Increasing Mobility at the Neolithic/Bronze Age Transition - sulphur isotope evidence from Öland, Sweden

Anna Linderholm[1,3], Elin Fornander[1,4], Gunilla Eriksson*[1], Carl-Magnus Mörth[2] and Kerstin Lidén[1,5]
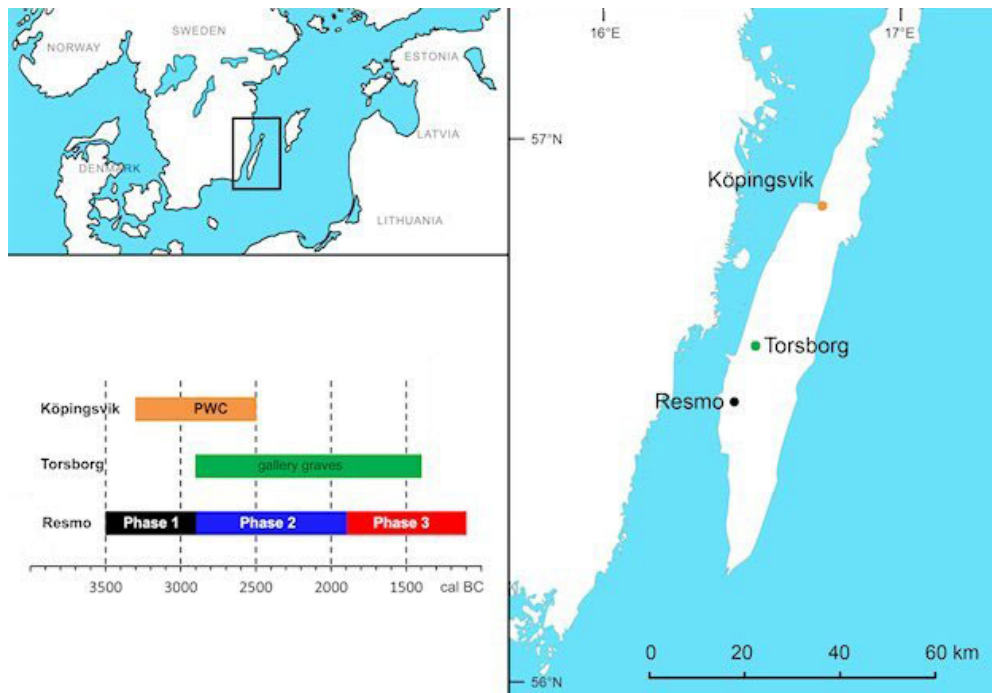
1. Archaeological Research Laboratory, Stockholm University, SE-106 91 Stockholm, Sweden. *Corresponding author: gerik@arklab.su.se

2. Department of Geological Sciences, Stockholm University, SE-106 91 Stockholm, Sweden

3. Department of Archaeology, University of Durham, Durham, DH1 3L, United Kingdom

4. Stiftelsen Kulturmiljövård, Stora Gatan 41, SE-722 12 Västerås, Sweden

5. Department of Archaeology and Social Anthropology, Breiviklia, University of Tromsø, NO-9037 Tromsø, Norway

Summary

The objective of this investigation is to look at the use of various aquatic, in this case marine, resources in relation to mobility during the Neolithic and Bronze Age periods. On the island of Öland, in the Baltic Sea, different archaeological cultures are represented in the form of material culture and skeletal remains at three sites. We have analysed δ^{34}S values in human remains representing 36 individuals, as well as faunal remains. We investigated intra-individual patterns of mobility from childhood to adulthood, primarily focusing on a passage grave. Taking into account previously published dietary data that demonstrate a wide range of dietary practices involving aquatic resources, we applied a model to estimate the contribution of δ^{34}S from terrestrial protein, to separate mobility from dietary changes, thereby identifying individuals who changed residence, as well as individuals with non-local origins. Evidence of mobility could be demonstrated at two sites. For the third site the consistently marine diet inhibits inferences on mobility based on δ^{34}S analysis. Chronologically, the frequency of non-locals was highest during the Bronze Age, when the diet was very uniform and based on terrestrial resources.

1. Introduction

Mobility and migration are of fundamental importance in human prehistory and have, as such, been debated ever since archaeology became an academic discipline. The discussion has focused mainly on the power of migration to explain cultural evolution and social development, and on the implications of mobility and sedentism. Clearly, there have been periods during prehistory when migration and changes in mobility patterns were more intense than during other periods, often in connection with the introduction of new crops, creatures or crafts. Scandinavia during the Neolithic and Bronze Age is one such instance, and the focus of the present article.

Mobility has previously been studied using carbon and nitrogen isotopes (e.g. Hakenbeck *et al*. 2010; Sealy2006), strontium (e.g. Price *et al*. 2001; Knudson and Buikstra 2007; Nehlich *et al*. 2009), or sulphur (e.g. Linderholm *et al*. 2008; Vika 2009; Oelze *et al*. 2012; Nehlich *et al*. 2012; Jay *et al*. 2013). However, the intricate issue of separating mobility from dietary changes has rarely been addressed (although see e.g. Knudson *et al*. 2010). In this article, we therefore set out to do this, studying Neolithic and Bronze Age people on the island of Öland in the Baltic Sea. In order to study individual mobility, we have focused on establishing intra-individual δ^{34}S variation by analysing, where possible, both tooth and bone elements from each individual, enabling the detection of residential changes during a lifetime. This is particularly challenging in aquatic environments, with individuals consuming various mixtures of terrestrial and marine foods, because the terrestrial δ^{34}S signal is masked by marine δ^{34}S influence. Here, we suggest that by modelling the δ^{34}S of the terrestrial component of human diet, it is possible to identify non-local origin and residential mobility for individuals consuming various mixtures of terrestrial/marine protein. In this study we accordingly make use of intra-individual data to distinguish between mobility and dietary change, by combining carbon, nitrogen and sulphur stable isotope data.

2. Archaeological Background
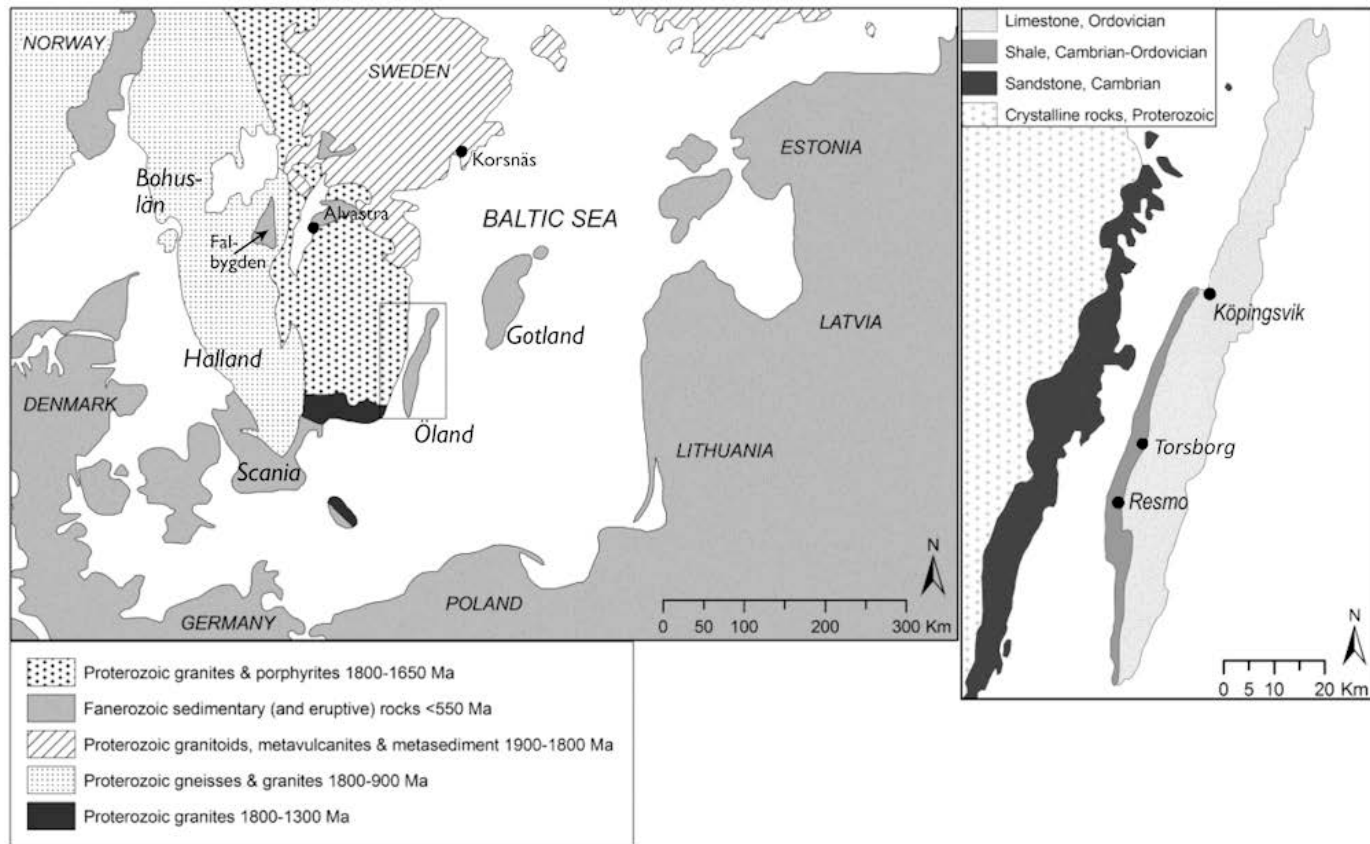
Figure 1: Geological map over Öland with the location of the archaeological sites analysed, as well as Swedish provinces and sites mentioned in the text.

In the region surrounding the brackish Baltic Sea, the water itself of course served as an excellent medium for mobility, but the Baltic was also of immense importance for subsistence, offering a wealth of resources for the provision of food, clothing, artefact production and fuel, to name just a few examples. The material analysed in this study originates from Öland, a *c.* 140km long island in the Baltic Sea (Figure 1). It is a narrow island, less than 20km across, in close proximity to mainland Sweden. The bedrock comprises primarily sedimentary rocks such as Ordovician limestone, with some Cambrian and Ordovician shales. Its current shape and relative closeness to the mainland have only changed marginally since the Mesolithic (Svensson 2001; for a chronological division of archaeological periods in southern Scandinavia, see Table 1), and while the natural boundaries of the island itself delimit the area of investigation, the proximity to the mainland still promotes contacts and mobility of people as well as animals. Furthermore,

the calcareous soils on the island provide favourable preservation conditions for skeletal material.

Table 1: Chronological periods for southern Sweden	
Period	**Approximate date (cal BC)**
Mesolithic	8200-4000
Early Neolithic	4000-3300
Middle Neolithic	3300-2300
Late Neolithic	2300-1800
Early Bronze Age	1800-1100
Late Bronze Age	1100-500

Öland is one of the few places in eastern Sweden where megalithic tombs occur. The erection of megalithic tombs such as dolmens and passage graves, clearly associated with the Funnel Beaker culture (the TRB), took place over vast areas of northern Europe during the Early and Middle Neolithic, around the middle of the fourth millennium BC (Midgley 2008). In Sweden, about 525 dolmens and passage graves are known (Sjögren and Price 2013), at least 255 of which are concentrated in the Falbygden area (Figure 1), located in the interior of the Swedish mainland, where a limited area of young sedimentary bedrock, primarily limestone, is surrounded by much older, Precambrian, igneous rock. The megaliths outside of the Falbygden area occur mainly along the coasts of the provinces of Bohuslän, Halland and Scania, with a few notable exceptions: the Alvastra dolmen in the province of Östergötland (located only a few kilometres from the Alvastra pile dwelling), a dolmen on the island of Gotland, and three passage graves and a dolmen in Resmo parish on Öland (Figure 1).

The Middle Neolithic in Southern Scandinavia (*c*. 3300-2300 BC) is characterised by the presence of archaeological remains associated with three different, partly coeval, material cultures. The Funnel Beaker Culture is the first farming culture in this region. It is followed in the archaeological record by the Battle Axe Culture (a regional version of the Corded Ware Culture), traditionally perceived as pastoralists. Chronologically partly overlapping with these two cultures is the Pitted Ware Culture (PWC), mainly found at coastal sites and perceived as marine hunter-gatherers. A primary focus for discussion in Scandinavian research on the Middle Neolithic concerns whether these differences in material culture can be attributed to different groups of people, or if the differences mainly reflect different activities of the same group (Lidén and Eriksson 2007 and references cited therein).

