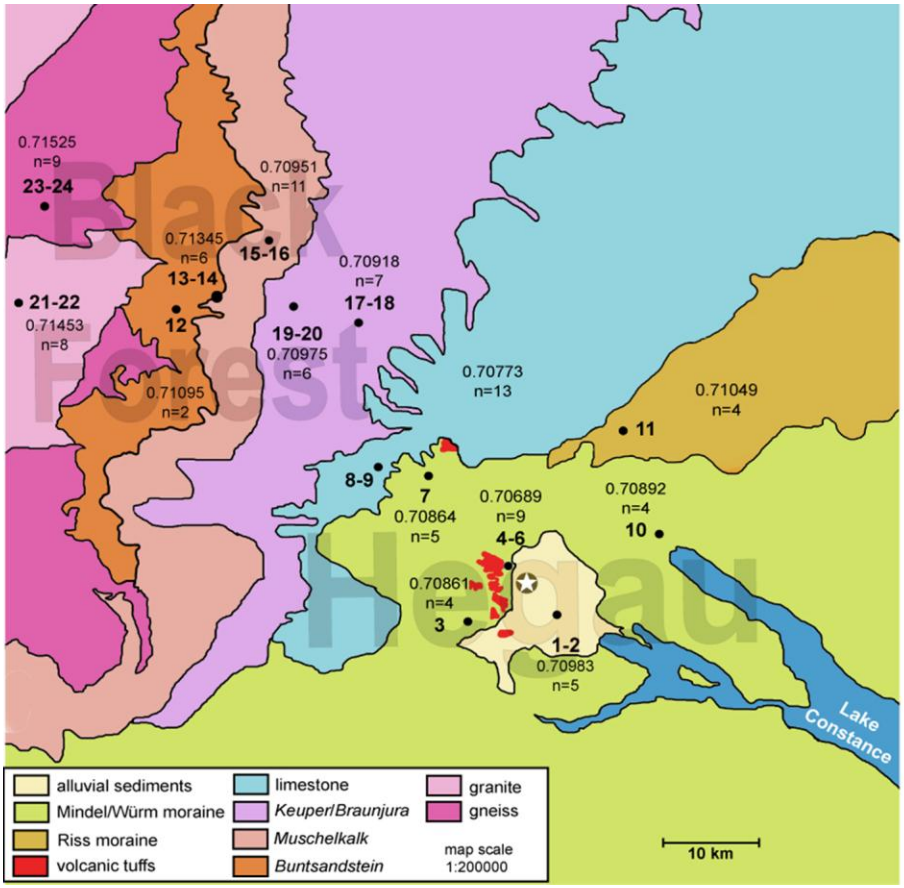

Figure 6.3: Geological map of the study area in south-western Germany. The archaeological site of Singen is marked with a star. The black dots mark the sites of environmental sampling. Information on the mean $^{87}Sr/^{86}Sr$ value and number of samples are reported for each sampling location:
Überlingen am Ried I-II (1-2), Gottmadingen (3), Hohentwiel I-III (4-6), Zimmerholz (7), Aulfingen (8-9), Espasingen (10), Hecheln (11), Pfaffenweiler (12), Magdalenenberg (13-14), Weilersbach (15-16), Tuningen (17-18), Hochemmingen (19-20), Furtwangen (21-22), Triberg (23-24).

location (recorded using GPS) snail shells were collected alongside botanical samples from a deep rooting deciduous tree, a shallower-rooted shrub and a shallow rooted terrestrial herb. We did not sample modern environmental samples for oxygen and sulphur, because $\delta^{18}O$ values may vary through time according to climate changes, and modern samples for $\delta^{34}S$ are likely affected by anthropogenic sulphur pollutants (Krouse et al., 1991).

6.3. Methods

Strontium was extracted and purified from tooth enamel and dentine as well as plants and snail shells following the ion exchange method outlined by 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, tooth samples were manually cleaned with a dental drill to remove superficial contaminations. Then, after cutting a chip of the tooth crown, the enamel was mechanically separated from attached dentine. The opposite procedure was applied to dentine samples, where the attached enamel was removed. The pieces of enamel and dentine were then cleaned by rinsing and in an ultrasonic bath with deionised water. Samples were transferred to the clean laboratory, rinsed in ultrapure acetone and dried overnight. Subsequently ~10-20mg of enamel or dentine was weighed into clean Teflon beakers and digested in 1ml of 14.3M HNO_3 on a hotplate (120°C). Snail shells were cleaned by repeated rinsing (and ultrasonic cleaning) with deionised water to remove attached sediments. Then each sample (1-4g) of snail shell or plant leaves was combusted at 800°C in clean ceramic beakers for 12 hours. The remaining ash was transferred to the clean laboratory where 10-50mg of ash was weighed into clean Teflon beakers and digested in 1-2ml of 14.3M HNO_3 on a hotplate (120°C).

The dissolved samples of enamel, dentine and ash 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 to maximize the amount of strontium attached to the resin. 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).

For the analysis of $\delta^{18}O$, we selected nine individuals. We extracted PO_4 radicals 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 was cut from the tooth crown, manually cleaned with a dental drill and then ground to fine powder. The sample was then dissolved in 1ml 2M HF. After 24 hours, the samples were centrifuged and the solution containing the phosphate was transferred into a new tube where 300µl of NH_4OH was added to buffer the HF. Several drops of BTB (Bromothymol blue) was previously added to check the pH (<7). When the sample was neutral, ~700µl 2M AgNO3 was added. Subsequently the silver phosphate crystals precipitated corresponding to the decrease in pH, while NH_3 was discharged from the solution. The resulting residue, consisting of Ag_3PO4 crystals of light yellow colour, was centrifuged and rinsed with deionised water four times. The residue was then dried down in a freeze dryer. The measurement of the Ag_3PO_4 samples in duplicates 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 (Vennemann et al., 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 two duplicates of the commonly accepted NBS 120c standard, as well as external (Durham horse enamel) and internal laboratory standards.

To analyse sulphur isotope ratios, we extracted collagen from 29 human bone samples. The collagen extraction followed a modified Longin method (Brown et al., 1988; Collins and Galley, 1998; Longin, 1971). Bone samples were cleaned by air abrasion and then demineralized in 0.5M HCl for several weeks at 4°C, with acid changes every few days. Demineralized samples were then rinsed three times with de-ionized water and gelatinized at 70°C in a pH3 solution for 48 hours. The insoluble fraction was first filtered with a 5µm EZEE© filter, and then again filtered using Amicon© ultra filters (>30kDa). The purified solution was frozen and freeze dried for 48 hours. Finally, 10mg of dried collagen sample was weighed into tin capsules. The 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.

6.4. Results

6.4.1. Strontium

The repeated $^{87}Sr/^{86}Sr$ measurement of the standard SRM 987 resulted in an average value of 0.710268 ± 0.000026 (2σ, n = 24) and was subsequently corrected to the accepted value of 0.710240 ± 0.00004 (Johnson et al., 1990; Terakado et al., 1988). Total procedural blanks, one for each batch of 13 samples, were considered negligible. The $^{87}Sr/^{86}Sr$ measured in 24 enamel samples ranged from 0.70740 to 0.70940 with a mean of 0.70838 ± 0.00044 (1σ). This mean $^{87}Sr/^{86}Sr$ value for enamel is almost identical with the mean value of $^{87}Sr/^{86}Sr$ measured in the dentine samples (0.70827 ± 0.00028, 1σ, n=8), which likely reflect the soil $^{87}Sr/^{86}Sr$ signature. Finally, the deciduous and permanent molars of two infants revealed $^{87}Sr/^{86}Sr$ ratio pairs that were almost identical (grave 6: 0.70833 and 0.70836; grave 66: 0.70877 and 0.70853). For further details see Table 1. Environmental samples were obtained from 24 sampling sites in 11 geological units, reaching from the Swiss-German border south of the site of Singen, to approximately 70km north-west in the southern Black Forest (Fig. 6.3). The mean values as well as more details on sampling sites for each geological unit are presented in Table 2.

6.4.2. Oxygen

Oxygen isotope ratios, reported relative to the relative to the international standard VSMOW (Vienna Standard Mean Ocean Water). The measurement error calculated from the standard materials was less than 0.6‰. The $\delta^{18}O$ values measured in the NBS 120c standards were 21.4 ± 0.3‰ and 21.8 ± 0.1‰ (1σ), which is in agreement to a value of 21.7 ± 0.5‰ reported for NBS 120c from other laboratories (summarized in Chenery et al. (2010). The duplicate measurement of an external lab standard (Durham horse enamel) yielded values of 14.7 ± 0.5‰ and 14.6 ± 0.6‰ (1σ). The average reproducibility of the analysis of human enamel was better than 0.30 ± 0.2‰ (1σ). The $\delta^{18}O$ ratios measured in the nine human enamel samples ranged from 13.8‰ to 16.6‰ with a mean of 15.5‰ (± 0.8, 1σ, n=9).

Table 6.1: Individual data (age, sex, bone/tooth sampled), collagen quality criteria (S wt%, C:S, N:S, %collagen) and isotope data ($\delta^{34}S$, $^{87}Sr/^{86}Sr_{enamel}$, $^{87}Sr/^{86}Sr_{dentine}$, $\delta^{18}O$) for each grave. The radiocarbon dates are reported after Krause (1988), the grave marked with an asterisks contained an 'Atlantic' dagger. infans=1-13 years, infans II=6-13 years; m=male, f= female, ?=sex undetermined; dec. molar = deciduous molar, perm. M1 = permanent first molar.

grave number	^{14}C calBC	old number	age	sex	bone	$\delta^{34}S$‰	S wt%	C:S	N:S	% collagen	tooth	$^{87}Sr/^{86}Sr$ enamel	Sr (ppm)	$^{87}Sr/^{86}Sr$ dentin	$\delta^{18}O$ enamel	±1σ	$\delta^{18}O_{dw}$
6		55/25	infans	?	long bone	1.0	0.23	480	149	5.27	dec. molar	0.70833	40				
6				?							perm. M1	0.70836	47				
7	2140-1985	55/24	adult	f?							M1	0.70853	21				
8		55/23	?	?	fragment												
12		55/18	infans II	?	fragment	-0.6	0.21	562	165	4.67							
19	2280-2050	55/13	infans II	?	long bone	1.7	0.19	592	191	8.44	M3	0.70825	38	0.70815	15.2	0.43	-12.17
33		52/27	?	?	fragment	0.6	0.20	568	162	2.01							
45		51/11	adult	?	rib	2.2	0.22	494	147	3.72	M1	0.70853	48				
46		51/6	infans II	?	long bone	1.5	0.21	528	166	9.41	M1	0.70829	30				
55		53/22	adult	m	skull						canine	0.70784	53		16.6	0.11	-9.13
57		53/18	adult	f	long bone	0.9	0.24	463	144	5.37	M3	0.70821	78	0.70825	15.7	0.35	-11.09
61		58/2	adult	?	long bone	1.2	0.24	435	130	4.86	premolar	0.70808	34	0.70868			
63		52/5	adult	m	rib	1.0	0.22	527	156	6.31	M3	0.70791	41	0.70773			
65	2460-2150	53/4	adult	f	long bone	-0.1	0.15	0	0	3.65	M3	0.70940	44		15.3	0.19	-11.96
66		52/24	infans	?	long bone						dec. molar	0.70877	40				
66											perm. M1	0.70853	24	0.70840			
68	2140-1975	52/19	adult	m	long bone	3.4	0.25	364	106	2.26	premolar	0.70847	38				
69		52/17	adult	m?	long bone	2.3	0.25	437	128	3.53							
70	2280-2135	52/14	adult	m	long bone	0.9	0.21	489	147	3.82	M2/M3	0.70850	21		15.8	0.00	-10.87
71		52/15	adult	m	long bone	1.0	0.26	372	110	4.76	incisivi	0.70804	94				
72		52/2a	?	?	rib	0.6	0.22	464	145	6.38	premolar	0.70805	41				
73		52/3	adult	m	skull	1.3	0.22	509	148	4.06	canine	0.70740	39		15.3	0.09	-11.96
74	2135-1950	52/6	adult	f	long bone	0.6	0.15	462	145	5.78	canine	0.70908	29		13.8	0.96	-15.22
77		50/19	adult	?	long bone	2.8	0.24	452	108	2.45	M2	0.70906	34	0.70842			
79	2140-1985	50/15	adult	?	long bone	1.0	0.19	581	178	5.56	M1	0.70877	40		16.0	0.50	-10.43
80	2175-1985	50/16	adult	f	fragment	2.1	0.21	452	132	1.82	premolar	0.70799	66	0.70817	15.9	0.04	-10.65
82		50/21	infans	?	fragment	0.1	0.21	540	159	4.33							
86		50/20	?	?	fragment												
87		50/18	?	?	skull	1.7	0.27	432	132	4.42							
101		59/1	adult	m	skull						M1	0.70845	95				
67*		52/22	adult	m	skull	1.4	0.26	415	120	2.39	M1	0.70834	47	0.70834			

