Identifying mobility in populations with mixed marine/terrestrial diets: Strontium isotope analysis of skeletal material from a passage grave in Resmo, Öland, Sweden

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Abstract

Strontium isotope analysis of skeletal material as a means to reconstruct prehistoric residential patterns has previously mainly been applied to populations with terrestrial diets. Here we present a model for populations with mixed marine/terrestrial diets, which is based on two-component mixing of strontium isotopes. Applying this model, we can estimate the original strontium isotope value of the terrestrial component of the diet. Accordingly it is possible to identify non-local individuals even if they had a mixed marine/terrestrial diet. The model is applied to tooth enamel samples representing nine individuals recovered from a passage grave in Resmo, on the island of Öland in the Baltic Sea, where at least five non-local individuals, representing at least two different geographical regions of origin, were identified. Non-local individuals were more frequent during the Bronze Age than during previous phases.

Keywords: Bronze Age, Neolithic, Öland, strontium isotopes, model, mobility, mixed marine/terrestrial diet

1. Introduction

Strontium isotope analysis of skeletal material has become a primary technique for the identification of non-local individuals in archaeological populations (Bentley et al. 2003; Bentley 2006; Cox and Sealy 1997; Price et al. 2001, Montgomery et al. 2007, Oelze et al. 2012; Ericson 1985; Grupe et al. 1997;). So far, most applications comprise populations where the diet is assumed to be terrestrial, and where non-local individuals therefore can be identified by comparison with the isotopic composition of local sources for bio-available strontium, such as plants and animals. However, when dealing with individuals known to have exploited both terrestrial and marine resources, the mixed sources of strontium will result in mixed isotopic ratios. In these cases, we need a model to identify non-local strontium values. Here, we elaborate and test such a model and evaluate the potential of strontium isotopes in reconstructing mobility patterns in populations with mixed diets, using an archaeological material from a passage grave in Resmo on the island of Öland in the Baltic Sea.

2. Background

2.1 Strontium isotope analysis

Strontium has four naturally occurring isotopes: ^{88}Sr, ^{87}Sr, ^{86}Sr and ^{84}Sr, where radiogenic ^{87}Sr is formed through the process of β-decay of ^{87}Rb (Rubidium, half-life 4.88×10^{10} years). The $^{87}Sr/^{86}Sr$ ratio in the bedrock varies depending on the age and the initial Rb/Sr ratio of the rock, and generally range between 0.702 and 0.750 (Bentley 2006; Faure and Mensing 2005:75ff). Low-

Ca granites of considerable age display the highest ratios, whereas lower ratios can be found in younger basaltic and carbonate rocks (Bentley 2006; Faure and Mensing 2005:75ff).

Present-day oceanic water has a very uniform $^{87}Sr/^{86}Sr$ ratio of 0.7092, because the residence time of Sr is significantly longer compared to the mixing time of the ocean (Faure and Mensing 2005:436–437). In the Baltic Sea, with a substantial freshwater inflow, the $^{87}Sr/^{86}Sr$ ratio is affected by the diverse bedrock exposed to weathering in the drainage basin. Rivers draining the Precambrian rocks of the Baltic shield have $^{87}Sr/^{86}Sr$ ratios between c. 0.718 and 0.745, whereas rivers draining the Phanerozoic formations in the south and southeast average 0.710. The $^{87}Sr/^{86}Sr$ ratios in the present day Baltic Sea range between c. 0.7092 and 0.7097, with values increasing towards the north (Andersson et al. 1992; Löfvendahl et al. 1990).

Strontium is incorporated into the food chain from the weathering of bedrock via soil- and groundwater (Åberg 1995; Capo et al. 1998). Fractionation of the isotopic composition of strontium by biological processes is negligible compared to the large effect of radioactive decay on the $^{87}Sr/^{86}Sr$ ratio (Blum et al. 2000). Thus the strontium isotope ratios in plants and animals reflect the composition of the local bedrock. Therefore, the $^{87}Sr/^{86}Sr$ ratio in human tooth enamel can provide information on residence and mobility. It is incorporated into the bioapatite of bone and teeth, where it substitutes for Ca (Elias et al. 1982). Since essentially no *in vivo* remodeling occurs in enamel (Hillson 1996) the $^{87}Sr/^{86}Sr$ ratio represents the isotopic composition at the time of enamel formation. Migration during the early stages of life of an individual could thus be traced through analysing the isotopic composition in a sequence of tooth samples. Although strontium isotopic ratios in the local environment can display considerable variation within plants and, more notably, soils, this variability is evened out in animal populations (e.g. Ezzo et al. 1997, Price et al. 2002). An average of the isotopic composition of the biologically available strontium in a region can thus be estimated from analyses of the local fauna. Fossil samples are preferred, but modern snail shells have been used in establishing the isotopic ratio of bio-available strontium (Price et al. 2001). However, if modern animals are used, there is always a concern for potential contamination from pollution and imported food (Price et al. 2002).