The overall importance of food and diet - not only for survival, but also for the construction of identity and culture - makes it crucial for archaeological understanding of cultural differences and change. In a previous study, we therefore used δ^{13}C and δ^{15}N data in order to reconstruct dietary patterns at several sites on Öland, chronologically including primarily the Neolithic and Early Bronze Age (Eriksson *et al*. 2008). In our study it became evident that in fact there *were* differences in diet between the Funnel Beaker Culture and the Pitted Ware Culture on Öland. The two major sites analysed were the passage grave in Resmo, and the Pitted Ware habitation and burial site in Köpingsvik (for more detailed information about the sites, see e.g. Papmehl-Dufay 2006; Eriksson *et al*. 2008). All analysed individuals were directly radiocarbon dated, revealing that the megalithic tomb in Resmo was in use during three phases. The first phase, *c*. 3500-2900 BC, can be attributed to the TRB presence on the island, and the diet during this period is characterised by a mixture of marine and terrestrial protein sources. During the following phase, *c*. 2900-1900 BC, the dietary components are still the same, but substantial inter- and intra-individual differences in the proportions of marine vs terrestrial protein are evident in the stable isotope data. The third phase, *c*. 1900-1000 BC, is characterised by a seemingly complete reliance on terrestrial (probably domesticated) resources (see further Eriksson *et al*. 2008). At the Köpingsvik site, located less than 50km from Resmo, the majority of the analysed individuals overlapped chronologically with Resmo Phases 1 and 2, *c*. 3300-2500 BC, displaying a diet dominated by marine mammal protein. At a third site, the Torsborg gallery grave complex, ranging in date from the Middle Neolithic to the Early Bronze Age, *c*. 2900-1400 BC, the dietary patterns correspond to their chronological equivalents at Resmo during Phases 2 and 3, respectively. Thus, while the Middle Neolithic Torsborg diet was characterised by various mixtures of

terrestrial and marine resources with substantial intra-individual differences, the Late Neolithic/Early Bronze Age diet was homogeneous and solely dependent on terrestrial resources.

The notion of two separate Middle Neolithic groups of people in this region - rather than different endeavours by only one group - is further supported by DNA studies. The genetic analysis of human remains associated with the Funnel Beaker Culture on the Swedish mainland on the one hand, and with the Pitted Ware Culture on Gotland and Öland on the other, suggests that these two material cultures represent two different genetic populations (Linderholm 2008; Malmström *et al*. 2009; 2010; Skoglund *et al*. 2012; 2014).

Following the cultural diversity of the Middle Neolithic and the more homogeneous Late Neolithic, we observe a boom in the archaeological record at the onset of the Bronze Age, including e.g. artefacts, settlement patterns and burial customs. These changes coincide chronologically with changes in δ^{13}C and δ^{15}N values observed on Öland. Our question is whether this can be explained in terms of increased contacts and interaction between different geographical regions and/or cultural groups. Here, we investigate the level of mobility and contacts during the Neolithic and Early Bronze Age by means of stable sulphur isotope analysis.

3. Material and Methods

3.1 Stable sulphur isotopes

Sulphur is incorporated into vertebrates through their diet. Experimental data has shown that it is mainly the protein portion of the diet that is reflected in collagen isotopic data (Ambrose and Norr 1993). Sulphur in collagen is present in only two amino acids, methionine and cysteine. Methionine is an essential amino-acid, which implies that it is derived directly from ingested protein, whereas the cysteine is non-essential, and synthesised either from the diet or from methionine (Bohinski 1979). There are four naturally occurring sources for sulphur: organic matter, minerals in rocks and soils, sea water, and atmospheric deposition of sulphuric gases. The δ^{34}S value in plants generally primarily mirrors that of its geological surroundings (Brady and Weil 1999). The terrestrial

sulphur isotopic signature thus varies depending on the geological setting, and terrestrial δ^{34}S values are far more varied than in marine environments. In sedimentary rocks, the δ^{34}S values range from -40 to +40‰. European granitic rocks display δ^{34}S values between -4 and +9‰, mafic rocks have δ^{34}S values close to 0‰, and metamorphic rocks exhibit δ^{34}S values ranging from -20 to +20‰ (Krouse 1980; Faure and Mensing 2005). However, the bioavailable sulphur displays ranges that are levelled out compared to the ranges in bedrock. The δ^{34}S values for the oceans, by contrast, are rather uniform, averaging +21‰, with marine vegetation having δ^{34}S values between +17‰ and +21‰ (Peterson and Fry1987). Due to the so-called sea spray effect (Kusakabe *et al*. 1976; Wadleigh *et al*. 1994), sulphur isotopes in plants growing close to the shore might be affected by marine sulphur to some extent. Freshwater systems are much more dispersed, the δ^{34}S values ranging from -22 to +20‰, as a result of the reduction of sulphate ions (SO_4^-) to hydrogen sulphide (H_2S) (Krouse 1980; Faure and Mensing 2005).

The isotopic fractionation between food and consumer is relatively small (-1‰ to +2‰), which means that the δ^{34}S value in bone or dentine collagen reflects the sulphur isotopic composition of the diet which, in turn, reflects the geology/locality where the food sources originated (Peterson *et al*. 1985; Bol and Pflieger 2002; Sharp *et al*. 2003; Richards *et al*. 2003; Fraser *et al*. 2006; Buchardt *et al*. 2007; Nehlich and Richards 2009; Nehlich *et al*. 2010). As a result, mobility in prehistoric populations can potentially be detected by comparing the human δ^{34}S values with values from local animals of approximately the same date.

Since Öland consists of sedimentary rocks, known to exhibit highly variable sulphur isotope signatures on a global scale, local faunal samples are crucial in order to establish the local terrestrial bioavailable δ^{34}S range. Like for other isotopes used in mobility studies, sulphur can only be used to exclude local values, not to pinpoint any specific region, that is, we can only positively identify non-local values. Hence, values falling within the established local terrestrial range, cannot with certainty be identified as local, although it will frequently be the most plausible interpretation (see Table 4). The analysis of both dentine and bone collagen from one individual, enables detection of change of residence during the lifetime of an individual, because the collagen is formed during different ages.

Table 4: Overview of the interpretation of individual dietary and mobility isotope data for Resmo (subjects 1–31) and Torsborg (Roman numerals), sorted by chronological phase

	Subject no.	Age	Dietary variation	Non-local	Change of residence
Phase 1	1	adult	limited	'local'	No
	2	adult	limited	non-local	Yes
	4	adult	–	–	–
	5	adult	–	–	–
	6	child	limited*	'local'	No
	8	adult	moderate	'local'	No
	10	adult	limited	non-local	Yes
	14	adult	–	'local'	–
	29	adult	moderate	non-local	–
	31	infant	–	non-local	–
Phase 2	3	child	limited*	non-local	No
	7	adult	–	–	–
	9	child	–	'local'	–
	11	adolescent	–	'local'	–
	12	adult	pronounced	'local'	Yes
	15	adolescent	limited*	non-local	No
	16	adult	pronounced	non-local	Yes
	19	child	moderate	non-local	Yes
	20	adult	limited	'local'	No
	21	adult	pronounced	'local'	Yes
	25	adult	pronounced	'local'	–
Torsborg	XXV	child	limited	'local'	–
Phase 3	13	adult	limited	non-local	Yes
	17	adult	limited	non-local	No
	18	adult	moderate	'local'	Yes
	22	adult	moderate	'local'	–
	23	adult	limited	'local'	Yes
	24	adult	limited	'local'	No
	26	adult	limited	non-local	No
	27	adult	limited	non-local	No
	28	adult	limited	non-local	No
	30	adult	limited	non-local	No
Torsborg	XIII	adolescent	limited	non-local	–
	XVI	adult	–	non-local	–

*= dietary variation classified as limited when elevated δ^{15}N values caused by breastfeeding are excluded

3.2 Analysed material

The sulphur isotope dataset presented here derive from human and faunal skeletal remains from three sites on Öland: Resmo, Köpingsvik and Torsborg (Figure 1). All analysed human subjects have been radiocarbon dated, spanning from the Middle Neolithic to the Early Bronze Age (*c*. 3500-1000 cal BC), whereas the faunal material is only partly dated, covering the same time period, but also extending the date range into modern times (Eriksson *et al*. 2008; the present study) (Table 2 and Table 3 – see end). Only samples previously analysed for δ^{13}C and δ^{15}N that fulfilled the collagen quality criteria with regard to collagen yield (van Klinken 1999 C/N ratio (DeNiro 1985) and C- and N-concentrations (Ambrose 1990) were selected for δ^{34}S analysis. In addition, we present radiocarbon dates for Resmo subject 31 - confirming its previously suggested Neolithic date - and for one Middle Neolithic and one Bronze Age cattle specimen from Köpingsvik (see Table 2 and Table 3).

Stable sulphur isotope data, along with other isotope data, for the Resmo individuals have been presented in a previous paper about the Neolithization on Öland (Eriksson *et al*. 2013). With regard to δ^{34}S analysis, a number of samples have since been rerun, with some additions, and with a more rigorous application of quality criteria. These measures have resulted in a smaller but hopefully more reliable dataset for Resmo, although as there are now fewer samples for some individuals, the interpretation regarding mobility has accordingly changed in some instances (Table 4).

The faunal samples, including both wild and domestic terrestrial species, as well as marine mammals, were included to serve as a necessary baseline for the interpretation of human sulphur isotope data. Their respective ranges of sulphur isotope values enable prediction of the local terrestrial range, reflecting the bioavailable δ^{34}S composition of the island, and also allow modelling of the δ^{34}S of the terrestrial component of the human diet (see Section 5 for details).

3.3 Collagen extraction and sulphur isotope analysis

Collagen, the main protein component of bone as well as dentine, was extracted from the skeletal material in a laboratory dedicated to bone chemical analysis. The skeletal

specimens were cleaned using deionised water and the outer surface was removed prior to sampling. Bone or dentine powder was obtained from each sample using a dentist's drill. Tooth samples were taken from the crown and cervix of the tooth, unless otherwise stated. Collagen was subsequently extracted following a modified Longin method (Brown *et al*. 1988). In short, this method includes the following steps: samples were demineralised for approximately 48 h in 0.25 M HCl. Inorganic materials were subsequently removed by filtration and the remaining organic material was rinsed in deionised water and then gelatinised in 0.01 M HCl at 58ºC for *c*. 16 h. The solution was filtered in a 30 kDa ultrafilter in order to eliminate fragmented collagen peptides, as well as other contaminants such as some humic substances. The residual >30 kDa fraction was frozen to -80ºC and freeze dried overnight.

The sulphur isotope analyses were performed using the EA-IRMS technique either at Iso-Analytical Limited, Crewe, UK, or at the Stable Isotope Laboratory (SIL), Department of Geological Sciences, Stockholm University, Sweden. Sulphur isotopic values are measured against the standard VCDT, and expressed in per mil, ‰. For each sample, approximately 5mg of collagen was weighed into tin capsules and combusted with an elemental analyser (unknown at Iso-Analytical and Carlo Erba NC2500 at SIL) connected to a continuous flow isotope ratio mass spectrometer (Europa 20-20 at Iso-Analytical and Finnigan MAT Delta+ or DeltaV Advantage at SIL), and the precision for δ^{34}S, based on standard measurements, was ±0.3‰ or better at Iso-analytical, and ±0.2‰ or better at SIL. The standards used at Iso-Analytical were IA-R036 ($BaSO_4$, +20.74‰), IA-R025 ($BaSO_4$, +8.53‰) and IA-R026 (Ag_2S, +3.96‰). At SIL they were MSS-2 ($BaSO_4$, +21.5‰), MSS-3 ($BaSO_4$, +3.35‰), SSS-2 ($BaSO_4$, +22.8‰), SSS-3 ($BaSO_4$, +3.8‰) and CDT ($BaSO_4$, 0‰).

4. Results

4.1 Quality

Of the analysed material from Resmo, Köpingsvik and Torsborg, 53 human and 18 faunal bone and dentine samples fall outside the acceptable ranges for δ^{34}S analysis with regard to %S, C/S and N/S (cf. Nehlich and Richards 2009). These samples are reported in Table 5 (see end), together with human samples from three additional Neolithic and Bronze Age sites on

Öland (previously analysed with regard to $\delta^{13}C$ and $\delta^{15}N$, see Eriksson *et al*. 2008), where no samples met the quality requirements. There is no correlation between %S and $\delta^{34}S$ and accordingly no indications that the $\delta^{34}S$ values have been affected by post-depositional contamination (cf. Kinaston *et al*. 2013).