Table 6.2: Details on the environmental sampling in the Hegau and Black Forest region. The sampling sites are named after the neighbouring village. For each sampling location the type of sample, species and GPS coordinates are reported next to a description of the geological conditions and the results of the $^{87}Sr/^{86}Sr$ analysis.

no.	**site**	**sample**	**species**	**GPS coordinates** **(UTM 32)**	**geology**	**sample** **(mg)**	**$^{87}Sr/^{86}Sr$**	**Sr conc** **(ppm)**
1a	Überlingen am Ried I	snail	*Helix pomatia*	T 0491659 5287798	alluvial sediments	39	0.70947	166
1b		herb	wild strawberry			30	0.70979	831
1c		bush	beech			4	0.71087	1060
1d		tree	broadleaf			17	0.71036	359
2a	Überlingen am Ried II	snail	snail	T 0491901 5287758	alluvial sediments	25	0.70865	240
						mean	**0.70983**	
						s.d.	**0.00085**	
3a	Gottmadingen	snail	*Helix pomatia*	T 0483490 5287939	moraine (Mindel glacial)	37	0.70823	210
3b		herb	gras			36	0.70849	84
3c		bush	young ash			30	0.70820	240
3d		tree	beech			25	0.70950	564
						mean	**0.70861**	
						s.d.	**0.00061**	
4a	Hohentwiel I	snail	*Helix pomatia*	T 0486328 5290351	tuffs (foot of the volcano)	27	0.70585	432
4b		snail	*Helix pomatia*			45	0.70570	465
4c		herb	ivy			29	0.70616	841
4d		bush	elder			31	0.70741	251
4e		tree	cestnut			43	0.70621	329
5a	Hohentwiel II	snail	*Helix pomatia*	T 0486333 5290134	tuffs (flanc of the volcano)	32	0.70763	437
5b		herb	dandelion			44	0.70754	191
5c		bush	hazelnut			31	0.70822	262
6	Hohentwiel III	snail	*helix pomatia*	T 0486433 5290179	tuffs, phonolith (top of volcano)	35	0.70733	217
						mean	**0.70689**	
						s.d.	**0.00091**	
7a	Zimmerholz	snail	*Helix pomatia*	T 0479491 5301541	molasse	27	0.70793	85
7b		snail	*Perforatella umbrosa*			25	0.70856	150
7c		herb	woodruff			24	0.70882	134
7d		bush	fern			33	0.70899	118
7e		tree	beech			24	0.70892	141
						mean	**0.70864**	
						s.d.	**0.00043**	
8a	Aulfingen I	snail	*Perforatella incarnata*	T 0473506 5304334	limestone	34	0.70726	166
8a		snail	*Perforatella umbrosa*			29	0.70738	127
8a		snail	*Trichia*			38	0.70735	155
8b		herb	dandelion			23	0.70868	129
8c		bush	elder			30	0.70866	439
8d		tree	ash			31	0.70797	246
9a	Aulfingen II	snail	*Perfortella incarnata*	T 0473597 5304272	limestone	20	0.70732	222
9b		snail	*Perfortella umbrosa*			26	0.70736	158
9c		snail	*Perfortella incarnata*			43	0.70731	179
9d		snail	*Helix pomatia*			32	0.70728	157
9e		herb	dandelion			33	0.70816	102
9f		bush	hazelnut			28	0.70783	202
9g		tree	beech			28	0.70785	92
						mean	**0.70773**	
						s.d.	**0.00052**	
10a	Espasingen	snail	2 small snails	T 0500938 5297032	moraine (Würm glacial)	37	0.70861	140
10b		herb	gras			43	0.70897	29
10c		bush	hazelnut			36	0.70896	287
10d		tree	oak			34	0.70914	326
						mean	**0.70892**	
						s.d.	**0.00022**	
11a	Hecheln	insect	dung beetle	T 0498697 5305654	moraine (Riß glacial)	10	0.71118	115
11b		herb	dandelion			31	0.70891	157
11c		bush	elder			45	0.71052	230
11d		tree	beech			46	0.71135	144
						mean	**0.71049**	
						s.d.	**0.00111**	
12a	Pfaffenweiler	snail	*Cepaea hortensis*	U 0455955 5321586	*Buntsandstein*	45	0.71035	193
12b		herb	wild strawberry				machine error	
12c		bush	elder				machine error	
12d		tree	ash			45	0.71154	234
						mean	**0.71095**	
						s.d.	**0.00084**	

13a	Magdalenenberg, site	herb	gras	U 0458595	5321374	*Buntsandstein*		machine error	
13b		bush	rose hip				41	0.71359	128
13c		tree	oak				37	0.71488	31
14a	Magdalenenberg, forest	snail	*Cepaea hortensis*	U 0458820	5321374	*Buntsandstein*	34	0.71143	221
14b		herb	clover				12	0.71214	171
14c		herb II	fern				15	0.71375	317
14d		tree	beech				20	0.71489	167
							mean	**0.71345**	
							s.d.	**0.00141**	
15a	Weilersbach I	snail	*Cepaea hortensis*	U 0462087	5326612	*Muschelkalk*	58	0.71175	123
15b		snail	*Helix pomatia*				31	0.70873	146
15c		snail	*Helix pomatia*				37	0.70887	101
15d		herb	clover				27	0.70965	146
15e		bush	rowan				37	0.70890	397
15f		tree	maple				29	0.70928	180
16a	Weilersbach II	snail	*Perforatella incarnata*	U 0463229	5327538	*Muschelkalk*	4	0.70898	118
16b		snail	*Perforatella incarnata*				31	0.70876	119
16c		herb	wild strawberry				51	0.71055	175
16d		bush	elder				28	0.70938	303
16e		tree	beech				34	0.70973	91
							mean	**0.70951**	
							s.d.	**0.00092**	
17a	Tuningen I	snail	*Helix pomatia*	U 0471959	5319218	*Braunjura*	30	0.70901	285
17b		herb	dandelion				37	0.70882	133
17c		bush	hazelnut				45	0.70939	124
18a	Tuningen II	snail	*Helix pomatia*	U 0472265	5319212	*Braunjura*	4	0.70863	174
18b		snail	*Cepaea hortensis*				3	0.70830	156
18c		herb	strawberry				39	0.70871	178
18d		tree	maple tree				30	0.71143	355
							mean	**0.70918**	
							s.d.	**0.00105**	
19a	Hochemmingen I	snail	*Helix pomatia*	U 0466814	5320049	*Keuper*	3	0.70893	139
19b		herb	wild strawberry				37	0.70951	340
19c		bush	elder				54	0.70938	259
19d		bush	hazelnut				53	0.70962	242
20a	Hochemmingen II	snail	*Helix pomatia*	U 0466369	5320144	*Keuper*	4	0.71059	110
20b		tree	beech				29	0.71046	164
							mean	**0.70975**	
							s.d.	**0.00065**	
21a	Furtwangen I	snail	*Cepaea hortensis*	U 0440858	5320973	gneiss, higher altitude	33	0.71502	85
21b		herb	gras				29	0.71614	68
21c		bush	rowan				42	0.71865	75
21d		tree	beech				41	0.71877	59
22a	Furtwangen II	snail	*Cepaea hortensis*	U 0441246	5321486	gneiss, foothills/floodplain	34	0.71272	221
22b		herb	dandelion				27	0.71033	419
22c		bush	rasberry				57	0.71233	235
22d		tree	apple tree				28	0.71228	718
							mean	**0.71453**	
							s.d.	**0.00313**	
23a	Triberg I	snail	*Cepaea hortensis*	U 0442326	5330273	granite	20	0.71532	278
23b		herb	fern				13	0.71564	339
23c		bush	rasberry				40	0.71421	116
23d		tree	beech				22	0.71677	267
23e		bush	elder				15	0.71518	406
24a	Triberg II	snail	*Cepaea hortensis*	U 0442237	5330302	granite	7	0.71318	179
24b		herb	fern				22	0.71156	80
24c		bush	elder				56	0.71346	188
24d		tree	beech				29	0.72190	343
							mean	**0.71525**	
							s.d.	**0.00293**	

Table 6.2: continued.

6.4.3. Sulphur

We extracted sufficient amounts of collagen (>9mg) for sulphur isotope analysis out of 23 human bone samples. Six bone samples had insufficient collagen yield for sulphur isotope analysis. The total amounts of extracted collagen (% collagen), atomic ratios (C:S, N:S) and measures of the sulphur weight% (S wt%) are presented in Table 1. All 23 samples meet the recommended quality criteria for collagen (Ambrose, 1990; DeNiro, 1985). The ratios of C:S and N:S meet the recommended values of 600 ± 300 and 200 ± 100 respectively, and the weight % of sulphur in the collagen ranges between 0.15 and 0.35 (Nehlich and Richards, 2009). The analytical error, calculated from repeated analysis of internal and international standards, was less than ± 0.6‰ for δ^{34}S. Sulphur isotope ratios, scaled against the standard V-CDT, measured in human collagen ranged from -0.6‰ to +3.4‰ (mean +1.2 ± 0.9‰, 1σ).

6.5. Discussion

6.5.4. Environmental samples

Most of the environmental background samples had ^{87}Sr/^{86}Sr values that mainly reflected the expected ^{87}Sr/^{86}Sr isotope values of the underlying bedrock, while a number of environmental samples had ^{87}Sr/^{86}Sr ratios that were outside of the expected values. The Hegau region (sample locations 1-11) west of the Lake Constance is the result of the formation and modification of the Alps. The region is dominated by alluvial sediments (1-2), molasses (7) and moraines from different glacial periods (3, 10-11). Except for the volcanic tuffs (4-6), these sediments revealed consistent ^{87}Sr/^{86}Sr signatures with an average of 0.70919 (± 0.00098, 1σ, n=22), reflecting relatively young geological formations.

