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SULPHUR ISOTOPE RATIOS OF MULTI-PERIOD ARCHAEOLOGICAL SKELETAL REMAINS FROM CENTRAL GERMANY: A DIETARY AND MOBILITY STUDY

ABSTRACT: Sulphur ($\delta^{34}S$), carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope data are presented for 120 humans and 33 animals from eight sites dating from the Neolithic to the Iron Age (Benzingerode, Westerhausen, Derenburg, Halberstadt, Karsdorf, Kölsa, Grebehna and Großstorkwitz) from central Germany. Sulphur isotope ratios from skeletal collagen reflect the dietary sulphur isotopic composition and therefore differ between environments and regions. Here it is shown that the majority of the analyzed individuals are consistent with a regional local origin; only three may be of non-local origin, namely one each from Benzingerode, Westerhausen and Derenburg. At Großstorkwitz the $\delta^{34}S$ values correlate with the $\delta^{15}N$ values and suggest the input of freshwater proteins. At the other sites the $\delta^{34}S$ values, along with the $\delta^{13}C$ and $\delta^{15}N$ values, reflect a terrestrial based diet. No significant difference in $\delta^{34}S$ values could be observed through time. Sulphur isotope signatures were not significantly different in animals with different $\delta^{15}N$ values and animals are assumed to have lived locally. However, there may not be much regional variability in $\delta^{34}S$ in this area, and the distribution of the archaeological $\delta^{34}S$ values displays little variation across the investigated landscape.

KEY WORDS: Sulphur isotopes – Neolithic – Iron Age – Bell Beaker – Diet – Migration

INTRODUCTION

Sulphur isotope analysis of ancient human bone collagen can reveal ecological, dietary and mobility information and is a recently developing technique in the field of biomolecular archaeology (Nehlich *et al.* 2010, 2011, 2012). The sulphur isotope ratio signatures of bone collagen from animals and humans reflect the averaged ratios of protein in their diets and these, in turn, reflect the environment in which plants at the base of the food

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chain have been grown. This means that the technique can be used, in conjunction with carbon and nitrogen isotope analyses, both to say something about the diet itself and about the source location of the foods consumed. The latter aids the study of mobility in both humans and animals. Here we have looked at material from eight archaeological sites in central Germany, dating from the Neolithic to the Iron Age, and used the results from ancient bone collagen of both animals and humans to discuss the detection of "local" and "non-local" individuals in the regional context, to reconstruct dietary patterns and to explore spatial variation in $\delta^{34}S$ values across this region of central Germany (*Figure 1*). In addition to giving information about the individual sites, this will provide a regional baseline for sulphur isotope ratio data for future comparative studies. It is important to have data from animals which are likely to have been part of the diet, as well as from humans, for this type of study. These usually provide the best way to reconstruct the trophic position of humans in the food web, with herbivorous animals, in particular, providing a direct connection to the isotope ratios found in the plants where they are feeding, so that they can provide an environmental baseline. If it is assumed that the majority of the animals analyzed originate close to their burial context (i.e., they did not move around significantly through trade or animal management practices), then their averaged $\delta^{34}S$ values should reflect the local bioavailable sulphur isotope composition. Hence, humans consuming these animals or their secondary products, together with local plant foods, will also reveal a local sulphur signature. Such information can be useful for detecting immigrants in both archaeological research and in modern forensic cases (Mützel (Rauch) *et al.* 2009, Nehlich *et al.* 2012, Oelze *et al.* 2012a, b).

TECHNICAL BACKGROUND

The ratios of carbon, nitrogen and sulphur stable isotopes ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$) in bone collagen mainly reflect the protein fraction of the consumer's diet. The data can be used specifically to consider the amount of animal protein that has been consumed (trophic level), the level of aquatic resource consumption, and whether C_4 plants (see below) have been included in the food chain. While sulphur isotope ratios do not demonstrate considerable trophic level effects, the position in the food chain is distinguishable using $\delta^{15}N$ and $\delta^{13}C$ values, the former increasing by 3‰ to 5‰ between diet and consumer and the latter by around 1‰ (Bocherens,

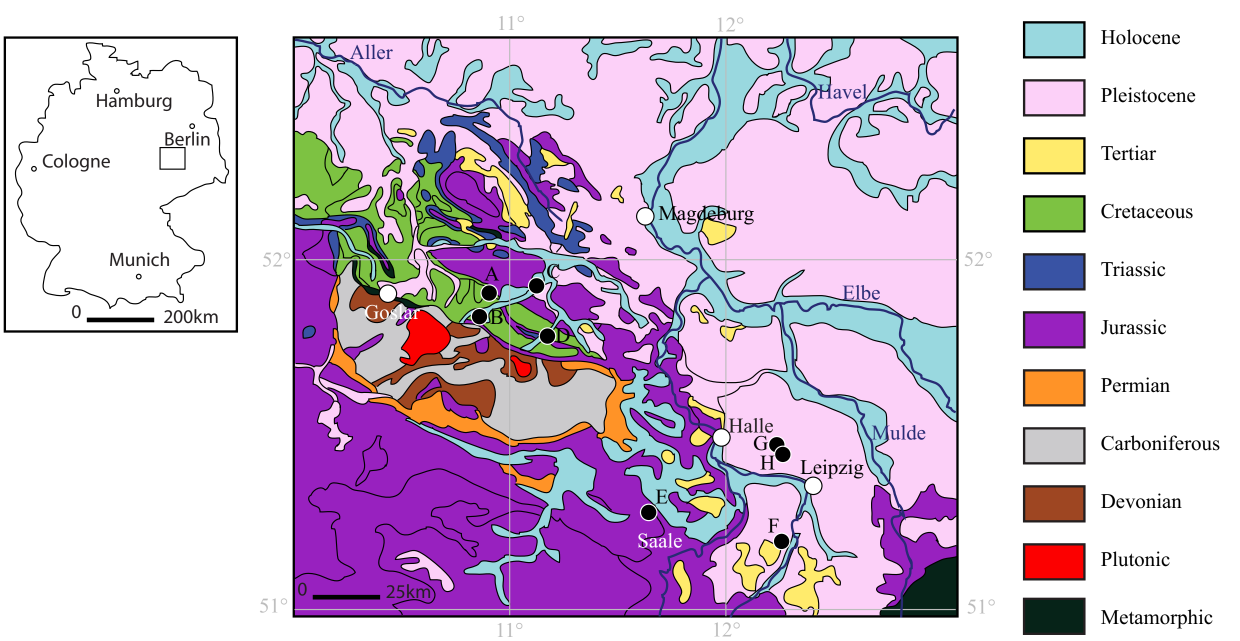


FIGURE 1. Geological setting and archaeological sites (black dots: A, Derenburg; B, Benzingerode; C, Halberstadt; D, Westerhausen; E, Karsdorf; F, Großstorkwitz; G, Kölsa; H, Grebehna) of this study.

Drucker 2003, Hedges *et al.* 2007). High levels of marine resource utilization lead to significant enrichments in both ^{15}N and ^{13}C (higher $\delta^{15}N$ and less negative $\delta^{13}C$ values), whilst freshwater and estuarine foods will also cause enrichment in ^{15}N, but more variable $\delta^{13}C$ values reflecting the individual niches of the plants and animals involved.

Plants take up inorganic sulphur from the soil and groundwater and incorporate this into their tissues (Trust, Fry 1992). The only sulphur-containing amino acid in bone collagen is methionine, an essential amino acid for animals and humans. It must be taken up with the food because it can only be synthesized by plants, not by the body. Bone collagen $\delta^{34}S$ values therefore reflect the averaged bioavailable sulphur isotope composition of the biome from which the animal obtained its food. Because there is little fractionation between diet and consumer in the sulphur system (Tanz, Schmidt 2010), human $\delta^{34}S$ values will reflect the averaged sulphur isotope composition of the dietary methionine from the animal and plant proteins consumed and this will, in turn, reflect the environment from which they came.

$\delta^{34}S$ values will be high where the effects of marine environments are present and may be lower for freshwater resources. Marine resources have high $\delta^{34}S$ values (around 20‰), whilst terrestrial and freshwater resources are more variable (ranging from around –20‰ to +20‰), depending on the local sources of sulphates (Peterson *et al*. 1985). It is believed that a "sea-spray" effect is visible when resources from locations close to the coast are consumed, leading to higher sulphur values affected by oceanic sulphates (Mizutani, Rafter 1969). Bedrock sulphur isotope ratios vary from −40‰ to +40‰, depending on the origin and geochemical history of the formation (Thode 1991). A combination of sulphur and nitrogen isotope data may help to differentiate diets containing freshwater and marine foods, this having been a problem in the past when using only carbon and nitrogen isotope ratios in archaeological studies (Nehlich *et al*. 2010, Richards *et al.* 2001) and since both sulphur and nitrogen systems are affected by soil and groundwater properties, their isotope ratios can be used to match skeletal collagen data to local environments.