In total, 70 human and 38 faunal samples fulfil the quality criteria with regard to %S, C/S and N/S, as suggested by Nehlich and Richards (2009). These include seven human and four faunal samples (highlighted by an asterisk in Table 2 and Table 3) which have been included as their values (either only %S or only N/S) fall within the desired ranges when corrected for weighing errors on the analytical balance. The only fish, a garpike, has a C/S ratio of 246, outside the stipulated range of 125-225 for fish. However, this range was established using a dataset that is heavily biased towards cod (>90% of the dataset: 89 out of 98 modern samples and 39 out of 42 historic samples) (Nehlich and Richards 2009). The bones of garpike, unlike cod, have a bluish-green colour, recently identified as biliverdin, associated with higher proportions of hydroxyproline (Jüttner *et al*. 2013), which could account for the relatively low sulphur concentration and thus elevated C/S ratio. Given the distinctive nature of garpike bone, it is therefore conceivable that the quality criteria for fish suggested by Nehlich and Richards (2009) may not be applicable. The sample has accordingly been included.

4.2 Faunal samples

Stable sulphur isotope data for the faunal samples are presented in Table 2 and Figure 2.
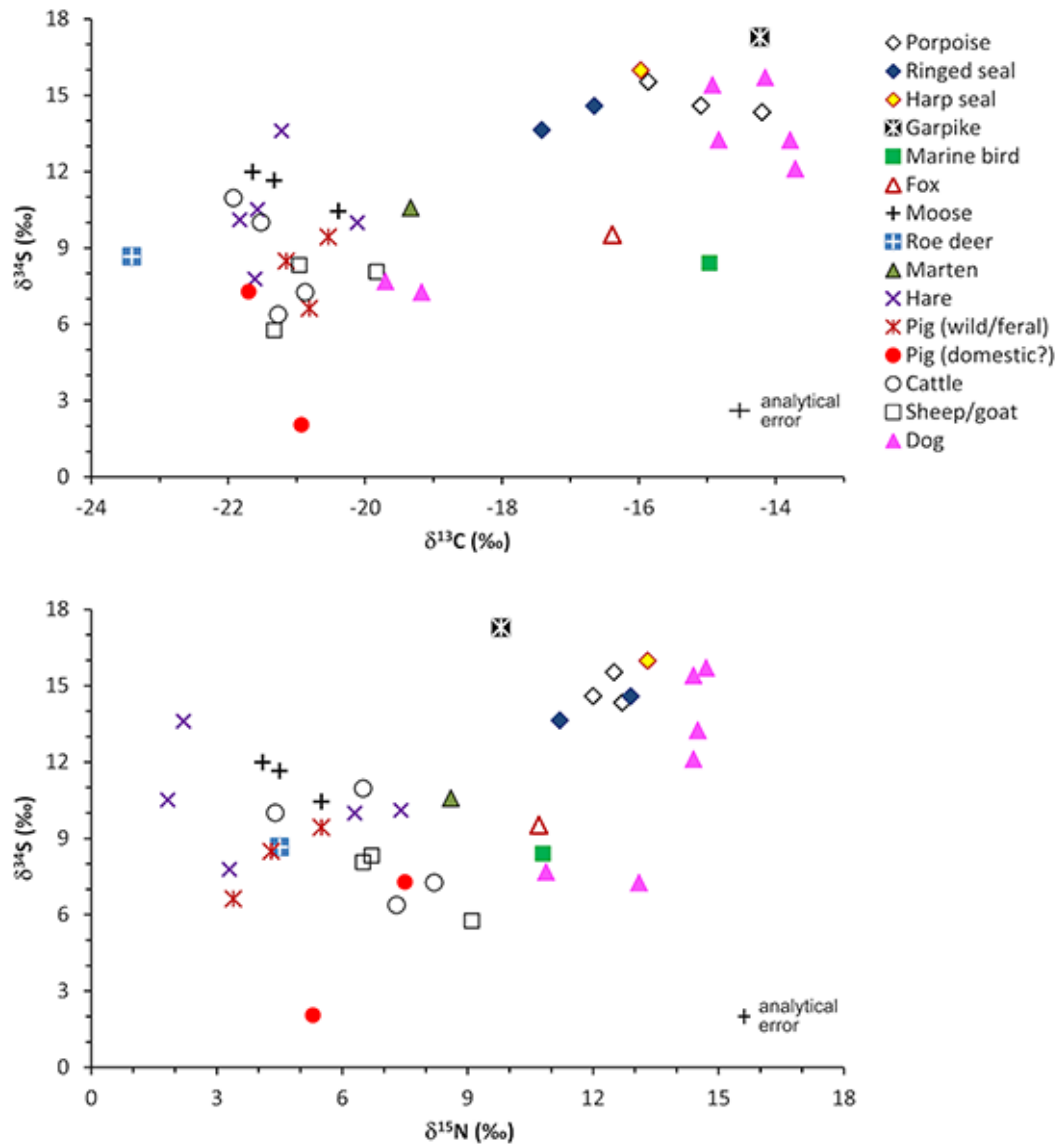
Figure 2: Observed δ^{34}S values plotted against δ^{13}C and δ^{15}N, respectively, for all faunal samples.

The total range for the marine mammals is from +13.6 to +16.0‰ (mean +14.8, sd 0.8‰, n=6), including harbour porpoise (+14.8 ± 0.6‰, n=3), ringed seal (+14.1 ± 0.7‰, n=2) and one harp seal (+16.0‰). The only analysed specimen of fish, a marine garpike, has a somewhat higher value of +17.3‰ (but see reasoning above). One unidentified marine bird (as inferred from its carbon isotope value), has a considerably lower δ^{34}S of +8.4. One red fox, which had a mixed marine/terrestrial diet, has a slightly higher value, +9.5‰.

Wild terrestrial species vary between +6.6 and +13.6‰ (+10.0 ± 1.9‰, n=13). These include moose (+11.4 ± 0.8‰, n=3), one roe deer (+8.7‰), one pine marten (+10.6‰), the mountain hares, which range from +7.8 to +13.6‰ (+10.4 ± 2.1‰, n=5), and the pigs from Köpingsvik (+8.2 ± 1.4‰, n=3). The Köpingsvik pigs were interpreted as wild/feral due to the lack of correspondence between human and pig δ^{13}C and δ^{15}N values, indicating that these animals did not feed on human food waste to any detectable extent (see further discussions on PWC pigs in Eriksson 2004; Fornander *et al.* 2008).

Cattle and sheep/goat range between +5.8 and +11.0‰ (+8.1 ± 1.9‰, n=7), whereas the two (possibly domestic) pigs from Resmo have values of +2.1‰ and +7.3‰, respectively. Dogs fall into two dietary groups, based on carbon isotope data. The two terrestrial dogs have uniform δ^{34}S values (+7.5 ± 0.3‰, n=2), whereas the dogs feeding off marine resources have a wider range, from +12.1 to +15.7‰ (+13.9 ± 1.5‰, n=5).

4.3 Human samples

Observed δ^{34}S values for the human samples are presented in Table 3 and Figure 3. The 70 samples derive from 36 individuals, and include intra-individual data for 22 of these individuals.

The δ^{34}S values for six Middle Neolithic individuals from Köpingsvik range from +13.3 to +15.3‰ (+14.0 ± 0.7‰, n=7), very similar to the range for marine mammals, and consistent with a diet of predominantly marine mammal protein. The only intra-individual data, for Grave Klinta A7, demonstrate no change in δ^{34}S from childhood to adult age.

Resmo phase 1
Resmo phase 2
Resmo phase 3
Köpingsvik
Torsborg
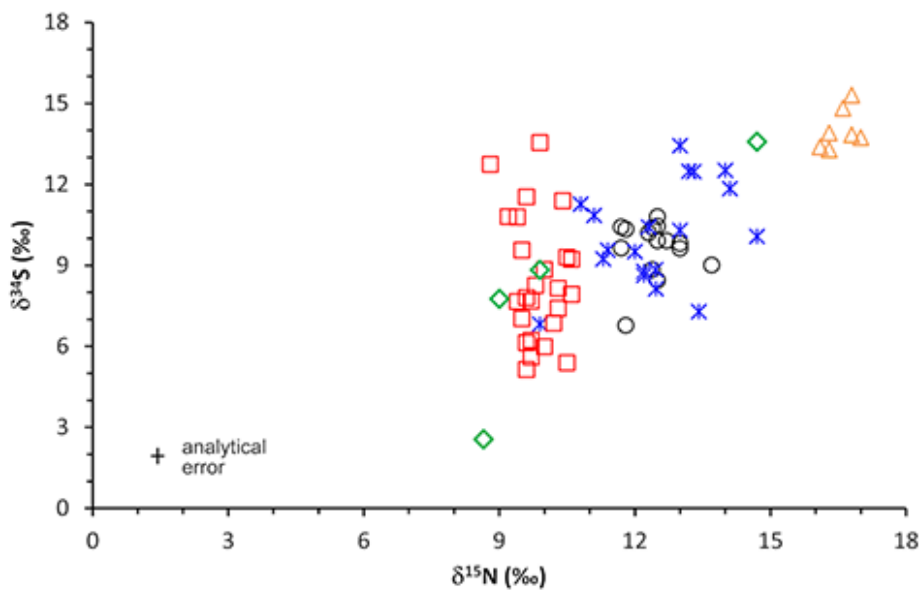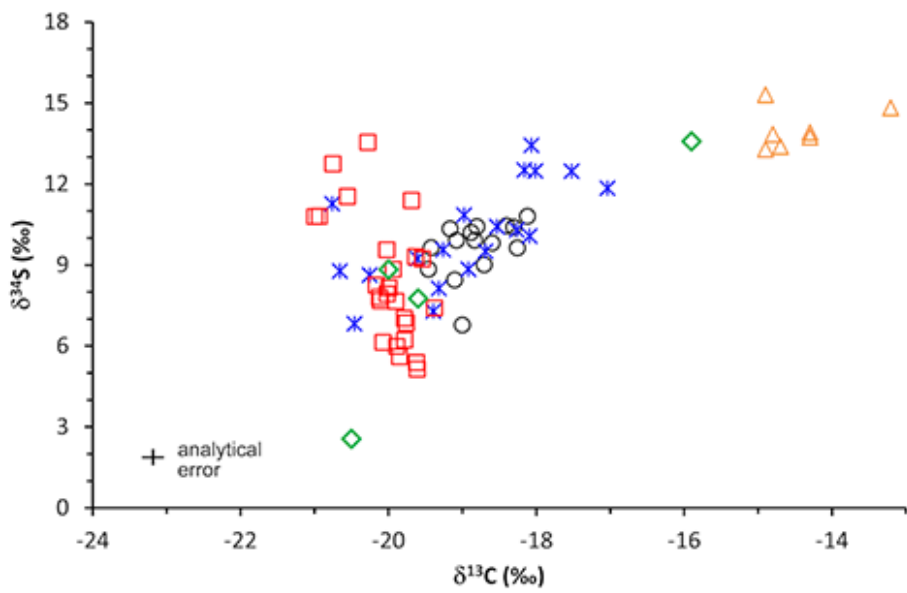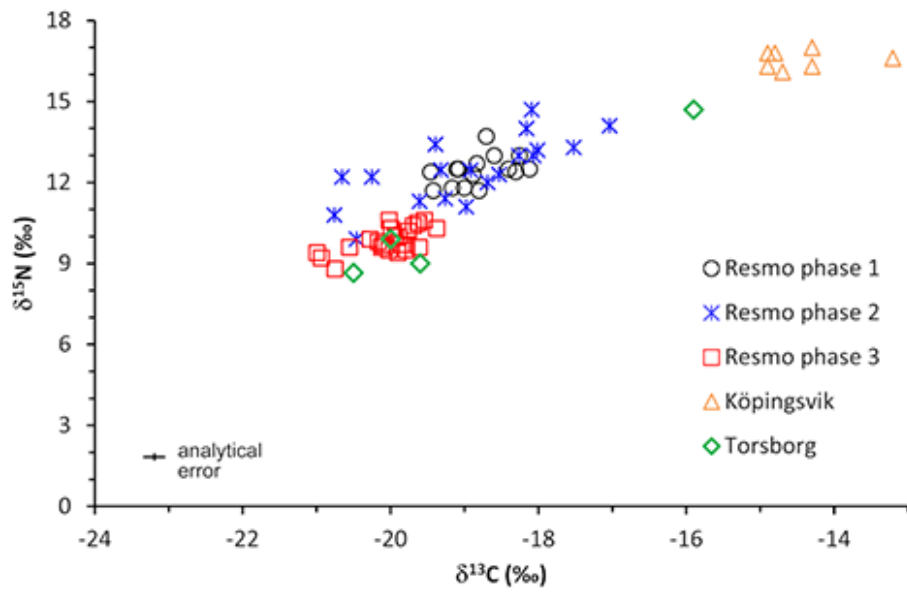
Figure 3: Observed $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values for all human samples subjected to $\delta^{34}S$ analysis.