The alluvial sediments surrounding the site of Singen were sampled at Überlingen am Ried (1-2) and revealed values of 0.70983 (± 0.00085, 1σ, n=5), similar to what was measured in biological samples from alluvial sediments by Price and colleagues (2003). However, it is important to note that the sample location of Überlingen am Ried is dominated by Holocene sediments superposed on the Pleistocene gravels. This stratigraphy likely caused slightly more radiogenic values in the deep rooting trees of this subset (1c and 1d), whereas the snails (1a and 2a) seem to have sourced less radiogenic ^{87}Sr/^{86}Sr, which is more representative for the more recent overlying sediments at Überlingen am Ried. The present day city of Singen itself is located in the alluvial sediments

(Fig. 6.3 and 6.4), while the burial site of Singen itself is likely partly covered by smaller extensions of the Würm moraine (represented by the sample location 10) and therefore also has been influenced by strontium from the moraine. The Würm moraine itself had a slightly lower mean $^{87}Sr/^{86}Sr$ signature of 0.70892 (± 0.00022, 1σ, n=4) which matches well with the $^{87}Sr/^{86}Sr$ ratios we measured in the human dentine (0.70827 ± 0.00028, 1σ, n=8).

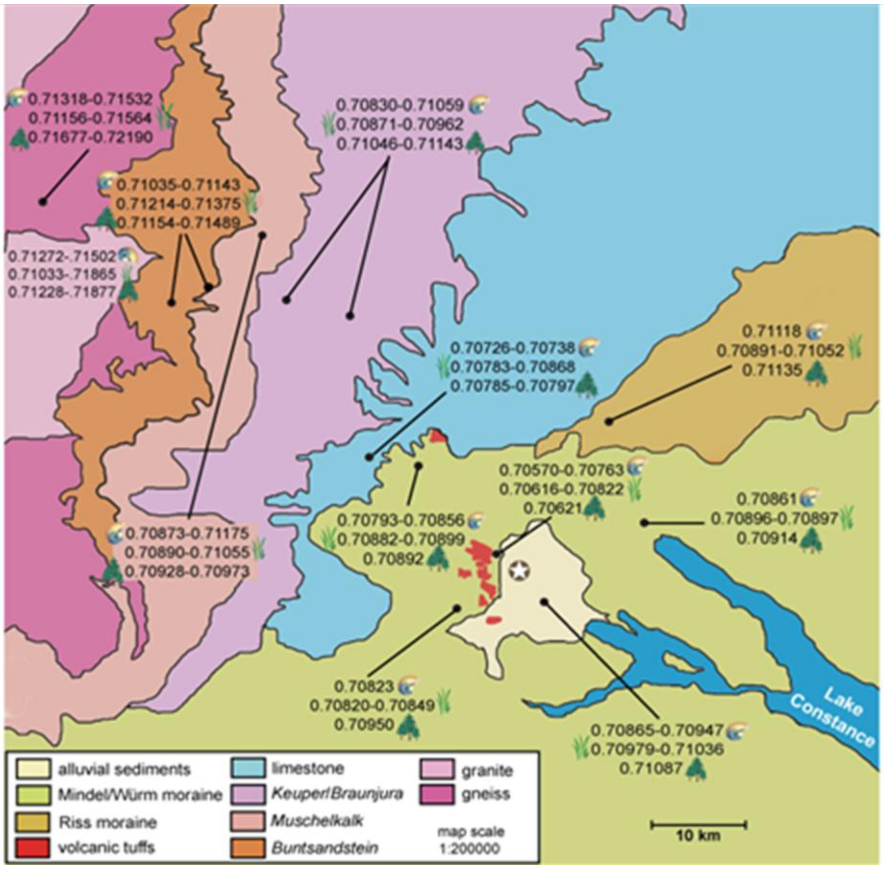

Figure 6.4: Geological map of the study area in south-western Germany with the according range of $^{87}Sr/^{86}Sr$ ratios measured in snail shells, herbs/shrubs and trees, as indicated by the according symbols.

The lowlands of the Hegau are interrupted by very small scale volcanic outcrops, e.g. the Hohentwiel volcano (4-6) west of the city of Singen. Samples from this volcano revealed the lowest $^{87}Sr/^{86}Sr$ values measured in this study. Here, the three different sample locations at the volcano demonstrate a range of $^{87}Sr/^{86}Sr$ values at one single geological site: Probably due to weathering and leaching of the rock, the 'lowest' values were measured in biosphere samples from the foot of the volcano (4a-e) with a mean of 0.70628 (± 0.00067 1σ, n=5). Slightly higher values (mean 0.70767 ± 0 .00038, 1σ, n=4) were measured at the volcano's flank (5) and top (6), which are dominated by phonolite rocks.

A strip of Late Jurassic limestone bordering the Hegau to the west revealed a mean ^{87}Sr/^{86}Sr value of 0.70773 (± 0.00052, 1σ, n=13) for the sample location Aulfingen (8-9). At Aulfingen we see only a small variation in ^{87}Sr/^{86}Sr among the 13 different samples, indicating that we likely sampled biological materials representative of the underlying geology. Even though the sampled forest patch at Aulfingen may also contain small outcrops of molasse, the values measured here are similar to what is reported for Jurassic deposits elsewhere (Horn et al., 1985; Price et al., 2004). Further north/northwest of the Hegau region the lithostratigraphy of the landscape changes to the middle Jurassic *Braunjura* and *Keuper* strata (17-20) of the Neckar valley, which had a mean ^{87}Sr/^{86}Sr value of 0.70944 (± 0.00090 1σ, n=13). One maple tree (18d) in the *Braunjura* at Tuningen revealed unusual radiogenic values of 0.71143, which is unusual and we have no explanation for this, as the geology in this area is very homogeneous. If the result from this tree is excluded, the ^{87}Sr/^{86}Sr values measured in the remaining 12 samples range from 0.70830 to 0.71059, resembling what was reported by Bentley and colleagues (Horn pers. comm. in Bentley et al., 2003). Further westwards are the foothills of the Black Forest with the characteristic *Muschelkalk* and *Buntsandstein* deposits. In the uniform *Muschelkalk* area at Weilersbach (15-16) we found very variable ^{87}Sr/^{86}Sr values, ranging from 0.70873 to 0.71175. Strontium isotope data reported for the *Muschelkalk* in southwest Germany range broadly between 0.708 and 0.709 (Price et al., 2003). The data from Weilersbach I (15) suggests that data measured in the plants and the two large snails (*Helix pomatia*) are representative for the *Muschelkalk*, whereas the more radiogenic ^{87}Sr/^{86}Sr value of 0.71175 measured in the white-lipped snail (15a) is likely due to Sr contamination, as the snail could possibly have been feeding on fertilised agricultural fields, which are located several hundred meters away from the sampling spot. At Weilersbach II (16) however, the highest value of 0.71055 is measured in a wild strawberry (16c), while the four remaining samples of snails and deeper rooting plants reveal a lower mean value of 0.70921 ± 0.00042 (1σ). It is possible that the strawberry was growing close to the forest path (which are often paved with non-local sediments) and may therefore not be representative. If these two samples (15a and 16c) are excluded, the range is 0.70873 to 0.70973 and the mean is 0.70914 (± 0.00038, 1σ, n=9) for the *Muschelkalk* at Weilersbach, which meets what was reported in previous studies (Price et al., 2003). The *Buntsandstein,* a red sandstone of the Black Forest, was sampled in two locations (12 and 13-14) which revealed distinct ^{87}Sr/^{86}Sr signatures. For Pfaffenweiler (12), a snail and a tree were measured, resulting in a mean of 0.71095 (± 0.00084, 1σ, n=2). Thus, the values measured for the archaeological site of Magdalenenberg (13) and the adjoining 'Laible' forest patch (14) are much more radiogenic. Magdalenenberg is located on a small accumulation of *Buntsandstein*, which had pushed through the *Muschelkalk* bedrock and formed a small hill. Contamination of the soil by leached fertilizers appears unlikely, as the sampling loci are elevated relative to the surrounding fields. The average ^{87}Sr/^{86}Sr signature measured for Magdalenenberg is 0.71345 (± 0.00141, 1σ, n=6). The range of values measured at Pfaffenweiler and Magdalenenberg compares well to what is reported for *Buntsandstein* bedrock (Bentley et al., 2003; Horwath, 2000; Price et al., 2003) but exceeds the values measured in the biosphere (Price et al., 2003). Much older geological units with even higher ^{87}Sr/^{86}Sr values for the biosphere appear approximately 40km northwest of the site of Singen in the more radiogenic gneiss (mean 0.71453 ± 0.00313 1σ, n=8) and granite bedrocks (0.71525 ± 0.00293 1σ, n=9) of the Black Forest, with values similar to what was reported for the bedrocks' isotope signatures (Baumann and Hofmann, 1988; Price et al., 2003). At the sampling location Furtwangen, a region strongly dominated by gneiss bedrock, we sampled in two locations, one in higher altitudes (21), and one in the foothills next to a small stream (22). The higher altitude sample location had much more radiogenic ^{87}Sr/^{86}Sr signatures ranging from 0.71502 to 0.71877 and with a mean of 0.71715 (± 0.00186, 1σ, n=4), which can be expected from older metamorphic rocks (Baumann and Hofmann, 1988). In the foothills of the gneiss however, we measured much lower ^{87}Sr/^{86}Sr values (mean 0.71192, ± 0.00107 1σ, n=4), which are less representative for gneiss. We suggest that we sampled a very small scale geological outcrop of a much younger geological stratum, which is likely caused by the small stream and is not marked on the geological maps. In the granite mountainous region above the waterfall of Triberg (23-24) we gained the highest ^{87}Sr/^{86}Sr value of our biosphere sampling. This value was measured in the leaves of deep rooting tree (24d with 0.72190), indicating that much of the ^{87}Sr/^{86}Sr utilized by the tree derived almost directly from the underlying granite rock. More shallow rooting plants on the other hand revealed much lower values, suggesting a more mixed sourcing for ^{87}Sr/^{86}Sr.

The critical aspect of the application of strontium isotope analysis of archaeological remains is to determine which isotope signature is local and which is not (Bentley et al., 2004; Budd et al., 2004). In this study, we mapped the landscape surrounding the archaeological study site to reveal the local and the more remote ^{87}Sr/^{86}Sr signatures. We found a quite homogeneous isotopic pattern for the site and the surrounding area of approximately 20km, if the small scale volcanic tuffs are excluded (Fig. 6.3, 6.4 and 6.5). Only the Hohentwiel volcano featured less radiogenic ^{87}Sr/^{86}Sr values (0.70570 to 0.70822), yet we can exclude that growing crops on the steep volcanic slopes was relevant for the local subsistence, despite the volcanic tuffs seem to have been relevant as pastures for livestock in the Neolithic (see below). The ^{87}Sr/^{86}Sr signature of the landscape becomes significantly more radiogenic 40km northwest of the site of Singen in the *Buntsandstein* and the older rocks of the gneiss and granite.

6.5.5. Strontium isotope signatures in human enamel

Although the cemetery of Singen was used over a time period of more than 200 years, the values we measured in the human enamel appear quite homogenous. We suggest that the overall variation in ^{87}Sr/^{86}Sr of 0.02000 within the 24 enamel samples can be explained by the consumption of plants and animals from local geologies close to the site. Additionally, none of the Singen individuals featured ^{87}Sr/^{86}Sr ratios higher than 0.70940, and hence none showed clear evidence for distant residence during the period of tooth formation (Fig. 6.5). All individuals incorporated an isotopic signature similar to what is present at the cemetery and its surroundings, leading to the conclusion that the location of residence and the source of everyday diet were closely linked to the Hegau region and the western shores of the Lake Constance, respectively. Given the strong correlation between the enamel and dentine ^{87}Sr/^{86}Sr ratios measured in eight individuals, mean values of 0.70830 (± 0.00036, 1σ) and 0.70827 (± 0.00028, 1σ), one could suggest that the area of residence was located in the proximity of the cemetery, or at least on very similar alluvial sediments and Pleistocene moraines. Thus, our finding accords to the discovery of pottery fragments near the cemetery site, which have been suggested to indicate the presence of a related settlement (Krause 2001).