C_3 and C_4 plants have different photosynthetic pathways and this dichotomy in carbon utilization results in $\delta^{13}C$ values which are significantly different and which can be traced through to the consumer. While C_4 plants are mainly found in tropical habitats and produce high $\delta^{13}C$ values, C_3 plants are typically depleted in ^{13}C, are usually found in temperate environments and are the main plant resources available in prehistoric Europe. C_4 plants are not found in significant quantities in prehistoric western Europe (see Hunt *et al.* 2008 for discussion), although millet (specifically broomcorn millet, *Panicum miliaceum*) appears to have been present in Bohemia, southern Germany and Austria in the Late Neolithic, and gained importance during the Bronze Age (Dreslerová, Kočár 2013, Kohler-Schneider, Caneppele 2009, Rösch 1998). In Northern Germany millet can only be seen as a weed during the whole Neolithic (Kirleis *et al.* 2012).

Plant isotope values are affected by local environmental conditions, such as climate, salinity, manuring practices and geology (Trust, Fry 1992). Sulphur isotope values tend to display large variations according to ecosystem and geographical location and are affected by local bedrock, atmospheric deposition and soil microbial processes (Krouse *et al.* 1991). These conditions affect the isotope ratios which are seen throughout the food chain, so that the consideration of absolute values for individuals can be problematic because variation is present both through time and space. This is why it is important to have an isotope baseline, here derived from herbivores, for the environment when interpreting human data.

Fewer sulphur isotope ratio data from bone collagen have been published than for carbon and nitrogen, since they have been technically more difficult to obtain and the amount of sulphur present in collagen is very small, requiring larger samples for systematic analysis. Whilst the technical problems are being overcome and this analysis is becoming increasingly important (Giesemann *et al.* 1994), available archaeological data sets are still very limited, particularly when associated with other isotopic data from the same material.

THE REGION

In this study we present here sulphur isotope ratios for eight Middle/Late Neolithic to pre-Roman archaeological sites (Benzingerode, Westerhausen, Derenburg, Halberstadt, Karsdorf, Kölsa, Großstorkwitz, Grebehna) from central Germany. The sites are located in the federal states Saxony-Anhalt and Saxony in close proximity to the Harz Mountains and covering an area of about 120 km by 80 km. The area is covered by Holocene and Pleistocene sediments and all sites are located on alluvial soils. *Figure 1* shows the geochemical features of the research area and *Table 1* lists the location of the archaeological sites and of the published sites from this area with geochemical data used here for comparison.

TABLE 1. Analyzed material of archaeological and geochemical sampling sites from Central Germany.

Location	Material	Reference
Zechstein	Anhydrite	Holser, Kaplan (1966)
Rhinow	Anhydrite	Legler, Schneider (2008)
River Böse Sieben	Freshwater	Strauch *et al*. (2001)
Mine Rammelsberg	Rock	Anger (1966)
Halle (Saale)	Freshwater	Osenbruck *et al*. (2007)
Falkenberg	Rainwater	Knöller *et al*. (2005)
Leipzig	Rainwater	Knöller *et al*. (2005)
Melpitz	Rainwater	Knöller *et al*. (2005)
Plessa	Sediment	Knöller *et al*. (2004)
Plessa	Groundwater	Knöller *et al*. (2004)
Plessa	Freshwater	Knöller *et al*. (2004)
Lake Hufeisensee	Groundwater	Asmussen, Strauch (1998)
Freiberg	Rainwater	Haubrich, Tichomirowa (2002)
Westerhausen	Bone collagen	This study
Benzingerode	Bone collagen	This study
Derenburg	Bone collagen	This study
Halberstadt	Bone collagen	This study
Karsdorf	Bone collagen	This study
Kölsa	Bone collagen	This study
Groβstorkwitz	Bone collagen	This study
Grebehna	Bone collagen	This study

Benzingerode

The burial chamber of Benzingerode contained 46 individuals which were densely packed. The archaeological artefacts date the site to the Middle Neolithic Bernburg Culture (approximately 3000 BC). The chamber is located on the northern slope of the Harz Mountains and the associated settlement is still undiscovered, but is expected to be in the lower region on the loess.

Meyer *et al*. (2008) presented carbon and nitrogen isotope data for this site from six animal samples and 20 humans (10 males, 9 female, 1 unknown). The humans have mean $\delta^{13}C$ and $\delta^{15}N$ values of −19.9 ± 0.2‰ and 9.4 ± 0.4‰ respectively. The four domesticated cattle have an average $\delta^{13}C$ and $\delta^{15}N$ value of −21.1 ± 0.2‰ and 5.8 ± 0.6‰ respectively.

Westerhausen

The multi-period cemetery of Westerhausen contained 25 individuals, nine of which were buried within a mass grave and had evidence of trauma. The use of the cemetery site spans from the Neolithic (n = 1) to the pre-Roman Iron Age (n = 18); several graves contained two or more burials, suggesting members of the same family or group. One Neolithic grave associated with the Globular Amphora Culture contained five domesticated bovids beside the burial in a stone chamber.

Strontium, carbon and nitrogen isotope ratio data from this site were presented by Nehlich *et al.* (2007/2009). Strontium data from tooth enamel provided information about the location of early childhood, and demonstrated that two out of the 25 individuals were of non-local origin and likely moved from the mountains to Westerhausen in a later life stage. Three cattle, a deer and one unidentified animal from undated contexts and two out of the three cattle from the Globular Amphora burial were analyzed. The animal $\delta^{13}C$ and $\delta^{15}N$ mean values are −20.7 ± 0.7‰ and 6.5 ± 0.9‰ respectively. Carbon and nitrogen isotope analyses of the humans showed that all burials had terrestrial diets, without any significant consumption of freshwater or marine proteins. The mean $\delta^{13}C$ and $\delta^{15}N$ values of the human samples are −18.8 ± 0.6‰ and 9.3 ± 0.8‰ respectively. The Neolithic burial of the Globular Amphora Culture seemed to have a slightly different diet than the majority of the analyzed individuals, probably composed of a higher percentage of wild faunal proteins.

Derenburg

The Early Neolithic site of Derenburg is located on the foothills of the Harz Mountains. The settlement is represented by longhouses and is separated from the cemetery containing a total of 44 burials of the *Linearbandkeramik* (LBK) Culture. With few exceptions, most individuals are buried in an east-west orientation and the majority of the graves contained typical LBK pottery and ornaments (Müller 2002).

The carbon and nitrogen isotope data were presented by Oelze *et al*. (2011). The animals from Derenburg (cattles, a pig and a sheep/goat) cluster very tightly in their $\delta^{13}C$ (−20.4 ± 0.5‰) and $\delta^{15}N$ (7.2 ± 0.2‰) values. The mean human $\delta^{13}C$ value is −19.8 ± 0.4‰ and the mean $\delta^{15}N$ value is 8.8 ± 0.5‰ (n = 39), which was interpreted by Oelze *et al*. (2011) as a terrestrial diet, based on proteins from domestic animals and C_3 staple foods. There are no exceptional isotope values reported within this data set from Derenburg.

Halberstadt

In contrast to the settlement of Derenburg, long houses and burials at the contemporary LBK site of Halberstadt are directly associated with each other. Six to eight individuals were buried next to individual longhouses, suggesting that they may represent a nuclear family or members of a single household (Autze 2005).

For isotopic analysis Oelze *et al*. (2011) sampled three cattle, one pig and two unidentified animals. The $\delta^{13}C$ values average −21.0 ± 0.4‰ and the $\delta^{15}N$ values 6.4 ± 0.9‰. The human $\delta^{13}C$ and $\delta^{15}N$ values have means of −19.8 ± 0.3‰ and 8.4 ± 0.5‰ ($n = 36$). There is one male adult outlier with an enriched ^{15}N isotopic signature, which was not buried in close proximity to any of the houses or other burials. It was suggested that this individual might be a foreigner to the population of the settlement.

Karsdorf

The settlement of Karsdorf is located on the river Unstrut approximately 100 km south of Westerhausen. Evidence from the Neolithic buildings suggests three settlement stages during the LBK around 5100 BC (Behnke 2007). Similar to the site of Halberstadt, the majority of the individuals were buried in association with longhouses. Within every house group, individuals with unusual grave goods could be identified who may represent a founding generation.

Carbon and nitrogen isotope data for 32 animals from Karsdorf were presented by Oelze *et al*. (2011). Mean $\delta^{13}C$ and $\delta^{15}N$ values are −21.0 ± 0.8‰ and 7.1 ± 1.0‰. These results reflect the local environmental variability of wild and domestic animals. The human values ($n = 22$) clustered more closely with a mean $\delta^{13}C$ value of −20.0 ± 0.3‰ and a mean $\delta^{15}N$ value of 9.0 ± 0.4‰. Similar to the LBK sites of Derenburg and Halberstadt, these values were interpreted as a terrestrial based diet consisting of domesticated animal protein and purely C_3 plant foods.