Stable sulphur isotope data for the four individuals from Torsborg (one sample each) range from +2.6‰ to +13.6‰. The Middle Neolithic individual, the only one with a carbon isotope value indicating any substantial consumption of marine protein, has the highest value, +13.6‰, comparable to values for Pitted Ware Köpingsvik. The Late Neolithic individual has a considerably lower value, +8.8‰, whereas the two Bronze Age individuals have even lower values of +2.6‰ and +7.8‰, respectively.

Observed $\delta^{34}S$ data for the Resmo individuals show a distinct chronological pattern, with increasing ranges for each phase. Eight individuals in Phase 1 (Early/Middle Neolithic) range from +6.8 to +10.8‰ (+9.6 ± 1.0‰, n=15), ten individuals from Phase 2 (Middle/Late Neolithic) range from +6.8 to +13.4‰ (+10.1 ± 1.9‰, n=19), and ten individuals from Phase 3 range from +5.1 to +13.6‰ (+8.4 ± 2.3‰, n=25). The implications of the Resmo data will be discussed in detail below.

5. Discussion and Conclusions

5.1 The megalithic tomb in context

The fact that the Resmo passage grave was used during three separate phases, makes it necessary to consider the cultural context for each phase separately. Phase 1 in Resmo is linked to the erection of the megalithic tomb and its first use, and can on good grounds be associated with the Funnel Beaker Culture (TRB). Comparison with $\delta^{34}S$ data from three other Swedish megalithic tombs may help put the Resmo data into a wider context. Data are available for the Rössberga and Frälsegården passage graves in Västergötland, both situated in the Falbygden area, and for the Alvastra dolmen in Östergötland - a monument which, together with the Resmo tombs and the Ansarve Hage dolmen on Gotland are isolated phenomena in the Swedish megalithic world, as they are the only ones located outside the core areas of Falbygden and the coasts of Bohuslän, Halland and Scania. The megalithic tombs at Resmo and Alvastra are consequently both unique features that can be expected to deviate from the Rössberga and Frälsegården tombs with regard to mobility patterns.
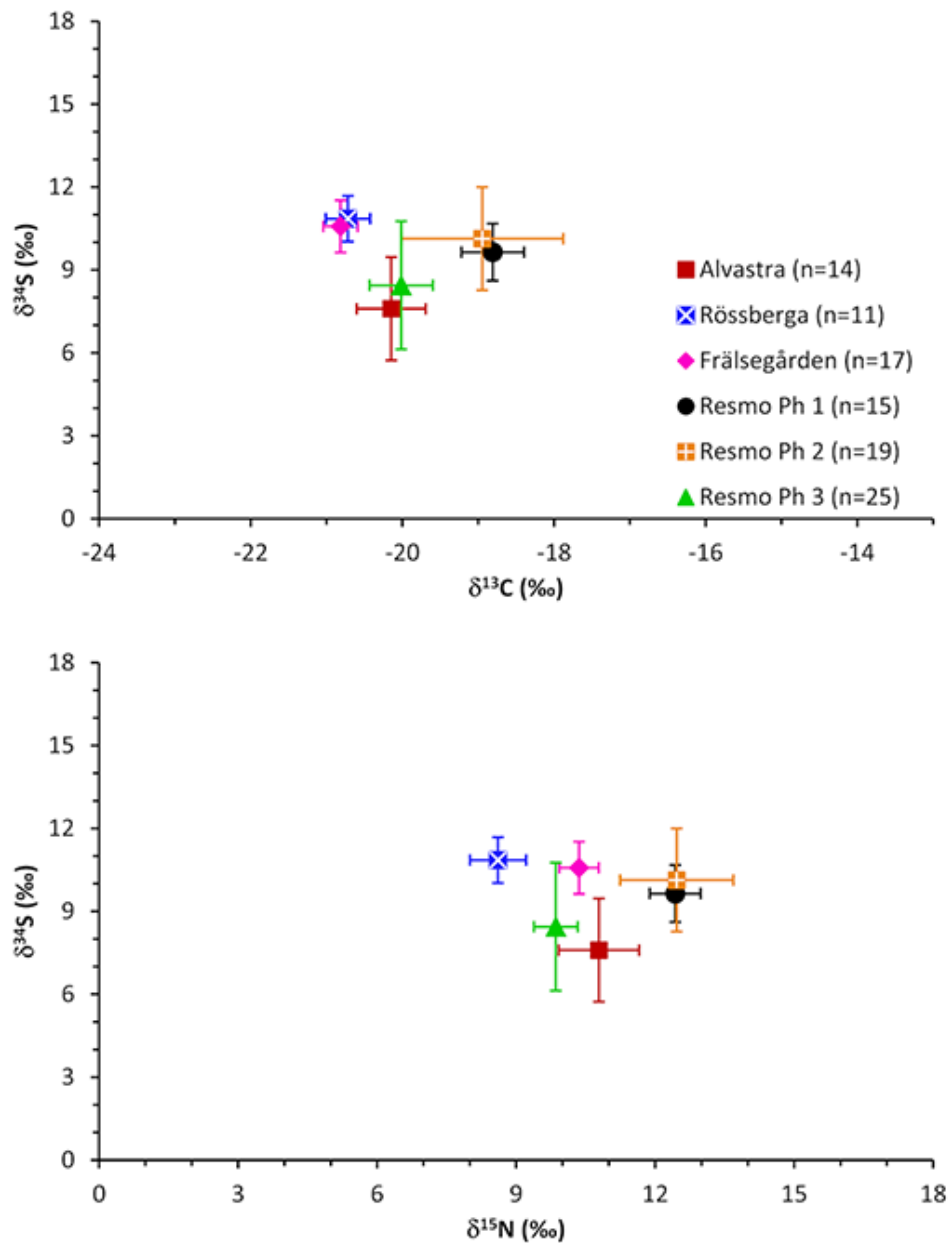
Figure 4: Observed $\delta^{34}S$, $\delta^{13}C$ and $\delta^{15}N$ values (mean ± 1 sd) for Resmo humans, grouped according to phase. Three megaliths on the Swedish mainland are also shown for comparison. Only radiocarbon dated individuals coinciding with Phase 1 in Resmo were included from the Rössberga passage grave, the Frälsegården passage grave and the Alvastra dolmen.

Only those human individuals from Rössberga, Frälsegården and Alvastra who have been directly radiocarbon dated, and coincide in date with Resmo Phase 1, have been included in the comparison (Figure 4). From Rössberga, the $\delta^{34}S$ values of bone collagen from eleven individuals range from +9.8 to +12.4‰ (+10.9‰ ± 0.8‰), indicating an exclusively local origin, based on the limited variation and compatibility with $\delta^{34}S$ of contemporaneous fauna from the tomb (Linderholm 2008). The fact that the Rössberga data derive solely from bone,

could potentially result in less variation than the inclusion of both bone and dentine values. This, however, does not seem to be the case, as δ^{34}S data from the other Falbygden megalithic tomb, Frälsegården, includes both dentine and bone values from eleven individuals (17 samples), with only a slightly larger range, from +9.1 to +12.3‰ (+10.6 ± 0.9‰). Bone and dentine collagen δ^{34}S values from eight individuals (14 samples) from the Alvastra dolmen, by contrast, are much more dispersed, ranging from +4.4 to +10.6‰ (+7.6 ± 1.9‰), extending outside the faunal range, most likely including people from a much wider area than the vicinities of Alvastra (Fornander 2011). Although the geology at Alvastra is different from both Rössberga and Resmo, a comparison is nevertheless considered justified (for a detailed argument, see Fornander (Fornander 2011, 134f).

Somewhat surprisingly, the standard deviations of δ^{13}C, δ^{15}N and δ^{34}S are largely similar for Rössberga and Resmo Phase 1, and there is much overlap between their δ^{34}S values. It is also noteworthy that although Rössberga has a geology resembling that of Öland, and any sea spray effect can be ruled out, the δ^{34}S mean for Rössberga is higher than for Resmo - the mere presence of δ^{34}S values >10‰ in Resmo accordingly does not inherently imply a sea spray effect. The Alvastra dolmen stands out with its much higher standard deviations and much less overlap in δ^{34}S values with the other two tombs. Thus, although Resmo is the site geographically most distant from the megalithic core area Falbygden, it was apparently not so different with regard to mobility.

In Figure 4, it is also evident that Phases 2 and 3 in Resmo are very different from the earlier phase, both in terms of variation and mean values. Especially Phase 3 seems to match the Alvastra dataset, which suggests that the level of mobility could be of a comparable magnitude.

5.2 Modelling the terrestrial δ^{34}S

There is a statistically significant positive correlation between δ^{13}C and δ^{34}S for humans (Spearman's r= 0.55, p<0.001), which is also obvious from Figure 3. The implication is that the marine component of the diet elevates the sulphur isotope value, thus obscuring mobility patterns. In order to discern mobility from such data, it is therefore necessary to isolate the δ^{34}S of the terrestrial dietary protein. This is required because only the terrestrial δ^{34}S values reflect the local environment, whereas marine δ^{34}S values are consistently elevated. Employing a model first suggested by Fornander *et al*. (in press) for ^{87}Sr/^{86}Sr, and

employed on δ^{34}S data by Eriksson *et al*. (2013), an estimate of the original terrestrial δ^{34}S value can be calculated, which can subsequently be compared to the local terrestrial range.

Previous δ^{13}C and δ^{15}N analyses (Eriksson *et al*. 2008) have demonstrated that the Neolithic and Bronze Age humans on Öland relied essentially on only two main protein sources - terrestrial herbivores and marine mammals. This was based on extensive faunal data showing a clear isotopic separation between fish and marine mammals, where the strong correlation between human δ^{13}C and δ^{15}N ruled out any substantial contribution of fish protein to the human diet (whereas dogs were suggested as the main consumers of fish, providing a better fit with the isotopic data cf. Eriksson 2004).

Because there are only two main protein sources, and because of the demonstrated association between δ^{34}S and δ^{13}C, a linear mixing model can be employed (making the use of more complex models superfluous). Accordingly, the estimated terrestrial δ^{34}S value, R_t, is calculated as:

$$R_t = R_{obs} + (R_{obs} - R_{mar}) \times M$$

where R_{obs} is the observed δ^{34}S value, and R_{mar} is the marine δ^{34}S end-point value, +15‰. M is the marine factor, which is calculated as

$$C_{mar}/(1-C_{mar})$$

where C_{mar} is the percentage of marine dietary protein, which is calculated from δ^{13}C, using -22‰ and -13‰ as terrestrial and marine end-points, respectively.

The calculation of the marine δ^{34}S mean (R_{mar}, +15‰) is based on marine mammals only, that is, harbour porpoise (n=3), ringed seal (n=2) and harp seal (n=1). The δ^{13}C and δ^{15}N evidence shows that the marine protein consumption derived mainly from marine mammals, and apparently not from fish or birds to any large extent. Moreover, the marine bird (+8.4‰) was not determined to species, and therefore whether it was migratory could not be established. This does not exclude the possibility that its flesh or eggs constituted a minor part of the diet, and its value is accordingly informative. Much the same could be said about the garfish (+17.3‰), with the addition that its C/S ratio indicates that it should be treated with caution. Including the bird and the fish would not substantially alter the mean

marine δ^{34}S value (from +14.8 to +15.2‰), and it was deemed reasonable to exclude them from the calculation.

The local terrestrial range, reflecting the bioavailable δ^{34}S composition of the island, is calculated as the δ^{34}S mean ± 2 standard deviations of wild local terrestrial fauna. The resulting range, +6.3‰ to +13.7‰, is thus based on δ^{34}S data from moose (n=3), roe deer (n=1), pine marten (n=1), mountain hare (n=5) and wild/feral pigs (n=3) (cf. Table 2). All these species are likely to have fed both at the coast and the interior, and their home ranges to have been naturally delimited by, and in most cases covered, the whole island, which is more or less geologically homogeneous. The mountain hare displays the widest range of δ^{34}S values, from 7.8 to 13.6‰, probably reflecting more limited home ranges of individual hares. In view of the limited size of the island, it is likely that the terrestrial plants, and by implication also the local fauna, are to some extent influenced by the sea spray effect - the hare displaying the highest terrestrial isotopic value, +13.6‰, is conceivably an example of this. However, the sea spray effect cannot be expected to be as substantial on Öland as on islands of comparable size in the ocean or the Mediterranean, first because of its proximity to the mainland, but above all because the size, morphology, salinity and history of the Baltic Sea differ radically from the oceans. The established local terrestrial range is consistent with these facts, also supported by δ^{34}S analysis of modern cod, demonstrating that Baltic cods have lower δ^{34}S than Atlantic ones (Nehlich *et al*. 2013). The impact of the sea spray effect is also considerably lower because of the lower marine δ^{34}S range.