Additional insights into the life histories of two infant individuals (graves 6 and 66) were possible, although their poor skeletal preservation did not allow a precise age estimate. From the deciduous molars we found that the residence of their mothers was local during pregnancy and first few months of breastfeeding. From the ^{87}Sr/^{86}Sr ratios measured in the crowns of two nonerupted permanent molars, we can reconstruct evidence that the children's residence remained the same over the following years (Humphrey et al., 2008; Reid and Dean, 2006).

Further data for the determination of the local bioavailable $^{87}Sr/^{86}Sr$ comes from archaeological fauna from prehistoric sites in direct proximity to the Singen cemetery. Bentley and Knipper (2005) analysed pig enamel samples from the Neolithic sites Hilzingen and Singen-Offwiese (<4km distance). The mean $^{87}Sr/^{86}Sr$ value of all three pigs is 0.708 (Bentley and Knipper, 2005), which would resemble the human enamel data from Singen. However, one of the Hilzingen pigs had a more radiogenic of $^{87}Sr/^{86}Sr$ value of 0.711 which could not have been formed from consuming foods from the local geology around the site of Singen. According to our biosphere data, a possible source of this higher Sr isotope signal could be the Riss moraine northwest of the Singen site or the *Keuper, Braunjura* or *Muschelkalk* layers to the west (Fig. 6.5). A second pig from Hilzingen had a much lower $^{87}Sr/^{86}Sr$ value of 0.706 which may reflect feeding on the slopes of the Hohentwiel volcano or the neighbouring volcanic tuffs (<2km distance). A similar pattern is found in the pig from Singen-Offwiese which had a $^{87}Sr/^{86}Sr$ signature of 0.707 (Bentley and Knipper, 2005) and may also have derived from a region of volcanic tuffs (Fig. 6.5). From our modern environmental samples we infer that, due to the potential of pigs to feed

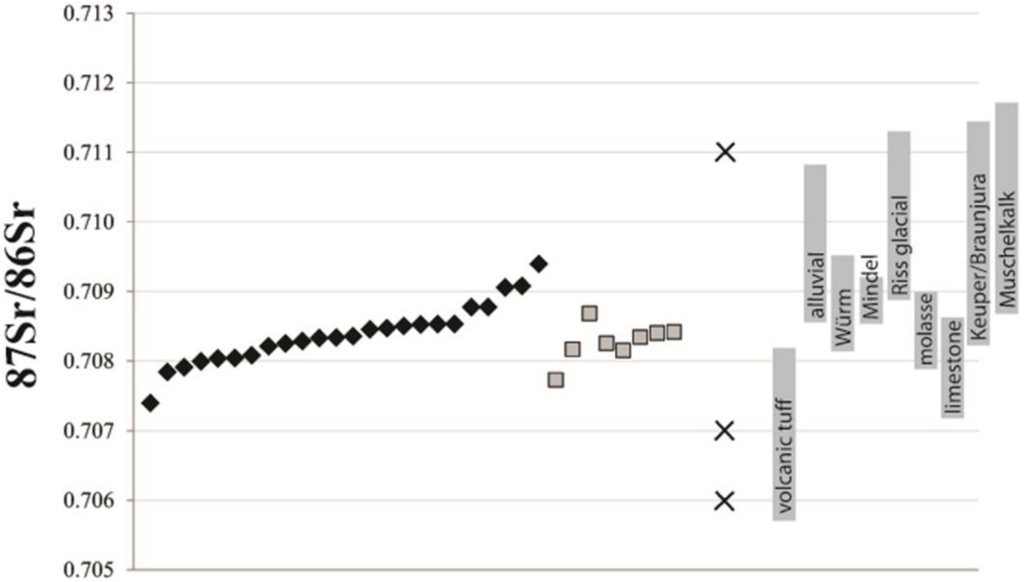

Figure 6.5: Strontium isotope ratios measured in human enamel (black diamonds), human dentine (gray squares) and Neolithic pigs (back cross, data reported by Bentley & Knipper, 2005). The grey bars represent the bioavailable $^{87}Sr/^{86}Sr$ ratios measured for the geological units in this study within a ~25km radius around the site of Singen.

in more remote or forested pastures, archaeological pig data might not always give a good proxy for humans, in terms of the local bioavailability of strontium.

Modern isotope data for comparison with the human enamel data in this study derives from the Lake Constance itself. Radiocarbon dated sediment cores from the lake revealed very homogeneous $^{87}Sr/^{86}Sr$ values for the Holocene. For the period of the Bronze Age the values measured in crustacean shell material ranged between 0.786 and 0.788 (Kober et al., 2007). Although strontium uptake from drinking water is negligible, these values give a good proxy of the lake basin geology, which is tertiary molasse. Modern $^{87}Sr/^{86}Sr$ data from molluscs collected in Lake Constance had values of 0.7085 and 0.7084 (Buhl et al., 1991), which are similar to the mean $^{87}Sr/^{86}Sr$ values for the Singen people (0.70838 ± 0.00044). Nevertheless, we find similar $^{87}Sr/^{86}Sr$ signatures in other parts of Europe, e.g. in Britain (Chenery et al., 2010), the Carpathian Basin (Giblin, 2009), other areas of southern Germany (Price et al., 2006; Schweissing and Grupe, 2003) and in the Swiss region between Lake Constance and Lake Zurich (Tütken et al., 2008). Therefore, although unlikely it is possible that if people had migrated from these other

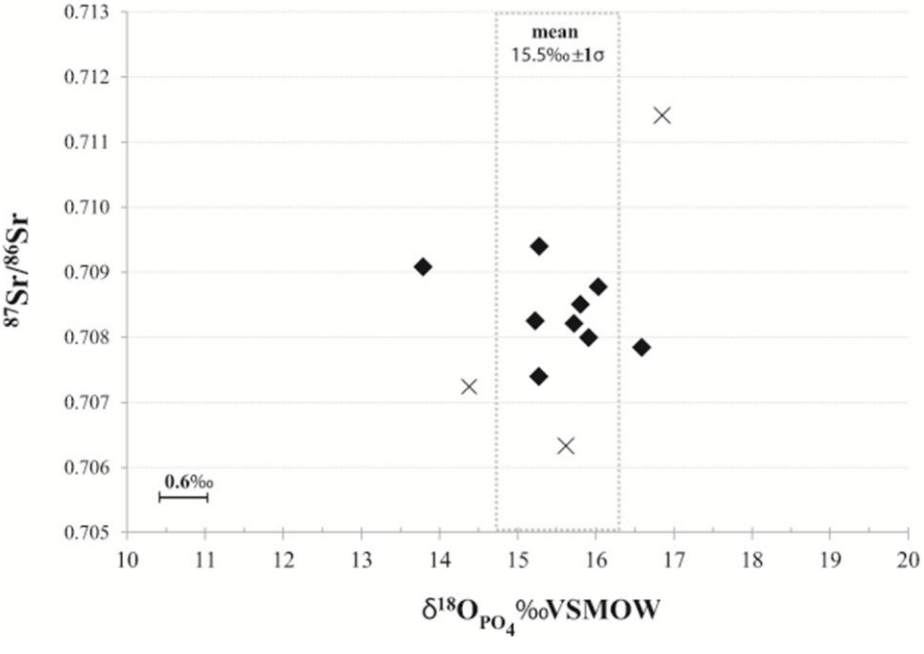

Figure 6.6: The $^{87}Sr/^{86}Sr$ ratios plotted against the $\delta^{18}O$ values measured in human enamel phosphate (n=9). The dashed box indicated the predicted local $\delta^{18}O$ range (mean value ± 1σ), and the ±0.6‰ represents the measurement error (1σ). The data from the three local Neolithic pigs (x) are taken from Bentley & Knipper (2005).

areas to Singen, they could have similar $^{87}Sr/^{86}Sr$ values to the local values, and therefore mistakenly be identified as local. Therefore, we also measured isotope ratios of other chemical elements to further confirm our conclusions that the humans we sampled from Singen are indeed local.

6.5.6. Oxygen isotope ratios in human enamel

Oxygen isotope ratios of enamel are related to the oxygen isotope composition of drinking water. Lake Constance serves as the major drinking water reservoir in the region and is a good proxy for the local oxygen isotope composition of the Hegau region, including its lakes, streams and groundwater. If the Early Bronze Age population from Singen lived in the Hegau area west of Lake Constance, as their strontium isotope ratios suggest, their oxygen isotope ratios should match the local water and meteoric precipitation oxygen isotope values. We found quite consistent $\delta^{18}O$ values in the human enamel from Singen (mean 15.5 ± 0.8‰, 1σ, n=9) with two outliers (Fig. 6.6). One individual from Grave 74 had a $\delta^{18}O$ value of 13.8‰ which is outside the average and 1σ range of our data set. This data point should be considered with caution, because the measurement error of this sample was high (0.96‰, 1σ, a-measurement: 13.11‰, b-measurement: 14.47‰), suggesting the sample was either contaminated, or an error occurred during measurement. The second sample falling slightly out of the 1σ range is a canine from grave 55, with a $\delta^{18}O$ value of 16.6‰. This tooth, and the canines from the graves 74 and 73, might be reflecting breastfeeding oxygen isotope values, rather than drinking water values. As the canine forms on average between the age of 1.5 and 5 or 6 years (Reid and Dean, 2006) the consumption of ^{18}O enriched mother's milk during this developmental stage may influence the tooth's isotopic composition (Wright and Schwarcz, 1998). However, the $\delta^{18}O$ value measured in the canine of grave 73 (15.3‰) falls close to the mean value, indicating no influence from mothers' milk. We can conclude then that the outliers in our small oxygen data set are more likely the cause of technical issues, than representing humans with slightly different drinking water sources. The approximate $\delta^{18}O$ value of the drinking water can be assessed by calculating the fractionation between $\delta^{18}O_{water}$ and $\delta^{18}O_{phosphate}$. We followed the calculation by Levinson et al. (1987) with a correction of the enamel phosphate value for the NBS 120c standard by -1.4, as outlined and recommended by Chenery et al. (2010). The corrected $\delta^{18}O$ values for the humans from the site of Singen result in a mean predicted $\delta^{18}O_{drinking\ water}$ of -11.5 ± 1.7‰, 1σ. This prediction matches with the modern water from Lake Constance itself. Water samples of the lake revealed $\delta^{18}O$ values of -12.1‰ and -11.9‰ in spring, and -13.4‰ and -12.2‰ in fall, demonstrating the influence of annual temperature variation on water $\delta^{18}O$ (Buhl et al., 1991). Also, the modern annual precipitation data for Germany shows remarkable similarity between the predicted $\delta^{18}O_{drinking\ water}$ for the site of Singen and the $\delta^{18}O$ values in meteoric water in the southern part of Germany, ranging from -10.6 to -11.2‰ (Tütken et al., 2004). Archaeological human $\delta^{18}O$ data with similar signatures are reported 35km south of Singen, in the Canton Zurich. With a mean of 14.7 ± 0.5‰ (n=4), these human enamel samples are regarded as typical for the southern German and Swiss region (Tütken et al., 2008). More local archaeological $\delta^{18}O$ data is available for the Neolithic pig enamel from Hilzingen (16.6‰ and 15.4‰) and Singen-Offwiese (14.2‰ and 13.6‰) (after Bentley and Knipper 2005, corrected after Iacumin et al. 1996). The range found in pig teeth is remarkably similar to the range we measured in the Bronze Age human teeth, including the previously discussed outliers (13.8‰ to 16.6‰). Bentley and Knipper (2005) reconstructed the local meteoric water of the Hegau using these samples and obtained mean annual meteoric water values (SMOW) of -12.2‰ for Singen-Offwiese and -9.7‰ for Hilzingen.