Kölsa, Großstorkwitz, Grebehna

No data from these sites has previously been published. With 11 burials the Bell Beaker site of Kölsa, dated to the period 2400 to 2200 BC (95% probability) (see *Appendix 1*), is the largest cemetery of this period in north-western Saxony. Only three of the burials are adults, the rest being infants and children up to the age of eight years (Conrad 2011, Teegen 2011a). The three adults associated with Bell Beaker pottery grave goods and animal remains of pig and sheep/goat have been analyzed and are presented in this paper. Burials 7 and 9 (male and female respectively) were found closely grouped with five infants and children and may represent a nuclear family.

Five individuals from the site of Großstorkwitz were analyzed for this study. They include one burial with Beaker associations and a radiocarbon date similar to those from Kölsa, along with two individuals with earlier dates (2900 to 2600 BC and 2600 to 2400 BC, (95% probability), see *Appendix 1*) (Conrad, Teegen 2010, unpublished report).

One human sample, an adult female with a relatively short stature (approx. 145 cm), was analyzed for this study from the site of Grebehna, which can be assigned to the Bell Beaker Culture according to the archaeological evidence.

Geochemical background

The geochemical baseline for human and animal $\delta^{34}S$ signatures is driven by the soluble available sulphur from underlying bedrocks, soils, atmospheric deposition and groundwater. Publications for the area of interest in central Germany cover geochemical and hydrochemical data from rock crystals, sediments, rainwater, freshwater and groundwater. These sources of information are consulted to reconstruct whether the location of burial is also likely to have been an individual's habitat of origin (see Oelze *et al*. 2012a, b). The published geochemical data referred to in this study are listed in *Table 1*. All $\delta^{34}S$ data reported so far have a mean value of 12.4 ± 10.3‰ and range from −23.4‰ to 54.2‰. However, the most extreme $\delta^{34}S$ values are found in bulk rock or sediment samples or in polluted ground- and freshwater in proximity to mines (Anger 1966, Knöller *et al*. 2004, 2005). Since these extremes are not visible in the overall trend, they do not seem to influence the $\delta^{34}S$ values of humans and animals. Most likely, the average $\delta^{34}S$ value found in human and animal tissues would resemble local waters. Based on the published $\delta^{34}S$ values of modern precipitation, surface water and groundwater, the average bioavailable $\delta^{34}S$ composition would range between 3 and 8‰ (Haubrich, Tichomirowa 2002, Knöller *et al*. 2004, 2005, Osenbruck *et al*. 2007). Published environmental data are used for comparison with the results obtained from archaeological material in the discussion to determine locality and estimate the influence of geochemistry on the local food chain.

METHODS

Collagen extraction was based on the Longin method (Longin 1971), modified by a two-step filtering process (Brown *et al*. 1988). Whole bone samples were demineralized in 0.5M HCl at 4°C. The remaining collagen was denatured in pH3 aqueous solution at 70°C for 48 hours. The solution was filtered using Ezee filters®, followed by centrifugal filtering using Millipore ultrafilters which separated molecules smaller than 30 kDa. The larger, less degraded collagen molecules were then freeze-dried. The resultant collagen product was weighed to tin capsules and the samples combusted to N_2, CO_2, SO and SO_2, and analyzed using either a Thermo Finnigan DELTAplus XL continuous helium flow gas isotope ratio mass spectrometer coupled with a Flash EA elemental analyser (for C and N) or a Thermo Finnigan Delta V Plus coupled to a Eurovector elemental analyser (for S), both at the Department of Human Evolution, Max-Planck Institute for Evolutionary Anthropology, Leipzig. The analytical standard deviation, averaged from laboratory working standards run with the samples (methionine for carbon and nitrogen, casein for sulphur), amounted to ± 0.2‰ for $\delta^{13}C$ and $\delta^{15}N$ and ± 0.4‰ for $\delta^{34}S$. Replicated collagen included in the sulphur runs gives reproducibility better than ± 0.6‰. The values presented are averaged from two replicates, analyzed in separate batches, except for some of the sulphur measurements where sufficient collagen for only one analysis was available.

The quality criteria for collagen $\delta^{13}C$ and $\delta^{15}N$ data are now widely accepted in terms of atomic C:N ratios of 2.9 to 3.6 and appropriate elemental percentages (Ambrose 1990, DeNiro 1985, van Klinken 1999). The corresponding quality indicators for sulphur percentages range from 0.15% to 0.35% and for atomic C:S and N:S ratios for archaeological material from 600 ± 300 and 200 ± 100 respectively (Nehlich, Richards 2009).

RESULTS

The mean values from the carbon, nitrogen and sulphur isotope analyses in human and animal bone collagen are shown in *Table 2* according to site. Detailed information about individual results is provided in *Appendix 2*.

All sulphur isotope results presented meet the collagen quality criteria given by Nehlich, Richards (2009). The sulphur content of the collagen ranges from 0.15% to 0.35%. There is a not significant difference in the $\delta^{34}S$ values between the humans and the animals per site.

The carbon and nitrogen isotope data from the sites Benzingerode (Meyer *et al.* 2008), Westerhausen (Nehlich *et al.* 2007/2009), Derenburg, Halberstadt and

TABLE 2. Average carbon, nitrogen and sulphur isotope values by archaeological site for human and animal samples.

Location	$\delta^{13}C$ [‰]	$\delta^{15}N$ [‰]	$\delta^{34}S$ [‰]
Benzingerode humans (*n* = 12)	−19.9 ± 0.2	9.5 ± 0.4	4.4 ± 2.8
Benzingerode herbivores (*n* = 3)	−21.1 ± 0.2	5.8 ± 0.8	2.5 ± 1.7
Westerhausen humans (*n* = 19)	−18.8 ± 0.6	9.3 ± 0.8	5.0 ± 2.8
Westerhausen herbivores (*n* = 6)	−20.5 ± 0.7	6.5 ± 0.9	5.4 ± 0.9
Derenburg humans (*n* = 31)	−19.8 ± 0.4	8.7 ± 0.5	0.5 ± 1.6
Derenburg animals (*n* = 7)	−20.4 ± 0.6	7.2 ± 0.2	0.3 ± 1.4
(herbivores; *n* = 6)	−20.4 ± 0.6	7.2 ± 0.2	0.5 ± 1.5
Halberstadt humans (*n* = 33)	−19.8 ± 0.4	8.7 ± 1.1	1.8 ± 0.9
Halberstadt herbivores (*n* = 4)	−20.9 ± 0.5	6.2 ± 0.7	0.5 ± 2.9
Karsdorf humans (*n* = 15)	−20.0 ± 0.3	8.8 ± 0.9	3.7 ± 1.6
Karsdorf animals (*n* = 10)	−21.3 ± 0.8	6.8 ± 1.2	5.4 ± 2.1
(herbivores; *n* = 7)	−21.0 ± 0.6	6.6 ± 1.3	5.6 ± 2.4
Kölsa humans (*n* = 3)	−20.2 ± 0.3	10.0 ± 0.4	3.0 ± 2.6
Kölsa pigs (*n* = 2)*	−22.0/−21.3	8.2/5.5	2.3/5.8
Großstorkwitz humans (*n* = 5)	−19.9 ± 0.6	11.2 ± 1.3	1.4 ± 1.9
Großstorkwitz cattle (*n* = 1)	−21.5	6.7	−0.8
Grebehna human (*n* = 1)	−20.4	10.1	2.3

* Kölsa – animals: the large differences could be caused by the fact that at least one individuals is a pig below 12 months of age and probably still a suckling (Teegen, 2011b).

Karsdorf are published elsewhere (Oelze *et al*. 2011). There are data for five humans from Großstorkwitz, three from Kölsa and one from Grebehna. The carbon and nitrogen data conform to the quality indicators after DeNiro (1985) and van Klinken (1999). The mean $\delta^{13}C$ and $\delta^{15}N$ values for these nine individuals are −20.1 ± 0.5‰ and 10.6 ± 1.0‰, respectively. The majority of the variation to be seen in the carbon and nitrogen is to be seen at Großstorkwitz. The means for Großstorkwitz alone (n = 5) are −19.9 ± 0.6‰ and 11.2 ± 1.2‰ for carbon and nitrogen respectively, with the averages for the sites Kölsa and Grebehna (n = 4) being −20.3 ± 0.2‰ and 10.0 ± 0.3‰. Therefore, the $\delta^{15}N$ values from Großstorkwitz are slightly higher than the other sites in this study. However, there are no statistical differences in the animal $\delta^{13}C$ and $\delta^{15}N$ values between sites or their spatial distribution.