Domestic species were not included in the calculation of the local terrestrial range, mainly because of the risk that they were imported, or subject to specific cultural practices affecting what they fed on, hence resulting in δ^{34}S values not representative of the bioavailable sulphur of the local environment. The Middle Neolithic cattle specimen from Köpingsvik - clearly contemporaneous with the Pitted Ware population, but culturally an 'exotic' - is an example of the former, dogs of the latter. Nevertheless, the majority of the domestic animals - including one pig from Resmo - display rather homogeneous δ^{34}S values, within the local terrestrial range, consonant with a local origin. This is not surprising, as it is highly unlikely that people in Neolithic and Bronze Age Scandinavia relied to any large extent on imported livestock. Two specimens from Resmo fall below the local terrestrial range; an ovicaprid tibia of historical date (thus probably imported) and a pig tooth (not dated).

The application of the model allows the identification of genuine mobility patterns at the individual level. As for any model, there are of course intrinsic uncertainties and errors, and these increase with the percentage of marine protein input. At a certain point there is accordingly so much imprecision that the estimate is no longer informative. Our assessment is that this point is reached at around 60% marine dietary input. Consequently it is not possible to make any estimates for the Köpingsvik individuals. Their δ^{34}S values correspond with previously published data from the Pitted Ware site Korsnäs in eastern central Sweden (Fornander *et al.* 2008), indicating that high marine protein consumers have uniform values throughout the Baltic Proper. Residential changes will accordingly not be discernible.

5.3 Human mobility in Resmo

Estimated terrestrial δ^{34}S values for human individuals with marine dietary input below 60% were calculated for 28 individuals from Resmo and three from Torsborg, including intra-individual data for 21 Resmo individuals. These are plotted separately for each phase in Figure 5, where the predicted local terrestrial range is shaded, black circles around symbols mark adult bone samples, black squares around symbols mark subadult bone samples, and the remaining symbols are dentine samples. It is important to remember here that the estimated terrestrial δ^{34}S value reflects only the terrestrial portion of the diet, which enables comparison between individuals and chronological phases with varying levels of marine dietary protein input.
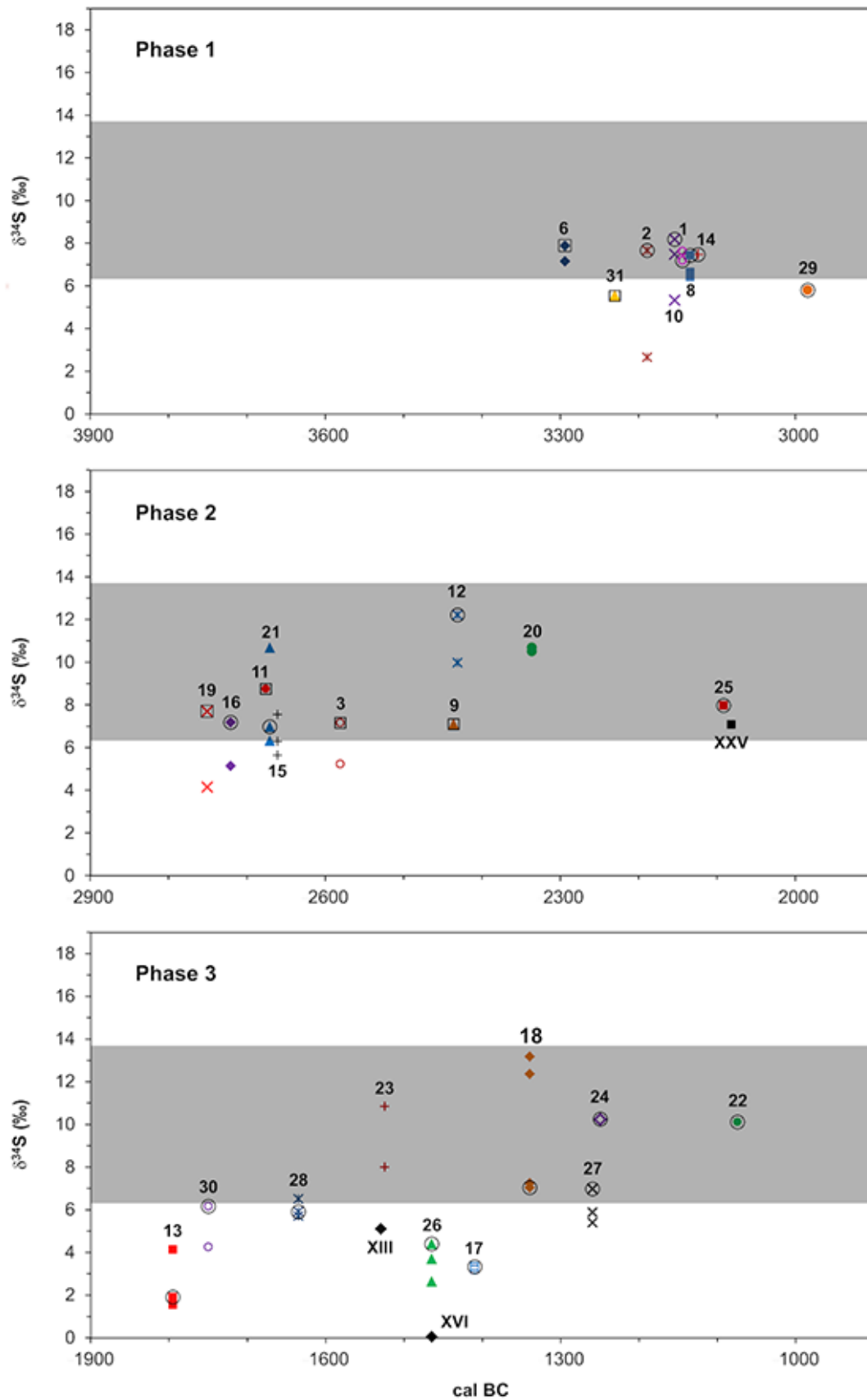
Figure 5: Estimated δ³⁴S values of the terrestrial food components for human samples, plotted against calibrated radiocarbon age (centre value of 2σ calibrated range) during Phase 1, 2 and 3,

respectively. The shaded area represents the predicted local terrestrial range. Numbers denote Resmo individuals, Roman numerals denote Torsborg individuals. Black circles around symbols mark adult bone samples, black squares around symbols mark subadult bone samples, the remaining symbols are dentine samples.

Two aspects of human mobility are considered here: non-local origin and change of residence during the lifetime. Any estimated terrestrial δ^{34}S value outside the local terrestrial range is considered as non-local. For subjects with intra-individual data, the individuals are identified as non-local if at least one value is outside the local terrestrial range. Change of residence is defined as an intra-individual δ^{34}S range exceeding 2‰. This level was chosen with consideration of the ±1 sd ranges for the Rössberga and Frälsegården populations, who were interpreted as homogeneous and likely to be local.

From Torsborg, estimates of the original terrestrial δ^{34}S values, all from dentine, could only be made for the three subjects with terrestrial diets. For the Neolithic individual, the value falls within the local terrestrial range, whereas the two Bronze Age subjects have estimated terrestrial δ^{34}S values well below the local range, indicating a non-local origin.

The estimated terrestrial δ^{34}S values for the 28 Resmo individuals range from +1.6 to +13.2‰, with values extending below the local terrestrial range thus indicating non-local origins. It is obvious from Figure 5 that the ranges increase for each chronological phase, something that was already evident from the observed δ^{34}S values.

During Phase 1, four individuals fall completely within the local terrestrial range (subjects 1, 6, 8 and 14), and none of them have an individual range suggesting any change of residence. Subjects 2 and 10 have non-local values from the earliest formed dentine (reflecting childhood), while later dentine and bone values are within the local terrestrial range. Their individual ranges suggest change of residence and childhoods spent outside of Öland in both cases. The bone value from the infant, subject 31, is also outside the local range, probably reflecting the mother's diet during pregnancy and lactation, as its elevated δ^{15}N indicates that the infant was breastfed. The bone value of subject 29 also supports a non-local origin.

During Phase 2, six individuals fall completely within the local terrestrial range (subjects 9, 11, 12, 20, 21 and 25). There is no detectable difference between the two dentine (childhood) values for subject 20, whereas subjects 12 and 21 have ranges >2‰, indicative of change of residence. For four subjects (3, 15, 16 and 19), dentine (childhood) values are

outside the local terrestrial range, whereas tissues formed later in life fall within the local range. Both subjects 16 and 19, an adult and a child, respectively, have individual ranges exceeding 2‰, suggesting change of residence, while the subadult subjects 3 and 15 have smaller individual ranges.

During Phase 3, four adult individuals fall completely within the local terrestrial range (subjects 18, 22, 23 and 24. Two of these, subjects 18 and 23, have intra-individual ranges suggestive of change of residence during the course of life, while the estimated terrestrial $\delta^{34}S$ values of subject 24, reflecting early childhood and adult age, are indistinguishable. Four individuals fall completely outside the local terrestrial range (subjects 13, 17, 26 and 30), and another two (subjects 27 and 28) have only one value each inside the local range. Only one out of these six non-local individuals, subject 13, has an individual range indicating change of residence.
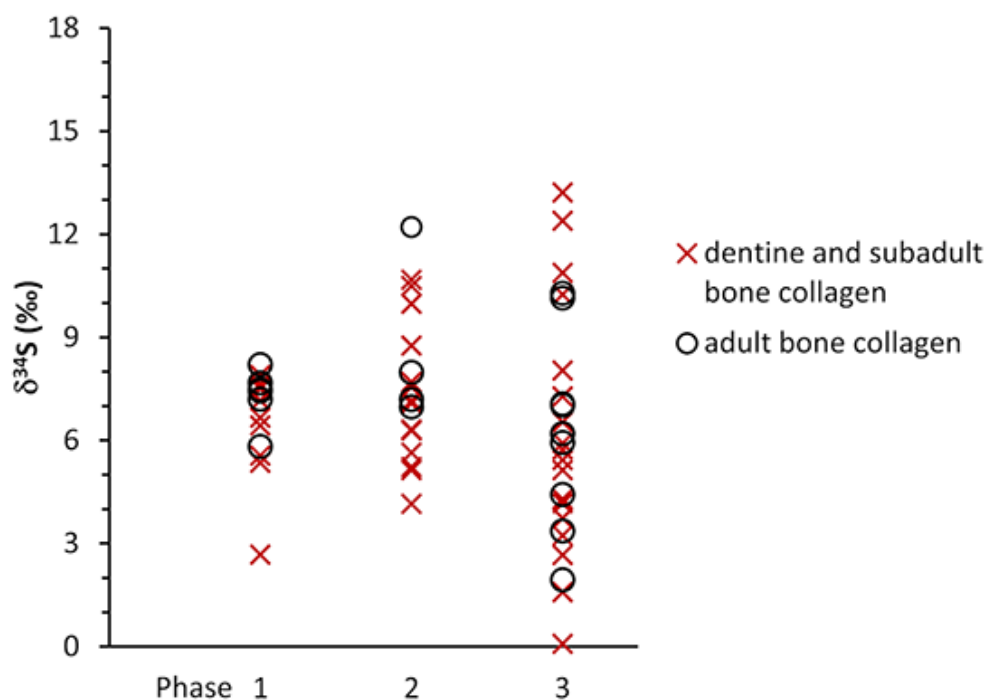
Figure 6: Estimated terrestrial $\delta^{34}S$ values for Resmo and Torsborg for each chronological phase. Crosses include all dentine and subadult bone values, while circles include only adult bone values.