These various data from archaeological and modern samples indicated that the $\delta^{18}O$ values measured in the Singen population resembles the local drinking waters, including lakes, streams and local rainfall. We found no evidence for a suggested coastal influence that was inferred from the ‘Atlantic’ style of metal artefacts. Drinking water in southern Britain has an oxygen isotope value of -5 to -7‰, which resulted in enamel $\delta^{18}O$ values of ~16-19‰ for prehistoric British populations (Chenery et al., 2010; Eckardt et al., 2009; Evans et al., 2006b). Though there is little data available for coastal France, $\delta^{18}O$ values of drinking water from northern Bordeaux (~50km from the Atlantic coastline) of -8.1‰ resulted in a $\delta^{18}O$ value of 18.3‰ for human enamel (Daux et al., 2008). Other clearly coastal data derives from two Neolithic sites from the Netherlands with $\delta^{18}O$ values between ~17 and 18‰ for local individuals (Smits et al., 2010). A range of historic human tooth samples from southern Lorraine (western France) revealed $\delta^{18}O$ values between ~16-18‰ (Daux et al., 2005). Currently, there is no archaeological or environmental $\delta^{18}O$ data available for Hungary or the Carpathian Basin for a comparison with the Singen data. Nevertheless, Evans et al. (2006a), also searching for points of comparison with

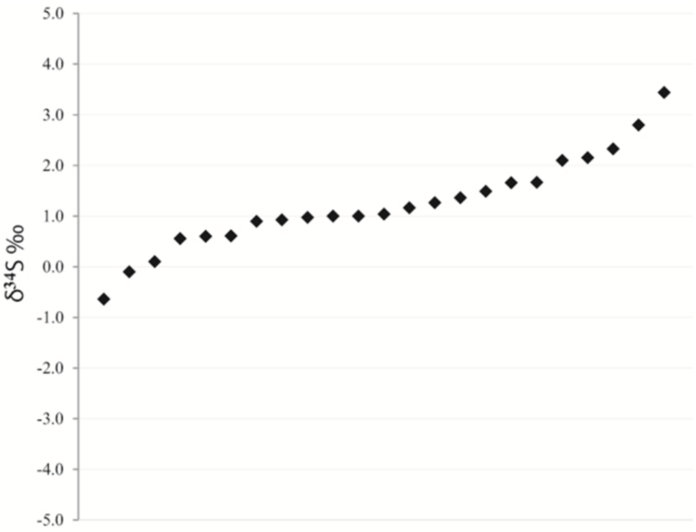

Figure 6.7: The distribution of all $\delta^{34}S$ values measured in human bone collagen.

present day Hungary, suggested the $\delta^{18}O$ values of drinking water to be lower than -9.0‰. Therefore, we conclude that the measured oxygen isotope values of the humans from Singen, despite the limited dataset, support the strontium isotope evidence for the individuals being local to the Singen region.

6.5.7. Sulphur isotope ratios in human bone

The humans bone collagen sulphur isotope values are very similar to each other, with a mean $\delta^{34}S$ value of 1.2 ± 0.9‰ (Fig. 6.7.) which is typical for a terrestrial diet in temperate Europe (Nehlich et al., 2010). The sulphur isotope data supports what we found in the oxygen isotopes; there is no evidence for a marine influence or slightly elevated $\delta^{34}S$ ratios due to sea spray effects (Craig et al., 2006). The mean $\delta^{34}S$ value of 1.2 ± 0.9‰ shows a clear terrestrial signal (Krouse and Levinson, 1984) and suggests no measurable input of freshwater fish protein in human diets from Lake Constance, since the average modern $\delta^{34}S$ value of the water sulphates from the Lake Constance is 7.6‰ (Hoeppner et al., 1981). The range of the $\delta^{34}S$ values is clustered tightly (Nehlich et al., 2010; Vika, 2009) and suggests a very homogenous composition of the diet. These results are similar to the carbon and nitrogen isotope data of these individuals, which demonstrate that the individuals from Singen had terrestrial omnivorous diets (K. Kupke, personal information). Unfortunately, there is no human or animal $\delta^{34}S$ data available from this region for comparison. The closest archaeological site with sulphur isotopic results is the Late Bronze Age necropolis of Neckarsulm (Nehlich and Wahl, 2011). The humans from Neckarsulm averaged at 2.2 ± 1.1‰, no immigrants or individuals with non-local sulphur isotopic compositions could be found. For rough estimations of the possible available local sulphur isotopic signature geochemical information might be helpful (Nehlich et al., submitted). Sulphur isotope ratios of the south-eastern Black Forest range from -3.4‰ to +9.8‰ (Gehlen et al., 1962). Evaporites from the Northern Alps range in their sulphur isotope values from 11.3‰ to 32.0‰ (Niedermayr et al., 1989). These geochemical signatures are not particularly helpful in this case because they are too far away from the cemetery site. Nevertheless, the results of the archaeological tissues fall within the range of the modern, local, geochemical data and suggest a probable local origin from the area around the Hohentwiel and the western shores of Lake Constance.

6.6. Conclusion

Following these various lines of evidence, the isotope evidence has shown that the sampled individuals from Singen can be considered to be a local population. Even the single male buried with an Atlantic dagger in his grave (grave 67) had local $^{87}Sr/^{86}Sr$ values of 0.70834 in both his enamel and dentine, implying that area of childhood and burial are likely the same. We also found no proof for exogamy, at least for the five sampled female individuals in this study. But if this group was largely local, how did they acquire foreign metal objects? We cannot rule out that exchange networks did require mobility by the Singen people. However, long distant traveling did not occur during childhood, and did not include long-term stays in coastal areas with significant inputs of marine diets. Were foreign metal objects traded into the Hegau by other related populations? If so, this likely required participation in exchanging networks which have been described for the Later Bronze Age in Europe (Wells, 2008). One could argue that if the Singen people can be considered as local elite, it is likely that goods were imported to Singen and exchanged for Singen copper. Evidence from copper mining sites in the Balkans indicates that there was a strong preference for exotic metal even close to the own mines (Chapman, 2008). However, the hypothesis considering the Singen community as some kind of social elite due to its control over the copper ores in the western Alps has been challenged. Kienlin and Stöllner (2009) argue that according to the archaeological and ethnological record, there is no need for social stratification in the development of mining and metallurgy. Additionally, the cemetery of Singen itself does not show strong indications for social ranking. Hence, we would rather expect to deal with a small-scale community. Also, we see no variation in $\delta^{34}S$ that could indicate freshwater fish consumption (Nehlich et al., 2010), known to indicate social stratification in other historic periods (Richards et al., 1998), although Lake Constance would have been suitable for local fishing.

By applying complementary isotope systems we found evidence that the Singen people we studied were all of local origin, and there was no evidence for migrants from the Atlantic regions of France or Great Britain. However, we cannot exclude the possibility that the Singen people were connected with the region between Lake Constance and Lake Zurich, as the region has very similar strontium and oxygen isotope values. The closest regional copper ores are located approximately 80km south-west from this region in the mountainous area of Grisony (*Graubünden*) and the Montafon valley, which could have been utilized for copper mining industries (Krause, 2009). Also, a connection to the Carpathian Basin cannot be ruled out due to the lack of isotopic background information from this region. Finally, the main limitation of this study derives from the fact that only 25 out of 96 graves were sampled for mobility patterns. We cannot completely exclude the possibility that some individuals, e.g. the three non-sampled males with 'Atlantic' daggers, were of foreign provenance. Due to the insufficient skeletal preservation, this question remains unresolved.

6.7. Acknowledgements

We would like to thank our project partners Julia Koch and Sabine Rieckhoff from the chair of Prehistory, Leipzig University, who made helpful comments on an earlier draft of the manuscript. We also thank the two anonymous reviewers for their valuable comments. We thank Jürgen Hald for support during sampling in the Hegau Museum, Singen and Dirk Krause from the State Office for Heritage Management and Archaeology, Baden-Württemberg, for sampling permission. Stephan M. Weise and Kay Knöller of the Helmholtz Centre for Environmental Research, Halle, are acknowledged for their support with the oxygen isotope measurements. And finally, we especially appreciated the assistance by Sandro Corrieri during environmental sampling. This research was funded within the project 'Life history reconstruction of mobile individuals in sedentary societies' by the Federal Ministry for Education and Science, Germany (*Förderkennzeichen* 01UA0811B), directed by Sabine Rieckhoff, and by the Max Planck Society.

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

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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).

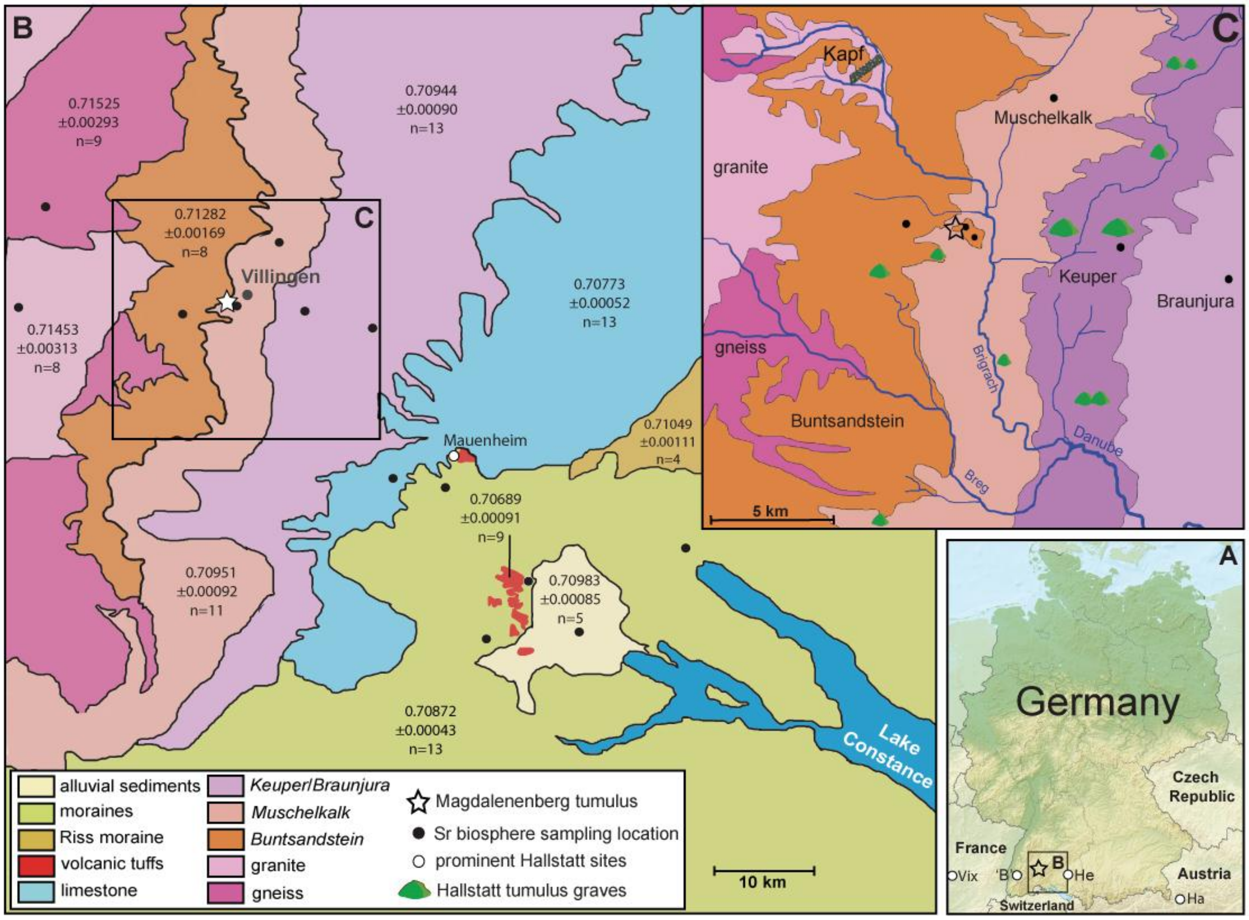

Figure 7.1: **A** map of Germany and bordering countries ('B' = 'Bürgle', He = Heuneburg, Ha = Hallstatt) **B** simplified geological map of the study region between Lake Constance (SW) and the Black Forest (NE), and sampling sites (black dots) and mean values for bioavailable ^{87}Sr/^{86}Sr are mapped (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.