DISCUSSION

Dietary reconstruction

The animals from this data set present two distinct patterns in carbon and nitrogen isotope ratios: first, there are animals from a single location which differ in their $\delta^{15}N$ values by more than 1‰, such as seen in Halberstadt, Derenburg and Karsdorf. This fact has been discussed by Oelze *et al*. (2011), and suggests differences in the methods of animal husbandry, such as transhumance or grazing on marsh land. To disentangle the different habitats sulphur isotope data can be helpful. Theoretically, there should be differences in the $\delta^{34}S$ values of animals feeding predominantly on resources obtained from different geological conditions, e.g., from close to the settlements as opposed to in the Harz Mountains (possibly involving transhumance), or from

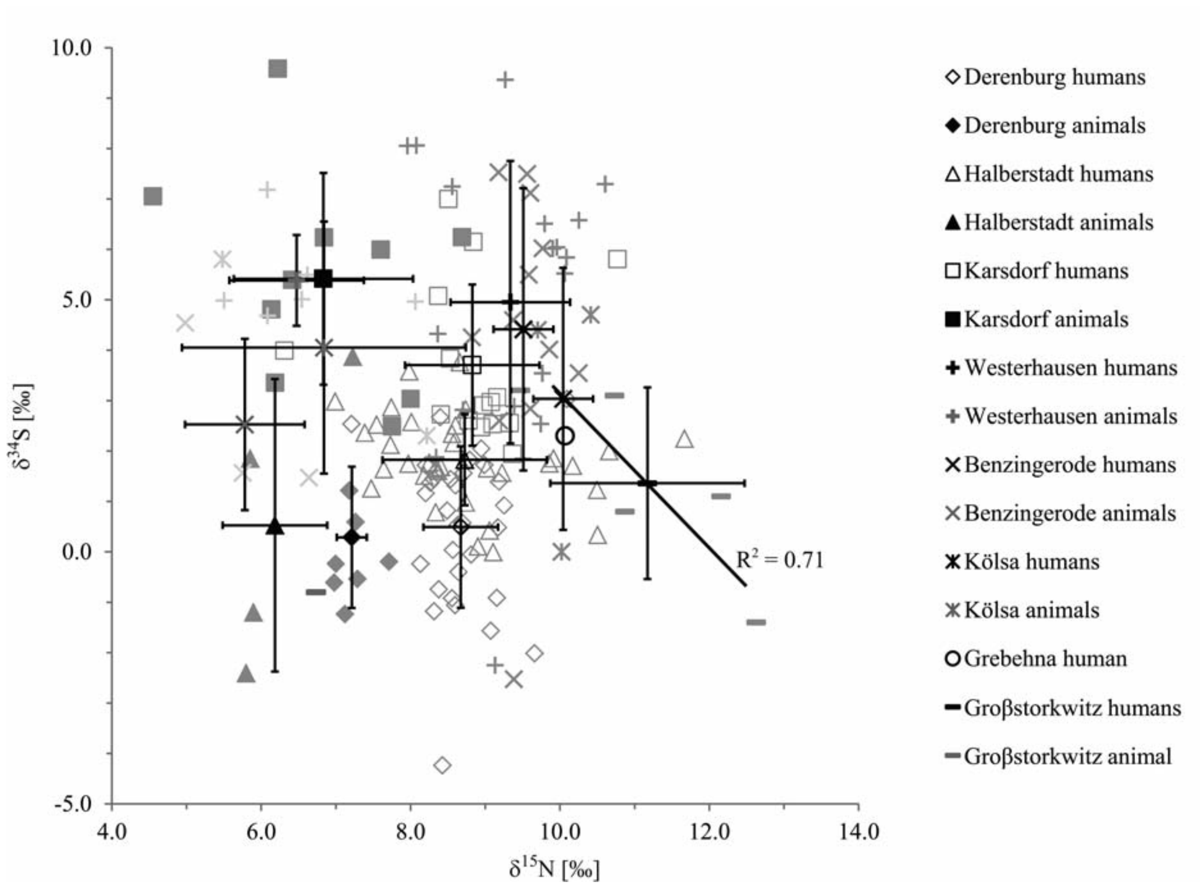


FIGURE 2. Nitrogen and sulphur isotope values of archaeological human and faunal skeletal remains from sites in Central Germany. Nitrogen isotope data for Benzingerode are taken from Meyer *et al*. (2008), for Westerhausen from Nehlich *et al*. (2007/2009), for Derenburg, Halberstadt, and Karsdorf from Oelze *et al*. (2011).

the floodplains of nearby streams (marsh land grazing); see below for a further discussion. The second pattern is a shift in δ^{13}C values at some sites. This shift seems to be correlated with the dates of the specimens. Faunal samples dating to the later period (Iron Age) have ^{13}C enriched values compared to the earlier periods (Neolithic, Bronze Age). A similar and even more pronounced effect can be observed in the human data set discussed below.

The nitrogen and sulphur isotope ratios of the analyzed archaeological samples are presented in *Figure 2*. The data for the humans from Benzingerode, Derenburg, Halberstadt, Karsdorf, Kölsa and Grebehna plot very close to each other. There are two humans from Großstorkwitz which have particularly high δ^{15}N values in the context of this data set. Both have been radiocarbon dated and calibrated to 2573–2475 BC and 2876–2635 BC (95%), see *Appendix 1*, and are not associated with Bell Beaker material. A third ^{15}N enriched human individual comes from Halberstadt and was interpreted as a person with a foraging subsistence strategy (Oelze *et al*. 2011). They are very significantly beyond the 95% range for the rest of the data set, with their nitrogen values being well outside three standard deviations from the average for the other humans. It is possible that these three individuals originated from areas with higher nitrogen "baseline" values, so that the δ^{15}N signal in bone collagen is reflecting the consumption of non-local resources. It is also possible that they consumed significant amounts of freshwater resources, such as fish or aquatic birds, although a more negative δ^{13}C value would usually be associated with this (see the Late Neolithic Bavarian freshwater resources from Bösl *et al*. (2006) or the southern German Neolithic freshwater fish from Dürrwächter *et al*. (2006)). Another possibility for enrichment in ^{15}N is metabolic stress factors such as starvation or disease (Fuller *et al*. 2005, Hatch *et al*. 2006, Katzenberg, Lovell 1999), although these would need to occur at extreme levels over many years to be detectable in bone collagen and, therefore, this is a less parsimonious explanation for these results than a movement between different environments or the consumption of freshwater proteins.

The δ^{34}S values of the humans from Großstorkwitz correlate with the δ^{15}N values (R^2 = 0.71). As shown for other archaeological sites, such a correlation can be a good indicator for freshwater influenced diets (Nehlich *et al*. 2010, 2011), although it could also suggest mobility between two distinct locations (Jay *et al.* 2013). High nitrogen isotope ratios are associated with lower sulphur isotope ratios and *vice versa*. The cattle sample from Großstorkwitz has a δ^{34}S value of −0.8‰, which is at the lower end of the human δ^{34}S range (3.2‰ to −1.4‰). This suggests that the animal was fed on plants growing on floodplains of the close-by river "Weiße Elster" (see also Nehlich *et al*. 2011). Unfortunately there are no further animals preserved to verify other types of husbandry at this site. The high level of animal protein in the diets of Beaker people fits with the importance of meat gifts in Bell Beaker graves (Conrad 2009).

The second pattern observed in the data set is a shift in δ^{13}C values over time (*Figure 3*). The humans from the site of Westerhausen have the highest δ^{13}C value within the data set and the mean δ^{13}C value is enriched by almost 1‰, with some of the δ^{13}C values larger than −19.0‰. This might be a result of the multi-period character of that site. The majority of the burials of that cemetery date to the pre-Roman Iron Age (Nehlich *et al*. 2007/2009). It is possible that this is either a systematic difference due to period and climate, temperature and deforested local habitats, or this is the effect of the subtle influence of the C_4 plant millet in the human and faunal diet, which has been observed at several Central European Iron Age sites (Murray, Schoeninger 1988). There is one sample from Halberstadt having a similar high δ^{13}C value; another sample from Halberstadt and one from Großstorkwitz are on the threshold of −19.0‰. Although the faunal shift is smaller, the fact that the animal data correspond to the humans suggests that the results are not reflecting a difference in human dietary

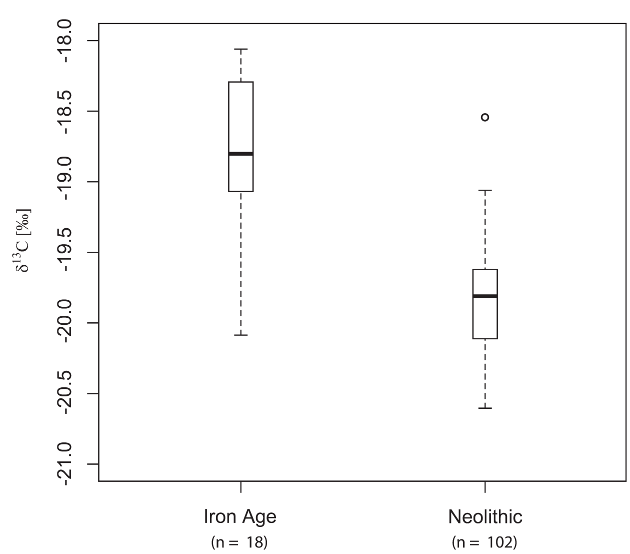


FIGURE 3. Boxplots of carbon isotope values of humans by archaeological period.

constituents between the groups, such as the inclusion of aquatic resources, but are demonstrating a change further down the food chain, either in the types of foods consumed by the animals or related to environmental conditions affecting local plants. There are no differences in the sulphur isotope values of the individuals with high $\delta^{13}C$ values compared to the individuals with depleted $\delta^{13}C$ values. The shift in the $\delta^{13}C$ values seems to be rather a general effect, than a change of locality.