In sum, there is an increase in the proportion of individuals classified as non-locals from the Neolithic (Phases 1 and 2), to the Bronze Age (Phase 3) - from 50% and 36% during the Neolithic, to 67% during the Bronze Age. This rise is clearly discernible but by no means remarkable. However, taking into account the overall range of variation for each phase, a

clear pattern emerges (Figure 6). The mean estimated terrestrial δ^{34}S value for Phase 1 is +6.7‰, and the standard deviation only 1.4‰ (n=15), while both the mean and the sd increase during Phase 2, to +7.7 ± 2.1‰ (n=20, incl. Torsborg). During Phase 3, the mean is below the local terrestrial range, +6.2‰, and the sd as large as 3.3‰ (n=27, incl. Torsborg). As expected, the subadult values (dentine and subadult bone) vary to a higher degree (both range and sd) than adult values (adult bone), since the former represent shorter tissue formation times, while the longer time of formation in adult bone tends to level out short-term variation such as seasonal differences. It is truly difficult to find a better explanation for the increasing ranges at the population level than increasing mobility.

5.4 Diet and mobility

Dietary life history data was available for the majority of the Resmo individuals. Based on individual ranges of δ^{13}C and δ^{15}N, their dietary variation was classified as limited, moderate and pronounced, respectively (Eriksson *et al*. 2008; Eriksson and Lidén 2013). Evidently, four individuals experienced changes in residence not accompanied by any major shifts in diet: subjects 2 and 10 in Phase 1, and subjects 13 and 23 in Phase 3. Five individuals have changed residence while also markedly changing diet (moderate or pronounced dietary variation): subjects 12, 16, 19 and 21 in Phase 2, and subject 18 in Phase 3. Of the twelve individuals for whom no change of residence was discernible, only one, subject 8 in Phase 1, had any notable dietary variation, while the remaining eleven individuals had limited dietary variation: subjects 1 and 6 in Phase 1, subjects 3, 15 and 20 in Phase 2, and subjects 17, 24, 26, 27, 28 and 30 in Phase 3. Consequently, it seems that major shifts in diet could be explained primarily by change of residence.

5.5 Archaeological implications

Food and cuisine are strongly associated with cultural identity, and, as such, typically resistant to change. A change of diet therefore suggests that a cultural transformation has taken place. In the case of the Resmo megalith, where no artefacts can be associated with individuals, the only individual cultural indicators besides the megalithic tomb itself are the

diet and date. The extended use of the passage grave makes it clear that the cultural affiliation with the TRB cannot be valid for all the interred individuals. Thus, after the initial erection and use in Phase 1, we interpret the changes in diet and mobility as reflecting a major cultural transformation, possibly connected to the appearance of the Battle Axe material culture. Phase 3, by contrast, is characterised by an increasing number of non-local people. These newcomers brought with them intensified agriculture, trade and metal craftsmanship; this is also reflected in the general material culture of the Bronze Age, where we see intensified contacts with continental Europe, e.g., in amber and bronzes (Kristiansen and Larsson 2005). The isotope analysis and the subsequent application of our model provide real insights into human mobility at the individual level - an important addition to studies of mobility based on the presence of exotic artefacts or analyses of population genetics.

Acknowledgements

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Table 2: Faunal samples from Resmo (RES), Köpingsvik (KOP) and Torsborg (TOR) successfully analysed for δ^{34}S, sorted according to species. Precision for δ^{13}C and δ^{15}N ±0.15‰ or better for all samples (data from Eriksson et al. 2008). Precision for δ^{34}S ±0.3‰ or better at Iso-Analytical (ISO) and ±0.2‰ or better at SIL.

*= %S or N/S falls within the desired ranges (cf. Nehlich and Richards 2009) when corrected for weighing errors on the analytical balance.

**=C/S outside range for fish, but see main text (Section 4.1)

Lab. code	Species	Common name	Element	^{14}C date (uncal BP)	δ^{13}C (‰)	δ^{15}N (‰)	δ^{34}S (‰)	% coll.	%C	%N	%S	C/N	C/S	N/S	δ^{34}S lab.
KOP 093	*Phoca groenlandica*	harp seal	femur		−16.0	13.3	+16.0	4.6	40.4	15.0	0.30	3.1	355	113	SIL
KOP 157	*Phocoena phocoena*	harbour porpoise	vertebra		−14.2	12.7	+14.3	2.5	41.0	15.2	0.22	3.2	504	160	SIL
KOP 166	*Phocoena phocoena*	harbour porpoise	vertebra		−15.9	12.5	+15.5	6.6	39.8	15.2	0.35	3.1	303	99*	SIL
KOP 169	*Phocoena phocoena*	harbour porpoise	vertebra		−15.1	12.0	+14.6	4.4	41.3	15.0	0.23	3.2	471	147	SIL
KOP 179	*Pusa hispida*	ringed seal	metatarsal		−16.7	12.9	+14.6	3.6	34.1	13.3	0.26	3.0	345	116	SIL
KOP 180	*Pusa hispida*	ringed seal	humerus		−17.4	11.2	+13.6	4.9	40.5	14.7	0.28	3.2	380	118	SIL
KOP 136	*Belone belone*	garpike	vertebra		−14.2	9.8	+17.3	4.9	39.3	14.6	0.43	3.1	246**	79	SIL
KOP 126	Aves indet.	indet. bird	ulna		−15.0	10.8	+8.4	6.1	40.0	15.3	0.35	3.1	301	99*	SIL
KOP 142	*Alces alces*	moose (elk)	antler		−21.3	4.5	+11.6	6.1	34.8	13.4	0.24	3.0	379	125	SIL
KOP 162	*Alces alces*	moose (elk)	antler		−21.6	4.1	+12.0	6.2	37.8	15.0	0.27	2.9	369	125	SIL
KOP 194	*Alces alces*	moose (elk)	humerus		−20.4	5.5	+10.4	3.7	43.1	16.0	0.21	3.1	553	176	SIL
KOP 116	*Capreolus capreolus*	roe deer	phalanx		−23.4	4.5	+8.7	5.9	39.2	14.6	0.30	3.1	348	111	SIL

KOP 105	*Lepus timidus*	mountain hare	innominate		−21.6	3.3	+7.8	4.4	40.2	14.6	0.27	3.2	395	123	SIL
KOP 114	*Lepus timidus*	mountain hare	femur		−21.2	2.2	+13.6	4.9	41.4	14.9	0.34	3.2	322	99*	SIL
KOP 184	*Lepus timidus*	mountain hare	metacarpal		−21.6	1.8	+10.5	4.3	39.9	14.4	0.32	3.2	333	103	SIL
RES 125	*Lepus timidus*	mountain hare	femur		−21.8	7.4	+10.1	3.9	42.6	14.9	0.35	3.3	325	97*	ISO
RES 146	*Lepus timidus*	mountain hare	tibia		−20.1	6.3	+10.0	5.9	42.3	15.6	0.34	3.2	332	105	ISO
KOP 165	*Martes martes*	pine marten	humerus		−19.3	8.6	+10.6	4.1	41.0	14.9	0.22	3.2	499	155	SIL
KOP 102	*Vulpes vulpes*	red fox	metacarpal		−16.4	10.7	+9.5	5.7	37.5	13.6	0.26	3.2	389	121	SIL
KOP 151	*Sus scrofa*	pig	calcaneus		−20.8	3.4	+6.6	6.5	38.8	15.2	0.29	3.0	355	119	SIL
KOP 151	*Sus scrofa*	pig	calcaneus		−20.8	3.4	+6.6	6.5	38.8	15.2	0.29	3.0			
KOP 156	*Sus scrofa*	pig	molar tooth		−21.1	4.3	+8.5	6.6	35.1	13.5	0.30	3.0	316	104	SIL
RES 126	*Sus scrofa*	pig	2nd molar tooth		−21.7	7.5	+7.3	5.6	35.9	13.6	0.23	3.1	416	135	ISO
RES 143	*Sus scrofa*	pig	deciduous incisor tooth		−20.9	5.3	+2.1	4.3	42.9	15.4	0.28	3.3	409	126	ISO
KOP 164	*Bos taurus*	cattle	talus	4150±48 (Ua-39360)	−21.9	6.5	+11.0	5.1	39.3	15.4	0.29	3.0	365	123	SIL
KOP 186	*Bos taurus*	cattle	humerus		−21.5	4.4	+10.0	4.2	39.4	14.3	0.23	3.2	466	145	SIL
RES 128	*Bos taurus*	cattle	1st molar tooth		−21.3	7.3	+6.4	2.5	42.2	15.4	0.28	3.2	402	126	ISO
RES 188	*Bos taurus*	cattle	femur	2015±30	−20.9	8.2	+7.3	2.3	42.0	15.9	0.33	3.1	340	110	ISO
RES 182	*Bos taurus*	cattle	tooth	2837±39 (Ua-39361)	−21.3	8.1			41.0	14.8		3.2			
KOP 183	*Ovis/Capra*	sheep/goat	tooth		−21.0	6.7	+8.3	9.5	40.3	15.1	0.30	3.1	357	115	SIL

ID	Species	Common name	Element	Date											Method
RES 127	*Ovis/Capra*	sheep/goat	tibia	270±20	−21.3	9.1	+5.8	1.5	40.7	15.2	0.30	3.1	362	116	ISO
RES 144	*Ovis/Capra*	sheep/goat	radius	3735±35	−19.8	6.5	+8.1	1.0	39.7	14.1	0.25	3.3	424	129	ISO
KOP 106	*Canis familiaris*	dog	humerus		−14.8	14.5	+13.3	7.1	34.2	13.3	0.26	3.0	351	117	SIL
KOP 107	*Canis familiaris*	dog	humerus		−14.2	14.7	+15.7	4.5	40.7	14.8	0.17	3.2	628	196	SIL
KOP 108	*Canis familiaris*	dog	humerus		−14.9	14.4	+15.4	6.9	39.3	15.7	0.21	2.9	500	171	SIL
RES 147	*Canis familiaris*	dog	canine tooth		−13.8	14.5	+13.2	6.0	43.1	15.8	0.28	3.2	411	129	ISO
RES 154	*Canis familiaris*	dog	canine tooth		−19.2	13.1	+7.3	5.0	42.6	15.6	0.30	3.2	380	119	ISO
RES 155	*Canis familiaris*	dog	canine tooth		−13.7	14.4	+12.1	5.9	42.5	15.9	0.30	3.1	378	121	ISO
TOR 030	*Canis familiaris*	dog	tooth	2500±40	−19.7	10.9	+7.7	4.6	40.8	15.9	0.21	3.0	519	174	SIL

Table 3: Human samples from Resmo (RES), Köpingsvik (KOP) and Torsborg (TOR) successfully analysed for δ^{34}S, sorted according to site and individual. Precision for δ^{13}C and δ^{15}N ±0.15‰ or better for all samples (data from Eriksson et al. 2008). Precision for δ^{34}S ±0.3‰ or better at Iso-Analytical (ISO) and ±0.2‰ or better at SIL. NB: Radiocarbon dates are indicated for each individual, not for samples

*= %S or N/S falls within the desired ranges (cf. Nehlich and Richards 2009) when corrected for weighing errors on the analytical balance

¤=%C corrected by a factor of 1.15 because of an elemental analyser error during one run, see Eriksson et al. 2008, 529, table 3, for details

Lab. code	Individual	Age	Element	^{14}C date (uncal BP)	δ^{13}C (‰)	δ^{15}N (‰)	Obs. δ^{34}S (‰)	Est. terr. δ^{34}S (‰)	Marine contr. (%)	% coll.	%C	%N	%S	C/N	C/S	N/S	δ^{34}S lab.
RES 084	Subject 1	adult	M2	4460±45	−18.1	12.5	+10.8	+7.6	43	1.7	43.4	15.9	0.31	3.2	374	117	ISO
RES 148	Subject 1	adult	mandible	4460±45	−18.3	12.4	+10.4	+7.2	41	1.8	40.6	14.9	0.35	3.2	310	97	ISO
RES 004	Subject 2	adult	M1	4500±45	−19.0	11.8	+6.8	+2.7	33	3.1	40.9	15.0	0.13*	3.2	840	264	SIL
RES 003	Subject 2	adult	mandible	4500±45	−18.9	12.3	+10.2	+7.7	35	4.8	41.3	15.4	0.31	3.1	356	114	SIL
RES 008	Subject 3	child	dm1	4030±45	−19.3	12.5	+8.1	+5.2	30	2.6	41.4¤	14.8	0.28	3.3	396	121	SIL
RES 065	Subject 3	child	mandible	4030±45	−19.6	11.3	+9.2	+7.2	27	6.4	40.9	15.5	0.30	3.1	364	118	ISO
RES 088	Subject 6	child	M1	4565±50	−18.8	12.7	+9.9	+7.2	35	2.2	44.4	16.2	0.33	3.2	360	112	ISO
RES 011	Subject 6	child	mandible	4565±50	−18.8	11.7	+10.4	+7.9	36	2.1	40.6	14.4	0.33	3.3	328	100	ISO
RES 090	Subject 8	adult	M1	4455±45	−19.5	12.4	+8.8	+6.4	28	4.7	43.3¤	16.1	0.26	3.1	445	142	SIL
RES 091	Subject 8	adult	M2	4455±45	−18.6	13.0	+9.8	+6.7	38	5.2	42.9	15.7	0.32	3.2	358	112	ISO
RES 022	Subject 8	adult	mandible	4455±45	−18.4	12.5	+10.5	+7.4	40	1.1	36.0	13.2	0.26	3.2	369	116	ISO
RES 153	Subject 9	child	mandible	3965±50	−20.3	12.2	+8.6	+7.1	19	3.7	40.8	15.1	0.34	3.2	320	102	ISO