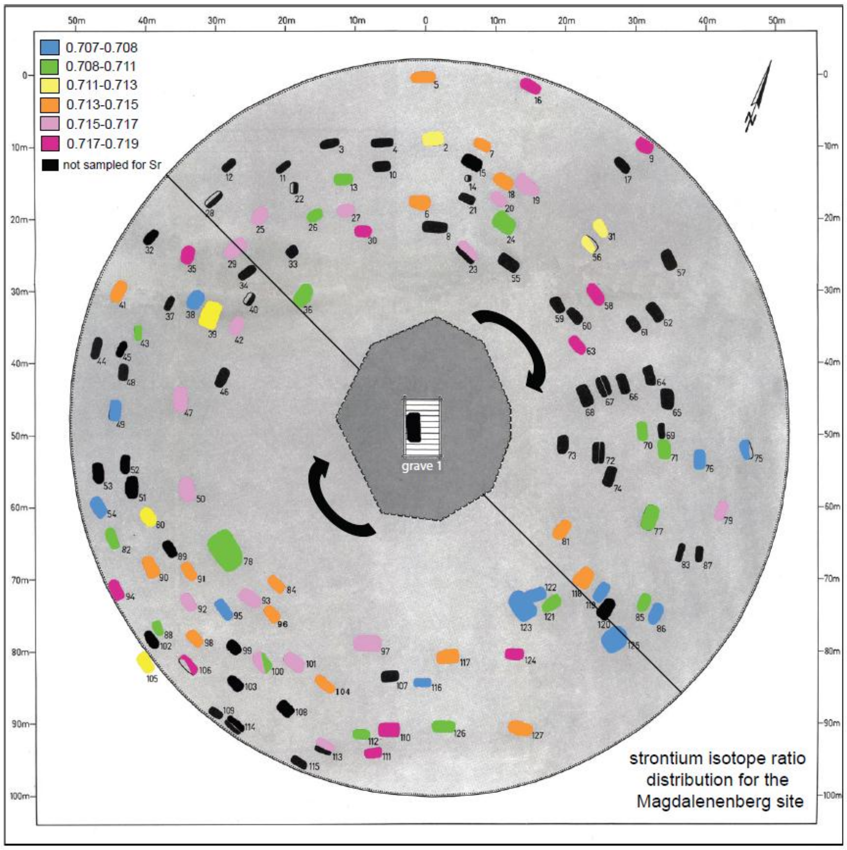

Figure 7.2: The Magdalenenberg tumulus with individual grave numbers (modified after Spindler 2004) and the strontium isotope range highlighted for each sampled grave. The arrows and black line within the cemetery specify the two distinct hemispheres (clockwise and counter-clockwise) of burial orientation 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 δ^{18}O values were corrected to NBS 120c by +0.5‰. $\delta^{18}O_{dw}$ values were calculated from enamel δ^{18}O values after Levinson et al. (1987), corrected by 1.4‰.

grave	bone	age	sex	δ^{13}C‰	δ^{15}N‰	%C	%N	C:N	%coll	δ^{34}S‰	%S	C:S	N:S	tooth	enamel ^{87}Sr/^{86}Sr	Sr (ppm)	δ^{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	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	~~-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).

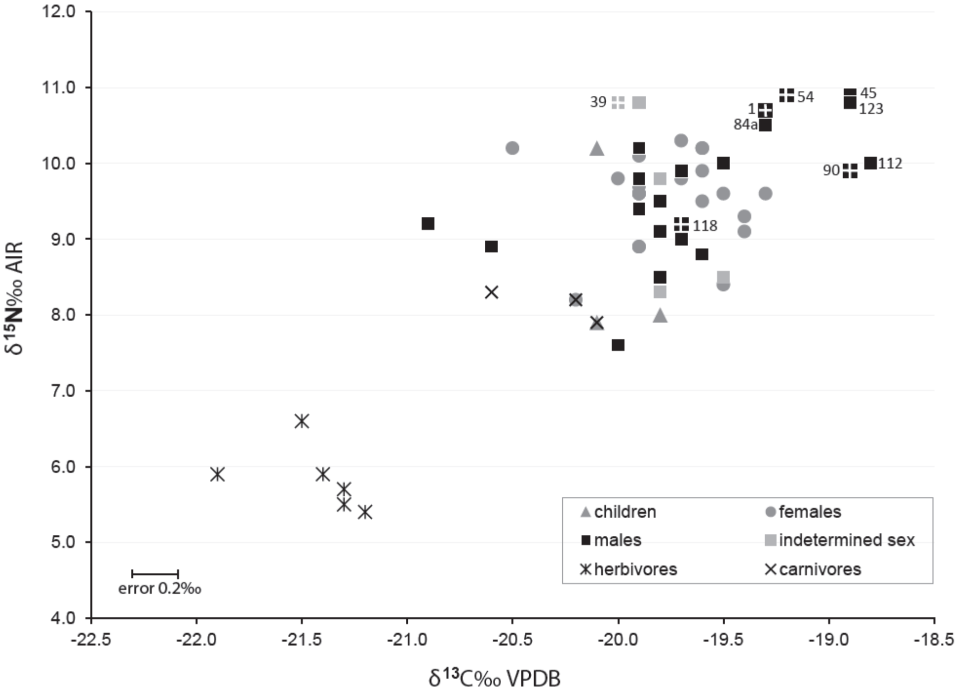

Figure 7.3: Carbon and nitrogen stable isotopes for the fauna and humans from the Magdalenenberg site. The 'prince' burial and 'warriors' buried with daggers are marked with a white cross. The analytical error in δ^{13}C is shown; the error in δ^{15}N is smaller than the symbols.

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.

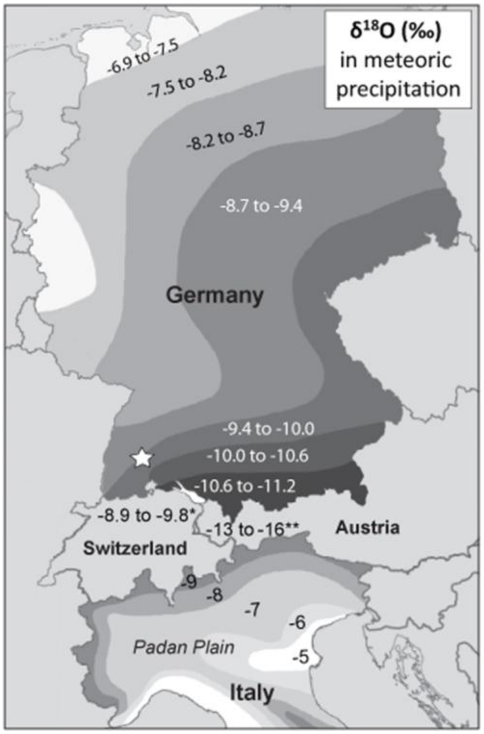

Figure 7.4: Oxygen isotope precipitation map for Germany and Italy (adapted after Tütken et al. 2004 and Longinelli and Selmo 2003) with additional δ^{18}O data from *faunal remains and **alpine spring water (after Tütken et al. 2008; Müller et al 2003). The site of Magdalenenberg is marked with a star.

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 δ^{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 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 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‰.

Additionally, early forming teeth can potentially be affected by breastfeeding signals. Thus, conclusions drawn solely on behalf of δ^{18}O evidence should be considered with caution. Here, we only consider the few outliers which have δ^{18}O values that likely indicate a non-local 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 coastline. The average $\delta^{18}O_{dw}$ value calculated from the Iron Age teeth is slightly more negative than the δ^{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 δ^{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 δ^{34}S signature incorporated in early childhood may be completely replaced by the local δ^{34}S signal in adulthood. Moreover, very similar δ^{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 δ^{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 δ^{18}O values lower than the mean δ^{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 δ^{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 δ^{18}O measurements, it is possible that these individuals with alpine δ^{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.

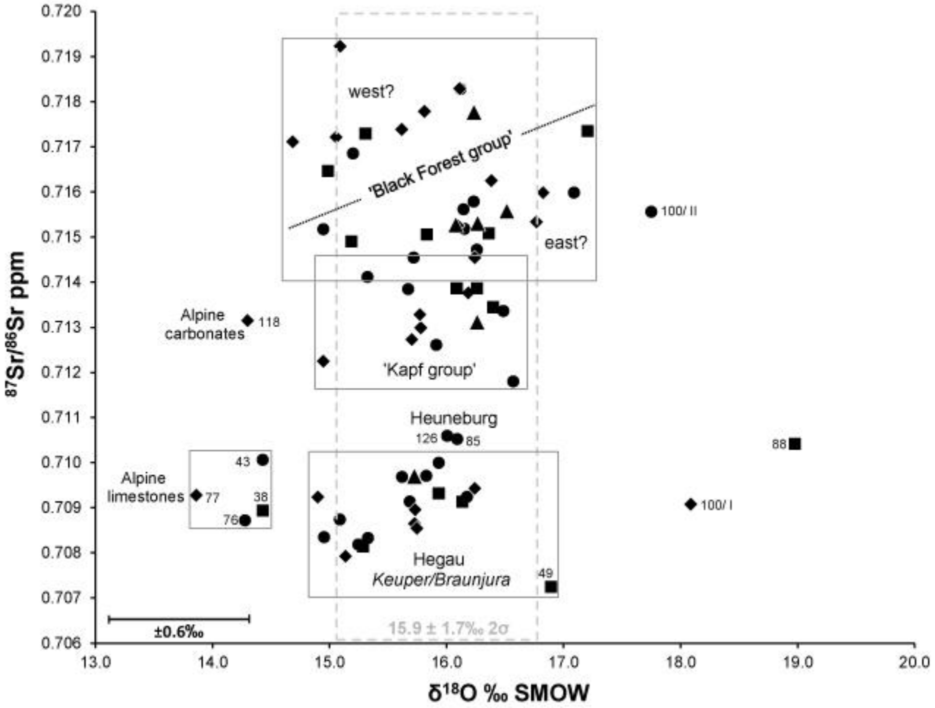

Figure 7.5: Plot of the strontium and oxygen isotope ratios measured in human enamel from the Magdalenenberg site. The analytical error in δ^{18}O is shown; the error in ^{87}Sr/^{86}Sr is smaller than the symbols (squares = males, circles = females, triangles = infants, diamonds = undetermined). The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

Another adult individual (grave 88) has a high δ^{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 δ^{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 δ^{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 δ^{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 δ^{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 δ^{18}O values. But even taking this into account, their δ^{18}O values (17.7‰ and 18.1‰) are elevated compared to the human mean value from the site and resemble δ^{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 δ^{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 δ^{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.