Reconstruction of locality, mobility and migration

Knowledge about the geochemical setting helps to explain the bioavailability of sulphur and the resulting isotopic signatures in animal and human tissues. Several geochemical and hydrochemical data sets have been published for the region of interest. *Figure 4* presents the published results by material type analyzed. The largest range is observed in rock minerals which come from a mining district in the Western Harz Mountain region close to Goslar (see *Figure 1*) (Anger 1966). These results are not very useful for the purpose of identifying the locally bioavailable isotopic signature because the isotope ratio of organic tissues depends on the water soluble isotopic composition which can be utilized by plants at the base of the food chain. The sulphur isotopic signatures of soil, groundwater and precipitation are, therefore, more reliable sources for comparison. However, sediments and groundwater reflect a large variability in this area, since there have been mining activities over the last few centuries which have led to alterations and contamination and which are difficult to distinguish from natural conditions. The most reasonable comparison may be found in precipitation and surface water sulphur isotope data. These data cover a large geographic range in the study region. Additionally, sulphur isotope data obtained for environmental pollution studies can be useful (Knöller *et al*. 2004, Strauch *et al*. 2001). Strauch *et al*. (2001) found a mean $\delta^{34}S$ value of 2.9‰ for the unpolluted part of the River "Böse Sieben". The river is located in close proximity to the archaeological sites of Benzingerode, Westerhausen, Derenburg and Halberstadt and their mean collagen $\delta^{34}S$ values are similar (see *Figure 5*). For Kölsa, Grebehna and Großstorkwitz the closest available hydrochemical $\delta^{34}S$ data are from a nearby former mining district (Asmussen, Strauch 1998, Knöller *et al*. 2004), rainwater (Haubrich, Tichomirowa 2002, Knöller *et al*. 2005) and freshwater (Osenbruck *et al*. 2007). Except the rainwater, the results of these studies are too variable to correspond to any of the archaeological sites. Overall, it does not seem useful to use modern day environmental data, since isotopic signatures of bone collagen are an average of the dietary input over a period of decades (Hedges *et al*. 2007) and rainwater might change its $\delta^{34}S$ value seasonally (Wakshal, Nielsen 1982). In addition, anthropogenic alterations of the landscape and the contamination of isotopic signatures in modern samples can make them useless as a base reference for

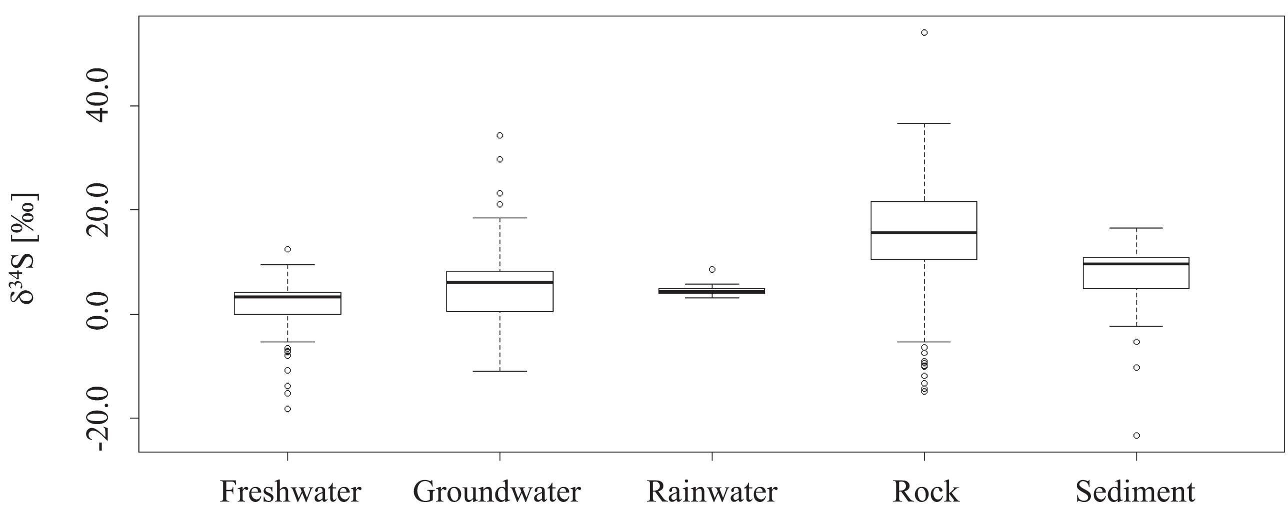
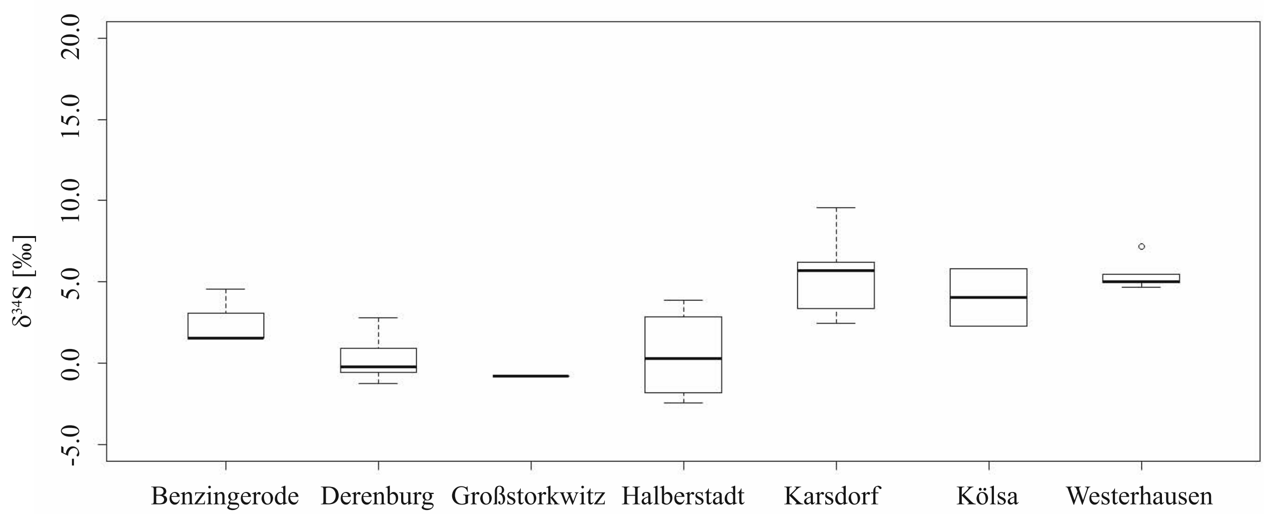


FIGURE 4. Boxplots of published sulphur isotope values from the study area. Data taken from Anger (1966), Holser, Kaplan (1966), Asmussen, Strauch (1998), Strauch *et al*. (2001), Haubrich, Tichomirowa (2002), Knöller *et al*. (2004, 2005), Osenbruck *et al*. (2007), Legler, Schneider (2008).

archaeological isotope data. In order to avoid such biases, isotope data obtained from associated archaeological animals can be referred to as an alternative. However, some difficulties may also arise with contemporaneous animals: firstly, domesticated animals particularly can be traded, or their products can be transported over long distances. This is especially the case in more recent periods (e.g., the Iron Age or the mediaeval period). Thus, the possibility of movement of animals over long distances should not be underestimated. Secondly, humans depend on multiple regional/environmental food sources, such as terrestrial, freshwater and/or marine, or ecological niches (floodplains, marsh land, etc.). Such situations, here probably present at the site of Großstorkwitz, result in individual isotope signatures which can be interpreted as non-local, although the data actually may reflect that these people lived on a multi-resource mixed diet. Keeping these two factors in mind, we can compare the animal and human $\delta^{34}S$ data which we have obtained from several archaeological sites.