RES 087	Subject 10	adult	M2	4465±45	−19.1	12.5	+8.4	+5.3	32	6.2	44.1	16.4	0.13*	3.1	906	289	SIL
RES 093	Subject 10	adult	M3	4465±45	−19.4	11.7	+9.6	+7.5	29	4.9	44.9	16.6	0.13*	3.2	922	292	SIL
RES 048	Subject 10	adult	mandible	4465±45	−19.2	11.8	+10.3	+8.2	32	4.2	41.3	15.3	0.21	3.2	525	167	SIL
RES 025	Subject 11	adolescent	mandible	4085±45	−19.0	11.1	+10.9	+8.8	34	2.9	39.3	14.7	0.27	3.1	388	125	ISO
RES 096	Subject 12	adult	M3	3940±45	−17.5	13.3	+12.5	+10.0	50	4.0	42.4	15.4	0.16	3.2	707	220	SIL
RES 044	Subject 12	adult	mandible	3940±45	−18.1	13.0	+13.4	+12.2	44	3.8	39.6	14.9	0.28	3.1	378	122	SIL
RES 130	Subject 13	adult	M2	3480±35	−19.8	10.2	+6.9	+4.2	25	2.7	43.1	15.7	0.32	3.2	360	112	ISO
RES 131	Subject 13	adult	M3	3480±35	−19.6	9.6	+5.1	+1.6	27	6.9	43.5	15.8	0.27	3.2	430	134	ISO
RES 026	Subject 13	adult	mandible	3480±35	−19.6	10.5	+5.4	+1.9	26	5.3	39.8	15.2	0.28	3.1	379	124	ISO
RES 071	Subject 14	adult	mandible	4430±35	−19.1	12.5	+9.9	+7.5	32	2.1	39.9	14.9	0.29	3.1	367	118	ISO
RES 097	Subject 15	adolescent	M1	4055±35	−18.1	14.7	+10.1	+6.3	43	2.1	37.6	14.8	0.28	3.0	358	121	ISO
RES 098	Subject 15	adolescent	M2	4055±35	−18.5	12.3	+10.4	+7.5	39	1.9	37.6	14.7	0.24	3.0	418	140	ISO
RES 132	Subject 15	adolescent	M3 germ	4055±35	−18.9	12.5	+8.8	+5.6	34	2.1	42.3	16.3	0.32	3.0	353	117	SIL
RES 100	Subject 16	adult	M2	4110±35	−20.5	9.9	+6.8	+5.1	17	4.4	41.9	16.0	0.14*	3.1	799	262	SIL
RES 166	Subject 16	adult	mandible	4110±35	−19.3	11.4	+9.6	+7.2	30	0.4	27.6	10.2	0.18	3.2	409	130	ISO
RES 103	Subject 17	adult	M2	3150±30	−19.9	10.0	+6.0	+3.2	23	3.4	40.8	15.6	0.30	3.1	363	119	ISO
RES 049	Subject 17	adult	mandible	3150±30	−19.8	9.7	+6.2	+3.4	25	3.7	41.4	15.0	0.31	3.2	356	111	ISO
RES 105	Subject 18	adult	M1	3060±30	−20.3	9.9	+13.6	+13.2	19	3.8	40.8	15.7	0.29	3.0	375	124	ISO
RES 106	Subject 18	adult	M2	3060±30	−20.8	8.8	+12.8	+12.4	14	4.9	40.9	15.8	0.26	3.0	420	139	ISO
RES 107	Subject 18	adult	M3	3060±30	−19.6	10.5	+9.3	+7.3	26	3.4	40.8	15.7	0.25	3.0	435	144	ISO

RES 033	Subject 18	adult	mandible	3060±30	−19.5	10.6	+9.2	+7.1	27	4.2	41.8	15.3	0.31	3.2	360	113	ISO
RES 108	Subject 19	child	dm1	4160±35	−19.4	13.4	+7.3	+4.1	29	4.8	40.9	15.5	0.30	3.1	365	119	SIL
RES 170	Subject 19	child	mandible	4160±35	−20.7	12.2	+8.8	+7.7	15	3.2	37.7	13.5	0.30	3.3	335	103	ISO
RES 109	Subject 20	adult	M1	3870±35	−18.0	13.2	+12.5	+10.5	44	4.4	41.9	15.7	0.28	3.1	400	128	ISO
RES 110	Subject 20	adult	M2	3870±35	−18.2	14.0	+12.5	+10.7	43	5.4	41.4	15.6	0.31	3.1	357	115	ISO
RES 111	Subject 21	adult	M1	4065±35	−18.7	12.0	+9.5	+6.3	37	3.0	41.5	15.5	0.29	3.1	382	122	ISO
RES 112	Subject 21	adult	M2	4065±35	−20.8	10.8	+11.3	+10.7	14	3.9	43.9	16.6	0.29	3.1	404	131	ISO
RES 052	Subject 21	adult	mandible	4065±35	−18.3	13.0	+10.3	+7.0	42	3.7	40.9	14.5	0.26	3.3	420	128	ISO
RES 175	Subject 22	adult	mandible	2890±40	−19.7	10.4	+11.4	+10.1	26	5.9	42.5	15.4	0.21	3.2	528	164	SIL
RES 114	Subject 23	adult	M1	3245±30	−20.6	9.6	+11.5	+10.9	16	0.9	39.2	14.9	0.29	3.1	361	118	ISO
RES 115	Subject 23	adult	M2	3245±30	−20.0	9.5	+9.6	+8.0	22	3.7	40.7	15.4	0.34	3.1	320	104	ISO
RES 117	Subject 24	adult	M1	2995±30	−20.9	9.2	+10.8	+10.2	12	6.2	41.5	15.7	0.24	3.1	461	149	SIL
RES 248	Subject 24	adult	mandible	2995±30	−21.0	9.4	+10.8	+10.3	11	4.3	41.0	14.8	0.22	3.2	499	155	SIL
RES 039	Subject 25	adult	mandible	3755±35	−17.0	14.1	+11.8	+8.0	55	4.3	42.0	14.5	0.13*	3.4	862	255	SIL
RES 135	Subject 26	adult	M1	3200±35	−19.9	9.7	+5.6	+2.7	24	5.7	41.9	15.6	0.27	3.1	414	132	ISO
RES 136	Subject 26	adult	M2	3200±35	−20.1	9.6	+6.1	+3.7	21	3.0	40.8	15.5	0.28	3.1	389	127	ISO
RES 058	Subject 26	adult	mandible	3200±35	−19.8	9.5	+7.0	+4.4	25	5.5	42.6	15.3	0.31	3.3	367	113	ISO
RES 120	Subject 27	adult	M2	3015±30	−19.9	9.4	+7.7	+5.4	23	1.2	38.6	14.4	0.29	3.1	356	114	ISO
RES 121	Subject 27	adult	M3	3015±30	−20.1	9.6	+7.8	+5.9	21	1.2	39.7	14.6	0.34	3.2	312	98	ISO
RES 078	Subject 27	adult	mandible	3015±30	−19.9	10.0	+8.8	+7.0	23	2.5	42.0	15.0	0.25	3.3	448	137	ISO

RES 122	Subject 28	adult	M1	3350±30	−20.2	9.8	+8.3	+6.5	20	4.7	42.2	15.5	0.28	3.2	403	127	ISO
RES 123	Subject 28	adult	M2	3350±30	−20.1	9.7	+7.7	+5.7	21	4.4	42.3	15.6	0.26	3.2	434	137	ISO
RES 062	Subject 28	adult	mandible	3350±30	−20.0	10.6	+7.9	+5.9	22	6.1	42.4	15.2	0.23	3.3	493	151	ISO
RES 064	Subject 29	adult	mandible	4325±40	−18.3	13.0	+9.6	+5.8	42	5.4	42.9	15.2	0.24	3.3	487	148	SIL
RES 137	Subject 30	adult	M3	3415±35	−19.4	10.3	+7.4	+4.3	29	6.1	41.5	15.7	0.26	3.1	426	138	ISO
RES 042	Subject 30	adult	mandible	3415±35	−20.0	10.3	+8.2	+6.2	22	5.0	40.1	15.4	0.31	3.0	345	114	ISO
RES 163	Subject 31	infant	femur	4534±43 (Ua-48669)	−18.7	13.7	+9.0	+5.5	37	8.6	43.1	16.0	0.33	3.1	349	111	ISO
TOR 19+64	Subject II	adult	M3+I2 root	4205±55	−15.9	14.7	+13.6		68	4.1	40.3	15.2	0.23	3.1	468	151	SIL
TOR 26+63	Subject XIII	juvenile/adult	P2+M1 root	3260±35	−19.6	9.0	+7.8	+5.1	27	2.7	42.0	15.2	0.20	3.2	560	174	SIL
TOR 59+60+73	Subject XVI	adult	P1+C +I2	3190±40	−20.5	8.7	+2.6	+0.1	17	2.3	37.7	12.7	0.26	3.5	387	112	SIL
TOR 57	Subject XXV	child	dm2+M2 germ	3695±40	−20.0	9.9	+8.8	+7.1	22	5.2	41.6	14.4	0.24	3.4	463	137	SIL
KOP 120	Grave 3X	adult	fibula	4385±40	−13.2	16.6	+14.8		98	8.2	42.7	15.8	0.22	3.2	519	165	SIL
KOP 004	Grave Klinta A7	adult	M2	4350±40	−14.3	16.3	+13.9		86	3.5	44.8	15.3	0.34	3.4	352	103	SIL
KOP 007	Grave Klinta A7	adult	mandible	4350±40	−14.8	16.8	+13.8		80	4.7	46.7	15.9	0.30	3.4	416	121	SIL
KOP 021	Subject J	adult	M1	4355±45	−14.9	16.3	+13.3		79	3.4	40.0	13.6	0.29	3.4	368	107	SIL
KOP 065	Subject M	child	maxilla	4055±40	−14.7	16.1	+13.4		81	1.4	43.1	14.7	0.30	3.4	384	112	SIL
KOP 027	Subject P	adult	maxilla	4420±50	−14.3	17.0	+13.7		86	3.5	43.8	14.4	0.32	3.6	365	103	SIL
KOP 054	Subject T	subadult	mandible	3935±45	−14.9	16.8	+15.3		79	1.2	44.4	15.1	0.29	3.4	409	119	SIL

Table 5: Human and faunal samples which fail to meet the quality criteria for sulphur isotope analysis with regard to %S, C/S or N/S (Nehlich and Richards 2009), and are accordingly excluded. None of the samples analysed from the sites of Kalleguta (KAL), Vickleby (VIC) and Algutsrum (ALG), comply with the quality criteria and they are therefore not discussed in the main text