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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

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9. Conclusion

9.1. Filling research gaps in prehistoric Germany

The general goal of this thesis was to fill the gaps in isotope research within Germany. This has been accomplished by the following: first, the human and animal samples from the LBK sites of Derenburg, Halberstadt and Karsdorf are the most substantial and detailed dataset of carbon and nitrogen isotopes available for prehistoric Germany and include unique information on LBK subsistence such as human diet and animal husbandry strategies. It therefore provides a relevant reference for future dietary studies on LBK people and later agricultural societies in Central Europe. Additionally, assumptions from palaeogenetic studies of lactose intolerance could be directly tested from the stable isotope analysis of human remains and may encourage future combined research between palaeogenetic and palaeodietary studies. Second, the strontium and oxygen dataset obtained from the Singen population is the first for Bronze Age Germany and the Bronze Age period in continental Europe. This data will be a useful reference in discussing Bronze Age mobility and socioeconomic networks, especially since current isotopic evidence disagrees to previous assumptions of a semi-migratory nature of this population. Further, the data strongly contradicts the findings of freshwater food consumption obtained by carbon, nitrogen and sulphur isotopes at a Late Bronze Age site in Germany (Nehlich and Wahl 2011), providing a new scope of research for future studies on aquatic resource utilization in the Bronze Age. Third, the site of Magdalenenberg yielded detailed isotopic information on migratory backgrounds of the elite individuals within this cemetery. Groups of individuals could be assigned to certain provenance regions as a result of the various lines of evidence provided by the different isotope analyses. Hence, issues of individual origin could be addressed. Also, the sphere of influence of the local political centre, represented by the central princely burial, was outlined. In this respect the findings of this isotope study are unique for Germany and Central Europe. Furthermore, the dietary data obtained from the Magdalenenberg community is the only other reference dataset for the western Hallstatt culture, and greatly adds to the first isotope study focussed on diet in the eastern Hallstatt culture, which was published more than twenty years ago. Fourth, the strontium biosphere data collected for the purpose of this thesis provides a foundation for future strontium isotope studies in the region, including all major geological formations in south-western Germany. This approach could demonstrate an alternative to the sampling of faunal remains, which were not available in sufficient numbers at the sites of Singen and Magdalenenberg to determine the locally bioavailable strontium isotope signatures. As this may be the case at other archaeological sites as well, the results from this thesis encourage similar sampling strategies, especially because the use of modern reference material provided an even higher strontium isotope resolution and precision than the analysis of prehistoric faunal material used in other studies (Bentley and Knipper 2005).

9.2. Early Neolithic subsistence

Apart from these contributions to isotope studies in Germany, direct evidence of prehistoric life history could be achieved. Dietary reconstruction using stable isotopes gave insight on different aspects of Neolithic subsistence and animal husbandry in Germany. The Neolithic humans practiced an omnivorous diet consisting of domestic plant crops in addition to a significant amount of animal meat from livestock. The C_4-plant millet was not an important staple food of these early farmers, although there is evidence for the presence of millet at LBK sites. Moreover, the consumption of unfermented dairy products is unlikely for the site of Derenburg due to direct palaeogenetic evidence of lactose intolerance previously identified in three burials (Burger *et al.* 2007). The overall lower quantities of animal protein consumed at this site may support this interpretation. Apart from this the site of Derenburg is characterized by a different burial custom (circular cemetery instead of interments in house pits), which many be an expression of cultural difference to the populations of the nearby site of Halberstadt and the more distant site of Karsdorf. It seems plausible that the contemporary populations from the sites of Halberstadt and Karsdorf were lactose intolerant as well. This hypothesis certainly requires further genetic investigation. With few exceptions, isotopic variation was quite similar within the LBK communities and no significant differences in the access to animal protein could be found between the sexes. At the site of Halberstadt, one male had higher amounts of animal protein in his diet. Given his remote burial location and his diverging diet this individual could be considered an immigrant to this LBK group. At the site of Karsdorf, one female had a dietary signal consistent with local herbivores indicating this female had a primarily vegan diet without regular animal protein. According to the data obtained from infant remains LBK children were solely fed with mother’s milk until of one or two years of age. By three years of age, the children were fully weaned and ate diets similar to adults. Isotopic signatures obtained from the large faunal dataset at the site of Karsdorf indicate the application of different livestock management strategies. Sheep and goats, assuming that both species were actually present in the faunal assemblages, fed on similar pastures even though they habitually have different feeding demands. According to isotope data, pigs were fed a more omnivorous diet from locations ranging from open landscapes to forested areas. The comparison of aurochs and domestic cattle indicates that the two species fed in distinct habitats. While the pastures of wild cattle may have overlapped with those of domestic sheep and goats, domestic cattle were kept on nitrogen enriched pastures. This enrichment could either be the result of an intensive stocking rate and pasture utilization resulting in the manuring of fodder plants, or conversely, could indicate that cattle were kept in the highly productive flood plains of the Unstrut River. If this proposed separation of wild and domestic cattle is correct, this could also imply that Neolithic farmers intentionally tried to avoid the introgression of aurochs in their domestic cattle populations.

9.3. Early Bronze Age and Early Iron Age mobility and provenance

The multiple isotope analysis on the Early Bronze Age necropolis of Singen revealed rather unexpected results. Although some grave goods can be connected to distant regions of Europe, this population can be considered to be of local origin and residence. As no complete contemporary settlement has yet been found, it remains unclear whether the main population lived locally or brought their dead to the necropolis at the foot of the Hohentwiel volcano. In this thesis the location of the Singen settlement could be quite confidently assigned to the proximity of the cemetery or at least to the Hegau region as no non-local isotope values were found and the sampled dentine and enamel pairs matched in their strontium signatures. By analysing different isotope systems, various mobility or migration ‘scenarios’ could be excluded for those individuals with good skeletal preservation. Travelling over large distances, e.g. from the Atlantic regions of France or Britain, did not occur during childhood. There is no evidence for long-term stays in coastal areas in adulthood or for exogamy. To explain the exotic artefacts at the necropolis of Singen the participation of this group in supra-regional exchange networks should be reconsidered. It seems possible that the Singen group controlled the regional copper mines and traded copper against imported exotic goods. The closest ores which could have been utilized for copper mining are located approximately 80km south-west from this region in the mountainous area of Grisony and the Montafon Valley. We cannot exclude the possibility that the Singen people were mobile in the region between Lake Constance and these mines as this would not necessarily be visible in the isotopic signatures of teeth and bones. The results of this isotope study may encourage archaeologists to develop novel concepts for the ascendancy of local copper mining industries and for the distribution and transfer of metals throughout Europe in the Early Bronze Age.

We also reconstructed mobility and provenance in the elite burial population from the site of Magdalenenberg and found very heterogeneous isotopic patterns indicating multiple regions of origin. While previous isotope studies on Iron Age populations in Central Europe and Britain focused on dietary behaviour, this is the first comprehensive study on the mobility of Iron Age humans using multiple isotope analysis. The dietary reconstruction had two major findings that were quite similar to those reported for other Iron Age sites in Central Europe. First, there were no gender related restrictions in the access to animal protein. Second, a small group of males, including the prince and two ‘warrior’ burials, were distinct in their dietary patterns, either due to different regional dietary habits or social status. Specifically, their diets were characterised by larger amounts of animal protein and small inputs of millet.

The isotopic information on Iron Age provenance and mobility presented in this work is unique and strongly supports the general assumption of a highly mobile Iron Age society. We identified three large clusters of human provenance in the wider region, as well as individuals that emigrated from distant locations. Only a fraction of the burial population could be inferred to be of local origin. These individuals likely originated from the settlement within the nearby Kapf hillfort and the surrounding territory, which is characterised by scattered Iron Age burial mounds. The Kapf had been described as a rather humble settlement according to its poor artefact assemblage. However, according to isotopic evidence it is likely that a part of the Magdalenenberg elite lived at this site. It is suggested that the archaeological interpretation of the Kapf hillfort should be reconsidered. Another major portion of the burial community can confidently be assigned to the Black Forest and probably to different areas within this mountainous region. This finding is quite unexpected as no Iron Age sites are known from the Black Forest itself with the exception of the large burial mound ‘Bürgle’ located in the western foothills close to the River Rhine (Pare 1992). From the isotopic evidence we have possibly found evidence for a direct connection between the upper Rhine Valley and the source of the Danube through the Black Forest Mountains. Another larger cluster of individuals can be assigned to the region between the site of Magdalenenberg and Lake Constance, although it has to be noted that isotope signatures within this region are relatively uniform over larger distances where more precise attributions are impossible. Some individuals from this cluster may be related to the tumulus graves found at nearby Mauenheim, which presumably represent members of a small settlement. Apart from these larger provenance regions, the combination of isotopic information allowed the assignment of several individuals to specific geographical areas, which are also evident in the material culture represented at the site of Magdalenenberg. Two females likely originated from the prominent chiefly site of Heuneburg located at the Danube as their strontium data is identical to what is reported from this site. Additionally, a group of four individuals may have originated from the cultural sphere of the site of Hallstatt in Austria as their oxygen and strontium isotope values suggest they were raised in a region of alpine limestone. A similar alpine oxygen pattern was found in a single male, which may have derived from the carbonate highlands according to his strontium isotope values. Three more individuals likely emigrated from a warmer climate, likely from southern Europe. Two of them were buried in the same grave; their isotope values suggest they may have spent their childhood in northern Italy, an interpretation supported by the inclusion of a north Italian style pendant in this grave. Hence, this multi-isotope study supports assumptions made according to archaeological findings in some cases. In others, isotopic evidence contradicts the interpretations of grave inventories and the claimed heritage of their owners.

Comparing the Bronze Age to the Iron Age, a significant shift in human mobility patterns can be observed. While the Bronze Age population from the site of Singen was of local origin and residence, the elite burial population at the Magdalenenberg tumulus had various migratory backgrounds and likely originated from the large area between the Black Forest and the northern Alps and probably even beyond. According to the data presented in this dissertation, the transfer of prestige goods like metal over long distances in ’barbarian’ Bronze Age Europe did not necessarily feature individual migration. Thus, other concepts explaining metal ore distribution across Europe need to be considered. For the Iron Age the contrary seems to be the case. Here the biochemical data strongly support a relationship between the presence of foreign raw materials and object styles and the migratory background of human individuals. However, exotic materials are not necessarily deposited in the migrant's graves themselves, but their inclusion in ‘local’ individuals’ graves may have been a result of exchange or the inheritance of the object by other kin. Finally, direct evidence in this work strongly confirms Wells’ general statement that Iron Age “individuals and groups moved regularly through the landscape, for purpose of trading, raiding, migrating, visiting relatives, on pilgrimage, and for many other reasons” (Wells 2002: 341). There are multiple possible reasons why people moved to the region of the Magdalenenberg, for example marriage or the maintenance of trading networks. However we cannot exclude that people were brought to the site from a larger catchment area merely for burial and to express social status and affiliation with the Magdalenenberg ‘prince’. Due to methodological limitations in current archaeological science this last question will remain unanswered, but may give food for thought for archaeologist focussing on early metallurgical societies in Europe.

10. Acknowledgements

First of all, I would like to thank the people who gave me the opportunity to start my PhD at the MPI for Evolutionary Anthropology. Since the first time I heard about the MPI-EVA and visited the Köhler Primate Research Center in the Leipzig Zoo as an undergraduate student of anthropology in 2002, I hoped that one day I could work at this fantastic institution. Mike Richards invited me to join his research group and offered me a PhD project that perfectly matched my university education background and interest. He gave me the opportunity to learn more about isotopes and archaeological science in one of the best isotope laboratories in Europe. This project was initiated and developed by Julia Koch and supervised and coordinated by Sabine Rieckhoff from the Department of Pre- and Protohistory at Leipzig University. I give sincerely thanks for their efforts in making this project fruitful. The German Federal Ministry for Education and Science is acknowledged for funding this PhD thesis from August 2008 to July 2011. I thank Jean-Jaques Hublin for welcoming me in his department and for supporting me in finishing my PhD thesis.