At all sites the mean $\delta^{34}S$ values of the animals are very close to the human means (*Figure 5*), suggesting



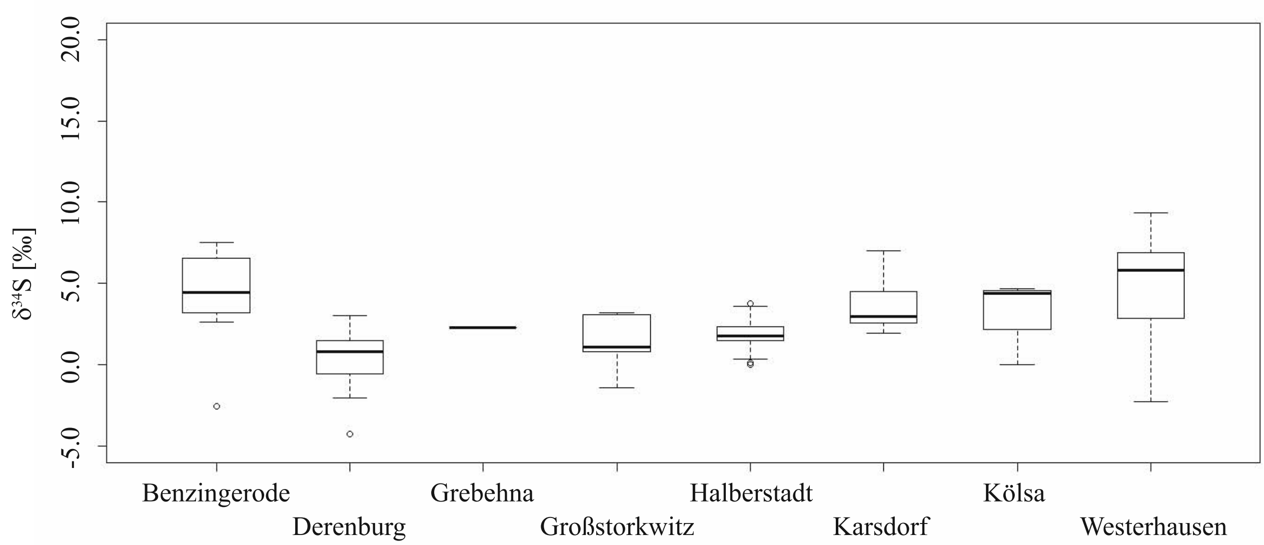


FIGURE 5. Boxplots of collagen sulphur isotope values of animals (upper plot) and humans (lower plot) per site.

that humans and animals lived in similar locations and/or these animals provided the predominant source of food. The sulphur isotope data from the humans from Großstorkwitz need to be evaluated carefully, since there is the possibility of freshwater protein consumption, which would have caused a shift in the $\delta^{34}S$ values of these individuals towards the sulphur isotopic signature of the freshwater reservoir (Nehlich *et al*. 2010, 2011). However, there are some inconsistencies in the data set. The largest ranges in animal $\delta^{34}S$ values occur at the sites of Halberstadt, Karsdorf and Kölsa. The large range at Kölsa is probably related to the small number ($n = 2$) of analyzed specimens and shall not be considered further. For the sites of Halberstadt and Karsdorf, Oelze *et al*. (2011) proposed that the large variation in $\delta^{15}N$ could be explained with transhumance practices or marshland feeding strategies. Both explanations are possible given the observed variability in the $\delta^{34}S$ values. However, in animals feeding on marshland and floodplains a significant correlation in the $\delta^{34}S$ and $\delta^{15}N$ values might be expected (Nehlich *et al*. 2011). This is not the case for any site discussed here, except Großstorkwitz. Overall, the results of the animal $\delta^{34}S$ values represent local animals without any significant outliers. It can be assumed, therefore, that the differences in the $\delta^{15}N$ values seen in the animal bone collagen seem to be a normal variability at these sites. The isotope data do not support the hypothesis of transhumance or marshland grazing when sulphur is taken into account.

The human $\delta^{34}S$ values reveal a slightly different pattern. In addition to the detected outliers in carbon and nitrogen isotope ratios, sulphur provides novel information on these people. Three individuals from the sites of Benzingerode, Westerhausen, and Derenburg have particularly low $\delta^{34}S$ values ($< -2.0‰$). The outliers from Benzingerode and Westerhausen are at the lower end of the range of $\delta^{34}S$ values from Derenburg and may have come from around there. The outlier from Derenburg has the lowest $\delta^{34}S$ value and is of unknown origin. The majority of the 120 analyzed humans have values which are consistent with a local origin or at least regionally sourced diets in the last decades of their life.

CONCLUSION

Archaeological material dating to the Neolithic and later periods was analyzed for sulphur isotope composition. It was considered whether differences in $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values of domesticated animals reflect differences in feeding practices, or if the observed variability is site specific and mainly reflects environmental conditions. Despite the slight animal variability there are only a few mobile animals identified and three possibly non-local humans in the data set. The sampled human population may represent a stable sedentary population with few incomers from outside the region over a long period of time. Either there has been exchange within this region with similar sulphur isotope ratios, or there was only very limited mobility. The comparison of these results with data from further regions will highlight variability in archaeological subsistence strategies across Germany.

The data set presented in this study is the largest regional multi-site data set of archaeological sulphur isotope ratios yet. It reflects a spatial and chronological history of a discrete study area in central Germany. The results from this study are showing the potential of sulphur isotope analysis for the understanding of large scale changes in subsistence strategies and culture. Further it can be used as a mapping tool in archaeological research. Such micro-local studies help to understand variation in isotope composition at larger scales and will support further comparison of modern and archaeological data sets to understand anthropogenic influences on the environment. Additionally, these data will usefully support other biomolecular studies such as mobility reconstruction by strontium isotope analysis or genetic analyses.

ACKNOWLEDGEMENTS

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APPENDIX 1. Sample details from sites in northwest Saxony, Germany.

S-EVA	Species	Skeletal element	Sample and context
3977	Human	Mandible	Kölsa, Wiedemar. Grave 7, male, 25–35 years. Arrowhead tip in humerus may be related to cause of death. Associated with undecorated Bell Beaker, pig remains, 5 flint arrowheads, flint dagger, 2 flint blades, whetstone, bone needle, boar teeth, antler spatula. Radiocarbon: Hd-22154, 3848 ± 15 BP; 2319 ± 29 calBC (95%). Excavation KQA-01, Befund 21, Bell Beaker.
3978	Human	Mandible	Kölsa, Wiedemar. Grave 9, female, 48–69 years. Wood remains associated with burial suggest possible coffin. Associated with decorated Bell Beaker and pig remains. Radiocarbon: Hd-22134, 3830 ± 19 BP; 2275 ± 42 calBC (95%). Excavation KQA-01, Befund 25, Bell Beaker.
3979	Human	Flat bone	Kölsa, Wiedemar. Grave 10, possible female, 30–50 years. Associated with undecorated Bell Beaker. Excavation KQA-01, Befund 11, Bell Beaker.
3991	Human	Mandible	Grebehna. Adult female. Excavation ZWC-09, Bell Beaker.
4002	Human	Mandible	Großstorkwitz. Grave 450, under Grave 153/452, which has pottery to be dated. Adult male. Excavation PEG-08, Befund 450.
4003	Human	Mandible	Großstorkwitz. Grave 128, adult female with pottery. Radiocarbon: Hd-21982, 3823 ± 16 BP; 2265 ± 35 calBC (95%). Beaker associations. Excavation PEG-08, Befund 128, Bell Beaker.
4004	Human	Mandible	Großstorkwitz. Grave 127, adolescent, 10–14 years. Radiocarbon Hd-21777, 4009 ± 19 BP; 2529 ± 31 calBC (95%). Excavation PEG-08, Befund 127, not classified.
4008	Human	Mandible	Großstorkwitz. Grave 337, adult, possibly female. Radiocarbon: Hd-21408, 4156 ± 22 BP; 2770 ± 75 calBC (95%). Excavation PEG-08, Befund 337, not classified.
4009	Human	Mandible	Großstorkwitz. Grave 363, young adult/adolescent. Early Neolithic pottery, but this may have been in the grave fill, rather than grave goods. Excavation PEG-08, Befund 363, LBK.
3981	Pig (*Sus scrofa*)	Ulna	Kölsa, Wiedemar. Related to Grave 7 (see S-EVA 3977 above), animal aged 12 months. Excavation KQA-01, Befund 21.
3982	Pig (*Sus scrofa*)	Ulna	Kölsa, Wiedemar. Related to Grave 9 (see S-EVA 3978 above), adult animal. Excavation KQA-01, Befund 25.
4006	Animal, probably cattle	Pelvis	Großstorkwitz. From later Neolithic Kugelamphoren Culture. Box 40, Inventory 331/874, Excavation PEG-08, Befund 331, Beaker.

APPENDIX 2. Average carbon, nitrogen and sulphur isotope values by individual.