Lab. code	Individual/Species	Age/Common name	Element	δ^{13}C (‰)	δ^{15}N (‰)	δ^{34}S (‰)	% coll.	%C	%N	%S	C/N	C/S	N/S	d34S lab.
ALG 07	subject I	adult	M1	−19.9	9.9	+1.2	3.7	41.8	16.4	0.57	3.0	196	66	SIL
ALG 01	subject I	adult	mandible	−20.5	9.6	+14.4	1.7	40.0	13.8	0.60	3.4	178	53	SIL
ALG 10	subject II	adult	M1	−19.7	8.9	+16.3	2.3	41.3	15.9	0.58	3.0	190	63	SIL
ALG 02	subject II	adult	mandible	−20.4	9.8	+4.5	3.3	40.0	14.4	0.50	3.2	214	66	SIL
ALG 13	subject III	adult	M1	−19.7	9.7	+16.9	4.4	40.9	16.1	0.49	3.0	223	75	SIL
ALG 03	subject III	adult	mandible	−20.0	10.0	+17.5	3.2	42.8	15.9	0.52	3.1	220	70	SIL
ALG 04	Subject IV	child	mandible	−20.2	10.0	+6.2	3.5	43.3	16.2	0.48	3.1	241	77	SIL
ALG 05	Subject V	adult	mandible	−19.7	10.2	+9.4	6.2	40.2	14.5	0.43	3.2	250	77	SIL
ALG 16	Subject VI	adult	M1	−20.4	8.9	+8.4	3.8	40.9	16.0	0.57	3.0	192	64	SIL
ALG 06	Subject VI	adult	mandible	−19.9	9.1	+7.9	7.4	43.1	15.8	0.44	3.2	262	82	SIL
KAL 04+05	(Subject II)	adult	M2+M3	−20.7	8.8	+15.3	2.0	40.8	15.6	0.43	3.1	253	83	SIL
KAL 03	(Subject II)	adult	mandible	−20.9	8.8	+7.7	3.2	41.0	15.6	0.57	3.1	192	63	SIL
KAL 01	Subject I (in situ)	adult	femur	−20.6	8.9	+14.7	2.6	41.9	15.0	0.51	3.3	219	67	SIL
KAL 02	Subject II (in situ)	adult	femur	−20.3	8.9	+10.7	2.7	41.6	15.1	0.53	3.2	210	65	SIL

KOP 10	Grave 1	adult	mandible	−13.8	16.4	+5.7	4.3	48.2	16.0	0.44	3.5	292	83	SIL
KOP 70	Grave 3	child	cranium	−15.5	16.8	+8.7	3.0	44.3	14.6	0.45	3.5	263	74	SIL
KOP 72+73+74	Grave 3	child	dm2+M2 germ	−14.4	16.5	+14.2	4.2	41.8	14.2	0.58	3.4	192	56	SIL
KOP 032	Grave Klinta A5	adult	M1	−13.1	17.1	+11.3	4.8	45.5	14.8	0.40	3.6	304	85	SIL
KOP 035	Grave Klinta A5	adult	mandible	−14.2	16.9	+12.3	2.7	45.5	13.9	0.46	3.8	264	69	SIL
KOP 002	Grave Solberga A11	adult	M3	−14.5	16.7	+11.8	4.2	45.4	15.9	0.79	3.3	153	46	SIL
KOP 084	Grave Solberga A11	adult	mandible	−14.9	16.8	+12.5	2.2	40.7	13.5	0.47	3.5	231	66	SIL
KOP 082	Subject H?	adult	clavicula	−14.8	16.9	+11.8	2.3	36.1	12.4	0.37	3.4	260	77	SIL
KOP 061	Subject K	adult	M2	−13.9	17.7	+10.7	5.0	41.1	14.1	0.40	3.4	274	81	SIL
KOP 015	Subject N	adult	M1	−14.9	16.0	+11.6	4.7	43.2	14.9	0.50	3.4	231	68	SIL
KOP 018	Subject N	adult	mandible	−14.8	16.0	+13.6	7.0	42.1	14.7	0.51	3.3	220	66	SIL
KOP 024	Subject P	adult	P2	−13.3	17.4	+14.7	4.3	40.9	13.1	0.42	3.6	260	71	SIL
KOP 047	Subject Q	adult	M1	−13.5	16.9	+12.0	4.1	39.9	13.3	0.42	3.5	254	72	SIL
KOP 050	Subject Q	adult	mandible	−14.0	17.5	+11.5	1.9	39.6	13.4	0.50	3.4	211	61	SIL
KOP 051	Subject R	adult	mandible	−14.5	17.2	+12.3	4.1	43.6	15.0	0.41	3.4	284	84	SIL
KOP 052	Subject S	adult	mandible	−13.9	17.5	+11.6	3.8	43.0	14.7	0.42	3.4	273	80	SIL
KOP 053	Subject T	subadult	M1	−14.4	16.5	+10.8	5.4	43.1	14.5	0.42	3.5	274	79	SIL
KOP 056	Subject U	child	M1	−14.3	17.4	+12.9	6.2	42.3	14.0	0.43	3.5	263	75	SIL
KOP 055	Subject U	child	mandible	−14.5	18.0	+13.1	4.0	45.3	14.8	0.43	3.6	281	79	SIL

KOP 043	Subject Z	child	cranium	−20.2	14.7	+12.2	3.7	43.3	14.6	0.51	3.5	227	66	SIL
KOP 029	Triple grave skeleton 1	adult	M2	−14.0	16.1	+14.0	5.7	46.4	15.0	0.43	3.6	288	80	SIL
KOP 014	Triple grave skeleton 2	adult	cranium	−14.8	16.2	+13.3	2.5	44.6	14.2	0.23	3.7	518	141	SIL
KOP 013	Triple grave skeleton 2	adult	M3	−14.1	16.0	+3.4	4.7	44.2	15.1	0.48	3.4	246	72	SIL
RES 002	Subject 1	adult	M1	−18.6	12.6	+12.7	1.3	41.5	15.0	0.38	3.2	291	90	ISO
RES 085	Subject 2	adult	M2	−18.8	12.3	+9.5	3.4	38.4	16.2	0.10	3.2	1025	371	SIL
RES 007	Subject 3	child	dm2	−19.4	11.8	+7.5	2.0	42.2	15.8	0.42	3.1	269	86	ISO
RES 006	Subject 3	child	M1	−19.6	11.3	+8.0	3.4	42.9	16.2	0.39	3.1	294	95	ISO
RES 010	Subject 5	adult	mandible	−19.0	12.2	+7.5	1.3	39.4	13.8	0.38	3.3	277	83	ISO
RES 092	Subject 10	adult	M1	−19.8	12.5	+14.5	5.2	43.0	16.1	0.12	3.1	957	307	SIL
RES 094	Subject 12	adult	M1	−19.4	10.5	+11.4	5.5	42.9	15.6	0.11	3.2	1042	325	SIL
RES 095	Subject 12	adult	M2	−20.3	8.8	+10.7	5.9	42.8	15.7	0.08	3.2	1429	449	SIL
RES 165	Subject 15	juvenile	mandible	−18.6	12.0	+10.1	0.7	35.5	12.9	0.34	3.2	279	87	ISO
RES 099	Subject 16	adult	M1	−18.4	12.7	+7.1	4.6	35.5	13.6	0.10	3.0	948	311	SIL
RES 101	Subject 16	adult	M3	−20.5	10.4	+11.8	4.1	40.4	15.7	0.10	3.0	1078	359	SIL
RES 104	Subject 17	adult	M3	−20.0	10.0	+8.5	3.2	41.7	15.7	0.39	3.1	285	92	ISO
RES 169	Subject 20	adult	mandible	−18.0	14.0	+9.4	0.4	33.0	11.7	0.37	3.3	238	72	ISO
RES 113	Subject 22	adult	M1	−20.1	9.1	+9.7	4.6	40.8	15.3	0.08	3.1	1361	438	SIL
RES 053	Subject 22	adult	mandible	−19.7	10.4	+5.7	5.9	42.5	15.4	0.13	3.2	873	271	SIL
RES 116	Subject 23	adult	M3	−20.0	10.6	+7.8	2.3	41.0	15.4	0.38	3.1	288	93	ISO

RES 038	Subject 24	adult	mandible	−21.0	9.4	+8.3	4.3	41.0	14.8	0.12	3.2	913	282	SIL
RES 118	Subject 25	adult	M1	−19.9	11.4	+5.9	2.6	39.7	14.9	0.08	3.1	1326	426	SIL
RES 124	Subject 29	adult	M1	−17.1	14.9	+7.3	3.9	41.3	15.2	0.09	3.2	1226	387	SIL
RES 133	Subject 29	adult	M2	−17.4	14.0	+7.3	5.8	33.2	12.3	0.07	3.1	1267	402	SIL
RES 134	Subject 29	adult	M3	−18.1	13.5	+4.0	4.6	40.7	15.2	0.10	3.1	1086	348	SIL
RES 063	Subject 29	adult	mandible	−18.3	13.0	+6.8	5.4	42.9	15.2	0.10	3.3	1146	348	SIL
TOR 28	(Subject X)	adult	ulna	−18.2	13.1	+5.4	2.9	44.5	15.3	0.60	3.4	198	58	SIL
TOR 07	Subject VII	child	mandible	−20.1	9.5	+9.6	3.2	42.6	15.6	0.65	3.2	175	55	SIL
TOR 11	Subject XI	adult	humerus	−20.1	11.8	+1.2	2.5	34.1	13.5	0.53	2.9	172	58	SIL
TOR 12	Subject XII	child	humerus	−16.3	14.3	+8.3	9.3	43.4	15.9	0.41	3.2	283	89	SIL
TOR 14	Subject XIV	adult	maxilla	−19.8	9.3	+8.0	3.2	41.9	15.8	0.54	3.1	207	67	SIL
TOR 15	Subject XV	juvenile/adult	maxilla	−20.4	8.5	+6.2	3.7	42.1	15.9	0.56	3.1	201	65	SIL
TOR 16	Subject XVI	adult	maxilla	−19.9	9.8	+5.5	3.9	41.8	15.7	0.49	3.1	228	73	SIL
VIC 04+11	Subject I	adult	M1+M2	−20.2	9.1	+5.4	2.9	37.8	16.2	0.52	2.7	194	71	SIL
VIC 07+08	Subject II	adult	M1+M2	−20.3	9.7	+7.0	2.7	40.9	14.7	0.52	3.2	210	65	SIL
VIC 03	Subject III	juvenile	mandible	−20.7	9.5	+7.0	3.9	42.2	15.3	0.51	3.2	221	69	SIL
KOP 129	*Halichoerus grypus*	grey seal	zygomatic	−14.9	13.3	+15.0	6.6	39.3	14.7	0.41	3.1	258	83	SIL
KOP 096	*Phoca groenlandica*	harp seal	temporal	−16.9	13.0	+11.6	3.5	17.8	6.1	0.83	3.4	57	17	SIL
KOP 127	Anatidae	indet. duck	radius	−15.6	16.2	+12.8	3.6	38.3	13.6	0.67	3.3	154	47	SIL
KOP 122	*Phalacrocorax carbo*	great	tarsometatarsus	−13.0	16.4	+15.8	5.4	40.9	14.8	0.38	3.2	285	88	SIL

cormorant

KOP 123	*Tringa nebularia*	common greenshank	humerus	−20.5	9.8	+12.6	4.8	41.6	14.5	0.41	3.3	268	80	SIL
KOP 125	Aves indet.	indet. bird	long bone	−14.6	15.8	+14.4	4.8	41.0	14.7	0.44	3.3	246	76	SIL
KOP 146	*Capreolus capreolus*	roe deer	calcaneus	−23.1	3.8	+10.2	4.7	36.9	13.7	0.38	3.1	257	82	SIL
RES 161	*Lepus timidus*	mountain hare	humerus sin	−22.4	6.2	+9.3	4.2	42.9	15.5	0.48	3.2	238	74	ISO
RES 162	*Lepus timidus*	mountain hare	humerus sin	−21.2	4.9	+9.7	5.7	42.6	15.7	0.41	3.2	278	88	ISO
KOP 118	*Martes martes*	pine marten	maxilla	−17.9	7.9	+15.4	5.1	41.9	15.2	0.55	3.2	203	63	SIL
KOP 155	*Sus scrofa*	pig	3rd molar tooth	−22.0	9.5	+6.9	1.9	34.8	13.6	0.39	3.0	238	80	SIL
TOR 31	*Sus scrofa*	pig	tooth	−22.0	6.3	+6.3	7.6	41.5	16.1	0.48	3.0	231	77	SIL
TOR 32	*Sus scrofa*	pig	tooth	−22.1	6.5	+4.0	4.4	40.1	16.1	0.47	2.9	228	78	SIL
RES 158	*Ovis/Capra*	sheep/goat	vertebra	−20.1	6.2	+7.8	4.4	42.4	16.1	0.44	3.1	258	84	ISO
TOR 34	*Ovis/Capra*	sheep/goat	long bone	−22.5	5.6	+8.3	3.6	38.8	15.5	0.50	2.9	207	71	SIL
RES 160	*Canis familiaris*	dog	metacarpal	−20.2	9.7	+7.2	3.7	42.3	15.5	0.45	3.2	251	79	ISO
TOR 33	*Canis familiaris*	dog	mandible	−19.9	8.7	+7.7	6.2	38.9	15.7	0.45	2.9	231	80	SIL
KOP 115	Indet.	indet. (human?)	fibula?	−14.9	16.9	+14.0	4.7	39.0	15.0	0.30	3.0	348	115	SIL