During my PhD studies at the department of Human Evolution, my supervisor Mike Richards supported my ideas and refocused my thoughts when I got discouraged. I am grateful to Mike for the chance to work with, and learn from the best researchers in this field. Among these great people, I would like to thank Olaf Nehlich, for encouraging me to apply for a position at the MPI-EVA in the first place, helping me to get started in the laboratory and introducing me to my new colleagues. Kate Britton was not only a good friend with an inspiring English accent and attitude, but also an experienced colleague that always had good comments on laboratory issues and scientific writing. I thank her for her patience in reading my papers and for her helpful suggestions as well as for many lovely evenings. Moreover, I thank Vaughan Grimes for patiently introducing me to the strontium extraction procedure in the ultraclean laboratory although he was packing up his home to move to Newfoundland. I also thank Ben Fuller, Maura Pellegrini, Marcello Mannino and Colin Smith for their encouraging advice, and Annabell Reiner, Sven Steinbrenner, Steff Bösel and Steffi Albert for help in the lab. I thank Silke Streiber, Conny Schicke, and most of all Diana Carstens for their kindness and administrative support. Furthermore, I thank Collin Moore and Rebecca Kinaston for proof reading parts of this thesis.

The Department of Human Evolution at the MPI-EVA has been an inspiring place to work, not only because of the different research areas and nationalities, but mainly because of the people working here. Especially, I thank Nicolas for several years of controversial, absurd and mostly boozy conversations in this ivory tower of knowledge. Thanks for being a true buddy to me and Sandro. I thank my fellow PhDs Tamara, Domingo, Collin and Andre for many occasions when we had a good time. And I thank Sarah for being a pleasant and quiet desk neighbor over the years.

At this point it is also time to thank my family for their support. My parents Michael and Konstanze have always believed in me, although I sometimes got lost finding out what I want to do and what profession I want to choose. I don't really know how they managed that, but I am very grateful to them for not letting me down, and encouraging me to go my own way. I am glad to see their happiness and pride about how things worked out and yet I know I should call more often…I dedicate this thesis to my parents, as it would not have happened without their support.

I also dedicate this work to my *Omutti* (grandmother) Annegret, who was not able to experience me finishing my masters in Mainz and moving to Leipzig for my PhD. She would have been amazed by the fact that I moved back to our family's roots and live in a city she has visited many times as a young woman, going to tea dance or the opera. I would have liked to tell her how much I feel at home here and how well I get along with the people from Saxony with their weird accents. I guess she would have smiled about my emotionalism.

And finally, I thank Sandro for everything. After seeing my unique chance to start a PhD at the MPI, he was willing to leave behind his unfinished university studies, job, friends and family, to start something new together. Doing that was anything but granted and I deeply acknowledge the personal sacrifices he made for our relationship. I consider myself very lucky; being aware that's more an exception than the rule. Further, I thank Sandro for taking care of maintaining friendships with old friends and socializing new contacts to so many fabulous and interesting people in Leipzig. He ensured me a healthy social life during my PhD work and I am very grateful for that. Last, I thank him for the many proof readings and corrections of papers, presentations and whatnot in both English and German. I hope one day I can recompense all the time and nerves he spent.

11. Samevatting

Het prehistorisch menselijk dieet kan gereconstrueerd worden door stabiele isotopen van koolstof (C), stikstof (N) en zwavel (S) in bot te analyseren, terwijl vroegere mobiliteit en herkomst bestudeerd kunnen worden met behulp van isotopen van strontium (Sr) en zuurstof (O) in tandglazuur en van zwavel in bot. Hoewel er dertig jaren verstreken zijn sinds de eerste toepassing van de stabiele isotopen methode op Europees skeletmateriaal zijn er binnen de Duitse archeologie grote lacunes gebleven in biochemisch onderzoek. Dit proefschrift poogt deze lacunes aan te vullen door nieuw bewijs aan te dragen van diverse isotopen analyses in verschillende overgangsperioden in de Duitse prehistorie, zoals de vroegste neolithische boeren van de Lineaire Bandkeramiek cultuur, de vroege-bronstijd necropool vindplaats Singen, en de elite grafheuvel bevolking uit de vroege-ijzertijd vindplaats Magdalenenberg. Om de lokale eigenschappen van Sr isotopen te bepalen in zuidwest Duitsland werden monsters (n=93) uit de omgeving verzameld and geanalyseerd van de verschillende geologische formaties tussen het Zwarte Woud en het Bodenmeer. Dit werk heeft ertoe geleid dat deze gegevens nu beschikbaar zijn voor toekomstig onderzoek.

Een aanzienlijke dataset van C en N isotopen werd verkregen uit de menselijke bewoners van de Lineaire Bandkeramiek vindplaatsen Derenburg, Halberstadt en Karsdorf (n=97) in Midden Duitsland. De data leveren informatie op over vroeg-neolithische middelen van bestaan en individueel dieet en kunnen in verband gebracht worden met bewijs uit een eerdere paleogenetische studie van melksuiker intolerantie. Tevens levert de analyse van moderne fauna (n=45) nieuw bewijs voor neolithische veeteelt strategieën. De reconstructie van vroegere mobilitieit met behulp van Sr, O en S isotopen leverde informatie op over de menselijke herkomst in de vroege-bronstijd necropool vindplaats Singen. Hoewel de bevolking als mobiel beschouwd werd op grond van exotische grafgiften die in de vindplaats aangetroffen waren, duidt biochemisch bewijs erop dat alle bemonsterde individuen afkomstig waren uit en lokaal leefden in het gebied van het Bodenmeer. Een duidelijk afwijkend patroon werd gevonden in de vroege-ijzertijd monumentale grafheuvel vindplaats Magdalenenberg in het Zwarte Woud. De resultaten van Sr, O en S analyses op het skeletmateriaal van deze elite grafheuvel bewoners uit de Halstatt cultuur duidt op menselijke herkomst uit verschillende gebieden. Slechts een klein deel van de mensen kwam oorspronkelijk uit die streek. Het merendeel van de grafheuvel bevolking is afkomstig uit de hogere gebieden in het Zwarte Woud of van de vlakten dichter bij het Bodenmeer. In een paar gevallen kan de individuele herkomst toegeschreven worden aan specifieke gebieden in de Alpen en Italië door toepassing van een combinatie van isotopen systemen.

12. Summary

Prehistoric human diet can be reconstructed by the analysis of carbon (C), nitrogen (N) and sulphur (S) stable isotopes in bone, whereas ancient mobility and provenance can be studied using the isotopes of strontium (Sr) and oxygen (O) in tooth enamel, and of sulphur in bone. Although thirty years have passed since the first application of the stable isotope method to European skeletal material, gaps in biochemical research have remained within German archaeology. This dissertation seeks to fill these gaps by providing novel evidence from multiple isotope analyses in different transitional periods of German prehistory, including the earliest Neolithic farmers of the *Linearbandkaramik* culture, the Early Bronze Age necropolis site of Singen, and the elite burial population from the Early Iron Age site of Magdalenenberg. To assess the local characteristics of Sr isotopes in south-western Germany, environmental samples (n=93) were collected and analysed from the different geological formations between the Black Forest and Lake Constance. As a result of this work, these reference data are now available for future research.

A substantial dataset of C and N isotopes was obtained from the human populations from the *Linearbandkeramik* sites of Derenburg, Halberstadt and Karsdorf (n=97) in Central Germany. The data provides information on early Neolithic subsistence and individual diet, and can be connected to evidence from a previous palaeogenetic study on lactose intolerance. Furthermore, the analysis of contemporary fauna (n=45) provides novel evidence on Neolithic livestock management strategies. The reconstruction of ancient mobility using the isotopes of Sr, O and S provided information on human provenance at the Early Bronze Age cemetery site of Singen. While the population had been considered mobile because of exotic grave goods found at the site, biochemical evidence suggests all sampled individuals (n=29) originated and lived locally in the region of Lake Constance. A very distinct pattern was found at the Early Iron Age monumental tumulus site of Magdalenenberg in the Black Forest. The results of Sr, O and S analyses in the skeletal remains (n=90) of this elite Hallstatt Culture burial population suggest various regions of human origin. Only a small proportion of the people originated locally. The majority of the burial population is derived from the Black Forest highlands or from the plains towards Lake Constance. In some cases, individual origin could be assigned to specific areas in the Alps and Italy through the application of various isotope systems.

13. Zusammenfassung

Die Rekonstruktion prähistorischer Ernährung mittels Analyse stabiler Isotope von Kohlenstoff (C), Stickstoff (N) und Schwefel (S), sowie die biogeochemische Untersuchung prähistorischer Mobilität und Herkunft mittels Strontium (Sr), Sauerstoff (O) und Schwefel in Skelettmaterial weist in Deutschland einige Forschungslücken auf. Ziel der vorliegenden Dissertation ist diese Forschungslücken zu schließen und neue Erkenntnisse über prähistorische Lebenswelten in Deutschland zu erzielen. Dazu wurden drei ‚innovative' Epochen und Kulturkreise ausgewählt: Die Linearbandkeramiker des Frühneolithikums, die Singener Gruppe der nordalpinen Frühbronzezeit, sowie ein Riesengrabhügelkomplex der frühen Eisenzeit. Für die Untersuchung prähistorischer Mobilität mittels Sr Isotope wurden zudem die Großregion zwischen Bodensee und Schwarzwald mit rezenten Umweltproben (n=93) geochemisch kartiert und die Daten für zukünftige Forschung zur Verfügung gestellt.

Durch die Analyse der stabilen Isotope von C und N wurde die Ernährung der linearbandkeramischen Bevölkerungen aus Derenburg, Halberstadt und Karsdorf (n=97) in Mitteldeutschland untersucht. Für die Interpretation der humanen Isotopenwerte wurde auch die verschiedenen Haustiere (n=45) der drei Fundplätze untersucht und neue Erkenntnisse zur bandkeramischen Viehhaltung gewonnen. Erstmals konnten auch palaeogenetische Erkenntnisse zur Laktose-Unverträglichkeit mit Isotopendaten korreliert werden. Die Untersuchung der Mobilität in der frühbronzezeitlichen Nekropole von Singen (n=29) in Südwestdeutschland mittels Sr, O und S ergab neue Erkenntnisse zur Herkunft der beprobten Individuen. Während exotische Artefakte aus Singen die Partizipation in überregionalen sozioökonomischen Netzwerken und somit eine gewisse Mobilität vermuten ließ, konnte dies biochemisch nicht bestätigt werden. Alle Individuen waren lokaler Herkunft und lebten wahrscheinlich in der Nähe der Nekropole in der Region des Bodensees. Ein gegenteiliger Befund wurde durch die Untersuchung der früheisenzeitlichen Mobilität gewonnen. Die Analyse der Isotope von Sr, O und S am Riesenhügelgrab von Magdalenenberg im Schwarzwald ergabt ein sehr heterogenes Bild für die späthallstattzeitliche Bevölkerung (n=90). Nur ein Teil der Bestatteten stammte aus der Umgebung des Grabhügels, die meisten jedoch aus höheren Lagen des Schwarzwalds und aus dem Hegau. Durch die Kombination der diversen Isotopensysteme konnte erstmals auch die Provenienz einiger Individuen auf Regionen in den Alpen sowie Norditalien eingegrenzt werden.

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- the PhD project was funded by the Federal Ministry for Education and Research, Germany, from August 2008 to July 2011, and by the Max Planck Society since August 2011

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