S-EVA number	Site	Species	Period	$\delta^{13}C$ [‰]	$\delta^{15}N$ [‰]	$\delta^{34}S$ [‰]	S amt [%]	C:N	C:S	N:S
12488	Derenburg	Human	Neolithic	−20.2*	8.4*	2.7	0.20	3.2	652	205
12431	Derenburg	Human	Neolithic	−19.5*	8.2*	1.7	0.20	3.3	540	165
12432	Derenburg	Human	Neolithic	−20.5*	7.2*	2.5	0.18	3.2	486	151
12433	Derenburg	Human	Neolithic	−20.2*	8.3*	1.4	0.16	3.3	510	155
12434	Derenburg	Human	Neolithic	−20.6*	8.6*	0.0	0.15	3.5	339	96
12489	Derenburg	Human	Neolithic	−19.4*	9.2*	−0.9	0.16	3.2	651	202
12435	Derenburg	Human	Neolithic	−20.5*	8.6*	0.5	0.19	3.5	454	130
12436	Derenburg	Human	Neolithic	−19.6*	8.7*	1.6	0.18	3.2	583	182
12490	Derenburg	Human	Neolithic	−19.8*	8.5*	0.8	0.16	3.2	696	220
12438	Derenburg	Human	Neolithic	−19.8*	8.9*	2.0	0.17	3.2	643	200
12439	Derenburg	Human	Neolithic	−19.2*	9.7*	−2.0	0.16	3.2	619	192
12491	Derenburg	Human	Neolithic	−19.2*	9.3*	0.9	0.17	3.2	654	206
12492	Derenburg	Human	Neolithic	−19.6*	8.6*	−1.1	0.19	3.2	579	181
12493	Derenburg	Human	Neolithic	−19.4*	9.2*	0.5	0.19	3.2	562	176
12494	Derenburg	Human	Neolithic	−19.7*	8.3*	−1.2	0.21	3.2	552	172
12495	Derenburg	Human	Neolithic	−19.4*	8.6*	−0.4	0.19	3.2	563	177
12496	Derenburg	Human	Neolithic	−19.4*	8.8*	−0.1	0.21	3.2	518	161
12497	Derenburg	Human	Neolithic	−19.7*	9.2*	1.4	0.17	3.2	619	195
12440	Derenburg	Human	Neolithic	−20.0*	8.4*	−0.8	0.16	3.3	543	165
12441	Derenburg	Human	Neolithic	−20.0*	9.0*	1.7	0.17	3.3	475	146
12442	Derenburg	Human	Neolithic	−20.3*	10.1*	3.0	0.19	3.4	312	91
12443	Derenburg	Human	Neolithic	−20.2*	8.6*	−0.9	0.19	3.2	515	159
12498	Derenburg	Human	Neolithic	−20.2*	8.8*	1.8	0.16	3.2	683	211
12499	Derenburg	Human	Neolithic	−19.8*	8.5*	1.4	0.20	3.2	558	173
12500	Derenburg	Human	Neolithic	−19.7*	8.3*	1.4	0.21	3.2	528	164
12501	Derenburg	Human	Neolithic	−19.8*	8.4*	−4.2	0.19	3.2	573	179
12507	Derenburg	Human	Neolithic	−19.8*	8.2*	1.2	0.21	3.2	500	158
12502	Derenburg	Human	Neolithic	−19.4*	8.6*	1.3	0.21	3.2	539	167
13468	Derenburg	Human	Neolithic	−20.0*	8.7*	0.6	0.21	3.2	433	133
12504	Derenburg	Human	Neolithic	−19.3*	9.1*	−1.6	0.17	3.2	562	175
12503	Derenburg	Human	Neolithic	−19.8*	8.1*	−0.2	0.19	3.2	577	181
12732	Derenburg	cattle	Neolithic	−20.2*	7.0*	−1.2	0.16	3.2	732	227
12733	Derenburg	Cattle	Neolithic	−20.1*	7.1*	−0.5	0.15	3.2	665	206
12734	Derenburg	Cattle	Neolithic	−21.4*	7.3*	−0.2	0.15	3.2	763	236
12735	Derenburg	Cattle	Neolithic	−19.6*	7.7*	1.2	0.27	3.3	398	120
12736	Derenburg	Pig	Neolithic	−20.5*	7.2*	−0.6	0.21	3.2	545	170
12737	Derenburg	Goat/sheep	Neolithic	−20.5*	7.0*	0.6	0.19	3.2	595	186
12738	Derenburg	Cattle	Neolithic	−20.2*	7.3*	2.8	0.28	3.2	425	131

APPENDIX 2. Continued.

S-EVA number	Site	Species	Period	$\delta^{13}C$ [‰]	$\delta^{15}N$ [‰]	$\delta^{34}S$ [‰]	S amt [%]	C:N	C:S	N:S
12545	Halberstadt	Human	Neolithic	−19.1*	9.1*	−0.0	0.15	3.2	668	212
12508	Halberstadt	Human	Neolithic	−20.1*	8.0*	1.8	0.19	3.2	524	161
12509	Halberstadt	Human	Neolithic	−20.2*	7.5*	1.3	0.17	3.2	636	199
12510	Halberstadt	Human	Neolithic	−21.3*	7.0*	3.0	0.20	3.2	558	175
12511	Halberstadt	Human	Neolithic	−20.4*	8.7*	2.8	0.18	3.2	588	182
12512	Halberstadt	Human	Neolithic	−19.5*	9.1*	0.4	0.25	3.3	454	137
12513	Halberstadt	Human	Neolithic	−20.0*	10.5*	0.3	0.20	3.2	575	179
12514	Halberstadt	Human	Neolithic	−19.2*	9.9*	1.8	0.23	3.3	486	148
12515	Halberstadt	Human	Neolithic	−20.1*	7.6*	1.6	0.24	3.3	476	146
10126	Halberstadt	Human	Neolithic	−20.0*	10.7*	2.0	0.22	3.6	520	146
12516	Halberstadt	Human	Neolithic	−19.8*	8.4*	1.7	0.22	3.3	498	153
12517	Halberstadt	Human	Neolithic	−19.8*	8.3*	0.8	0.21	3.3	482	148
12518	Halberstadt	Human	Neolithic	−19.5*	8.6*	2.3	0.25	3.3	403	123
12519	Halberstadt	Human	Neolithic	−19.6*	10.2	1.7	0.26	3.3	454	138
12520	Halberstadt	Human	Neolithic	−20.1*	8.0*	3.6	0.19	3.2	527	162
12521	Halberstadt	Human	Neolithic	−19.6*	11.7*	2.2	0.19	3.2	576	180
12523	Halberstadt	Human	Neolithic	−19.9*	8.3*	1.6	0.19	3.3	587	180
12524	Halberstadt	Human	Neolithic	−19.7*	7.5*	2.5	0.18	3.2	577	182
12525	Halberstadt	Human	Neolithic	−19.9*	8.6*	2.5	0.23	3.3	488	150
12526	Halberstadt	Human	Neolithic	−19.6*	8.3*	1.8	0.19	3.2	551	170
12527	Halberstadt	Human	Neolithic	−20.2*	8.6*	2.2	0.17	3.2	511	158
12528	Halberstadt	Human	Neolithic	−19.6*	9.0*	1.7	0.18	3.2	631	197
12529	Halberstadt	Human	Neolithic	−19.4*	9.2*	1.6	0.19	3.2	569	179
12530	Halberstadt	Human	Neolithic	−19.4*	10.5*	1.2	0.19	3.3	508	155
12531	Halberstadt	Human	Neolithic	−19.8*	7.4*	2.4	0.20	3.2	555	175
12532	Halberstadt	Human	Neolithic	−19.9*	7.7*	2.1	0.18	3.2	513	160
12534	Halberstadt	Human	Neolithic	−19.7*	8.9*	0.1	0.22	3.2	505	156
12535	Halberstadt	Human	Neolithic	−20.2*	8.7*	3.8	0.19	3.2	555	174
12536	Halberstadt	Human	Neolithic	−19.7*	8.7*	1.0	0.18	3.2	590	185
12537	Halberstadt	Human	Neolithic	−19.9*	8.0*	2.6	0.20	3.3	526	160
12539	Halberstadt	Human	Neolithic	−19.8*	7.7*	2.9	0.18	3.2	606	189
12540	Halberstadt	Human	Neolithic	−19.7*	8.4*	1.6	0.18	3.2	625	197
12541	Halberstadt	Human	Neolithic	−18.5*	9.9*	1.9	0.18	3.2	592	186
12543	Halberstadt	Human	Neolithic	−19.7*	8.2*	1.5	0.18	3.2	619	195
12744	Halberstadt	Cattle	Neolithic	−20.5*	7.2*	3.9	0.24	3.2	400	123
12739	Halberstadt	Cattle	Neolithic	−21.6*	5.8*	−2.4	0.20	3.2	562	177
12741	Halberstadt	?	Neolithic	−20.8*	5.9*	−1.2	0.22	3.3	466	143
12745	Halberstadt	?	Neolithic	−20.8*	5.8*	1.9	0.20	3.2	531	167

APPENDIX 2. Continued.

S-EVA number	Site	Species	Period	$\delta^{13}C$ [‰]	$\delta^{15}N$ [‰]	$\delta^{34}S$ [‰]	S amt [%]	C:N	C:S	N:S
12546	Karsdorf	Human	Neolithic	−19.7*	9.2*	3.1	0.18	3.2	530	163
12547	Karsdorf	Human	Neolithic	−20.1*	10.8*	5.8	0.26	3.4	413	123
12549	Karsdorf	Human	Neolithic	−19.9*	8.4*	2.7	0.19	3.2	543	168
12550	Karsdorf	Human	Neolithic	−19.5*	9.3*	2.6	0.18	3.3	534	164
12551	Karsdorf	Human	Neolithic	−20.1*	9.4*	1.9	0.19	3.2	561	174
12552	Karsdorf	Human	Neolithic	−20.2*	6.3*	4.0	0.19	3.2	547	169
12553	Karsdorf	Human	Neolithic	−20.0*	9.1*	2.5	0.19	3.2	528	163
12556	Karsdorf	Human	Neolithic	−19.6*	8.9*	2.5	0.20	3.2	551	174
12559	Karsdorf	Human	Neolithic	−20.5*	8.8*	2.6	0.20	3.3	539	166
12560	Karsdorf	Human	Neolithic	−20.3*	8.8*	6.1	0.20	3.2	534	166
12561	Karsdorf	Human	Neolithic	−19.7*	8.5*	3.8	0.16	3.2	646	202
12563	Karsdorf	Human	Neolithic	−20.1*	8.4*	5.1	0.22	3.3	483	148
12564	Karsdorf	Human	Neolithic	−19.8*	8.5*	7.0	0.35	3.2	308	97
12565	Karsdorf	Human	Neolithic	−20.0*	9.1*	3.0	0.21	3.2	509	159
12567	Karsdorf	Human	Neolithic	−19.9*	9.0*	2.9	0.18	3.2	594	184
12632	Karsdorf	Cattle	Neolithic	−20.7*	7.8*	2.5	0.20	3.4	403	124
12633	Karsdorf	Cattle	Neolithic	−21.1*	6.2*	3.4	0.18	2.9	585	184
12636	Karsdorf	Cattle	Neolithic	−22.2*	4.5*	7.1	0.18	3.3	568	176
12638	Karsdorf	Cattle	Neolithic	−21.3*	8.7*	6.2	0.21	3.3	458	141
12643	Karsdorf	goat/sheep	Neolithic	−20.6*	6.2*	9.6	0.19	3.2	530	167
12644	Karsdorf	goat/sheep	Neolithic	−20.2*	6.4*	5.4	0.15	3.3	672	210
12646	Karsdorf	Pig	Neolithic	−22.2*	7.6*	6.0	0.17	3.3	646	202
12647	Karsdorf	Pig	Neolithic	−22.4*	6.8*	6.2	0.20	3.2	487	152
12649	Karsdorf	Pig	Neolithic	−21.7*	8.0*	3.0	0.16	3.2	465	143
12651	Karsdorf	Aurochs?	Neolithic	−20.8*	6.1*	4.8	0.18	3.2	576	181
964	Westerhausen	Human	Iron Age	−18.3**	9.5**	1.8	0.24	3.1	451	143
965	Westerhausen	Human	Iron Age	−18.6**	8.7**	2.8	0.27	3.1	430	137
966	Westerhausen	Human	Iron Age	−18.1**	9.7**	2.5	0.26	3.2	431	136
967	Westerhausen	Human	Iron Age	−19.1**	9.1**	−2.3	0.27	3.2	417	131
968	Westerhausen	Human	Iron Age	−19.1**	9.4**	2.9	0.26	3.2	451	141
969	Westerhausen	Human	Iron Age	−18.5**	9.9**	6.0	0.26	3.2	455	143
970	Westerhausen	Human	Iron Age	−19.0**	10.2**	6.6	0.22	3.2	509	157
971	Westerhausen	Human	Iron Age	−18.2**	10.1**	5.5	0.22	3.2	540	170
972	Westerhausen	Human	Iron Age	−19.7**	8.1**	8.1	0.25	3.2	474	149
963	Westerhausen	Human	Iron Age	−19.0**	8.6**	7.3	0.24	3.1	484	155
960	Westerhausen	Human	Iron Age	−18.2**	10.6**	7.3	0.18	3.1	626	201
961	Westerhausen	Human	Iron Age	−19.2**	10.0**	6.0	0.21	3.1	563	180
950	Westerhausen	Human	Iron Age	−19.0**	9.3**	9.4	0.21	3.2	556	176
951	Westerhausen	Human	Iron Age	−19.2**	10.1**	5.8	0.19	3.4	633	189
956	Westerhausen	Human	Neolithic	−19.8**	8.4**	4.3	0.28	3.2	369	117
952	Westerhausen	Human	Iron Age	−18.1**	9.8**	3.5	0.18	3.1	637	203
953	Westerhausen	Human	Iron Age	−18.4**	9.8**	6.5	0.16	3.1	732	235
957	Westerhausen	Human	Iron Age	−18.6**	8.0**	8.1	0.21	3.1	539	173

APPENDIX 2. Continued.

S-EVA number	Site	Species	Period	$\delta^{13}C$ [‰]	$\delta^{15}N$ [‰]	$\delta^{34}S$ [‰]	S amt [%]	C:N	C:S	N:S
958	Westerhausen	Human	Iron Age	−20.1**	8.3**	1.9	0.31	3.1	364	116
975	Westerhausen	Deer	Iron Age	−19.5**	6.5**	5.0	0.19	3.2	604	187
976	Westerhausen	Deer	Iron Age	−20.6**	8.1**	5.0	0.20	3.2	599	184
977	Westerhausen	n.d.	Iron Age	−19.8**	6.1**	4.7	0.19	3.1	620	197
978	Westerhausen	Deer	Neolithic	−21.3**	6.1**	7.2	0.18	3.3	629	192
979	Westerhausen	Cattle	Neolithic	−20.6**	6.6**	5.5	0.24	3.2	485	152
974	Westerhausen	Cattle	Neolithic	−21.1**	5.5**	5.0	0.22	3.2	532	164
11154	Benzigerode	Human	Neolithic	−20.3***	9.4***	−2.5	0.23	3.2	469	146
11155	Benzigerode	Human	Neolithic	−19.6***	9.4***	4.6	0.23	3.2	513	159
10277	Benzigerode	Human	Neolithic	−19.7***	9.8***	6.0	0.18	3.2	546	173
10280	Benzigerode	Human	Neolithic	−19.8***	9.6***	7.5	0.26	3.3	496	148
10274	Benzigerode	Human	Neolithic	−19.7***	9.6***	7.1	0.23	3.2	497	157
10284	Benzigerode	Human	Neolithic	−19.6***	10.3***	3.5	0.25	3.2	399	125
10269	Benzigerode	Human	Neolithic	−20.0***	9.6***	2.8	0.22	3.3	463	140
10270	Benzigerode	Human	Neolithic	−19.9***	9.9***	4.0	0.25	3.2	475	150
10274	Benzigerode	Human	Neolithic	−19.8***	9.2***	7.5	0.26	3.2	458	145
10275	Benzigerode	Human	Neolithic	−20.2***	9.2***	2.6	0.25	3.2	495	156
10276	Benzigerode	Human	Neolithic	−20.1***	8.8***	4.3	0.22	3.2	505	157
	Benzigerode	Human	Neolithic	−19.8***	9.6***	5.5	0.17	3.1	540	173
980	Benzigerode	Cattle	Neolithic	−20.9***	5.7***	1.6	0.19	3.2	595	186
981	Benzigerode	Cattle	Neolithic	−21.3***	6.6***	1.5	0.18	3.3	627	191
984	Benzigerode	Marten	Neolithic	−21.1***	5.0***	4.5	0.21	3.3	520	159
3977	Kölsa	Human	Neolithic	−20.1	9.7	4.4	0.17	3.2	697	220
3978	Kölsa	Human	Neolithic	−20.0	10.0	0.0	0.17	3.2	701	222
3979	Kölsa	Human	Neolithic	−20.6	10.4	4.7	0.20	3.2	577	183
3981	Kölsa	Pig	Neolithic	−22.0	8.2	2.3	0.18	3.2	668	207
3982	Kölsa	Pig	Neolithic	−21.3	5.5	5.8	0.16	3.2	732	230
3991	Grebehna	Human	Neolithic	−20.4	10.0	2.3	0.26	3.3	451	138
4002	Großstorkwitz	Human	Neolithic	−19.6	10.7	3.1	0.20	3.2	590	183
4003	Großstorkwitz	Human	Neolithic	−20.5	10.9	0.8	0.19	3.2	603	191
4004	Großstorkwitz	Human	Neolithic	−20.5	12.6	−1.4	0.19	3.2	609	190
4006	Großstorkwitz	Cattle	Neolithic	−21.5	6.7	−0.8	0.17	3.2	700	217
4008	Großstorkwitz	Human	Neolithic	−19.1	12.2	1.1	0.17	3.2	694	219
4009	Großstorkwitz	Human	Neolithic	−19.6	9.5	3.2	0.22	3.2	537	166

* Data taken from Oelze *et al*. (2011).
** Data taken from Nehlich *et al.* (2007/2009).
*** Data taken from Meyer *et al*. (2009).

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