2.2 Archaeological setting

The Baltic Sea is an intra-continental, brackish system with a complex Holocene history of alternating saline and freshwater stages, of which the brackish Litorina stage (c. 6500 BC to the present) is of relevance in this study. The Baltic Sea is divided into three sub-basins, where the island of Öland is located in the southernmost basin, the Baltic Proper.

The Baltic Sea drainage basin includes various geological settings, with Precambrian basement rocks covering most of the Finnish and Swedish mainlands, and predominantly Phanerozoic sedimentary rocks in the south and southeast. Overall the present day drainage basin is composed of about 55% Phanerozoic sedimentary bedrock, while Precambrian crystalline basement dominates to the west, east and north.

The island of Öland is located about 10 km east of the Swedish mainland in the Baltic Sea. The bedrock is dominated by Ordovician limestone, but also includes Cambrian and Ordovician shales, with an age of about 450 to 500 Ma (Loberg 1999) (Fig. 1). The mainland west of Öland is dominated by granites formed around 1800 Ma. The archaeological material studied originates from a passage grave situated in Resmo on the south-western coast of Öland (Fig. 1). Stable carbon and nitrogen isotopic data on a radiocarbon dated skeletal material from Resmo has provided evidence for three phases of use. The first phase, c. 3500-2900 BC, can be attributed to the TRB presence on the island, and the diet during this period was characterized by a mixture of marine and terrestrial protein sources. During the following phase, c. 2900-1900 BC, the dietary components were 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. Several subjects from this phase have experienced dietary changes during the course of life. 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).

2.3 Modelling $^{87}Sr/^{86}Sr$ ratios in populations with mixed diets

Here we present a two-component mixing model, taking into account both the local terrestrial strontium isotope range and the corresponding marine range. The model is based on a known marine dietary contribution, as derived from stable carbon and nitrogen isotope data, and also accounts for biopurification of strontium. Existing stable-isotope mixing models generally deal with "too much variation" (e.g. Parnell et al. 2010), but in our model only one of the strontium sources display any considerable variation, whereas the other is roughly constant.

Due to the fact that the analysed population has used both marine and terrestrial resources, it is necessary to establish two local $^{87}Sr/^{86}Sr$ ranges – one terrestrial and one marine. Price et al. (2002) suggested that the mean ±2 s.d. of (preferably fossil) local animal tooth samples should be used as a representative for local biologically available strontium isotopic ratios. Here, we have analysed faunal bone samples from local archaeological contexts, together with modern terrestrial snail shells, and marine mollusc shells from the literature (Widerlund and Andersson 2011).

The previously published $\delta^{13}C$ and $\delta^{15}N$ data from the Resmo individuals indicate a two-component diet comprised of varied proportions of terrestrial herbivores and marine mammals (Fig. 2). The various contributions of marine and terrestrial protein to the diet of each human individual, can be calculated as a percentage using $\delta^{13}C$ (Eriksson et al. 2008), where the marine end member value, –15‰, represents the mean for marine mammal fauna, whereas a terrestrial end member value of –21‰ represents the mean for wild terrestrial herbivores. The estimated end member values include a +1‰ correction for trophic level $\delta^{13}C$ fractionation (Schoeninger and DeNiro 1984). One should of course keep in mind that the $\delta^{13}C$ data is derived from bone collagen, thus reflecting the protein intake, whereas Sr isotopic analyses on bioapatite reflect the entire diet. Plant products will therefore tend to be under-represented in the carbon isotope data.

Through the process of biopurification, the Sr/Ca ratio in skeletal tissues decreases up the food chain by on average about a factor of five per trophic level (Bentley 2006; Elias et al. 1982). This factor is an estimate, and the extent of the Sr/Ca fractionation is somewhat uncertain. Due to the long residence time of Sr, seawater has a high concentration of Sr, yielding correspondingly high Sr/Ca ratios in marine organisms at low trophic levels. However, due to the length of the food chains, marine mammals exhibit Sr/Ca ratios comparable to those of terrestrial carnivores (Burton and Price 1999), thus much lower than terrestrial herbivores. As a result, the terrestrial dietary components could hypothetically contribute up to approximately five times more Sr to the human diet than the marine ones. When taking this biopurification process into account, the $^{87}Sr/^{86}Sr$ ratio in human skeletal tissue will be dependent on (1) the strontium isotopic ratios of the different dietary components, (2) the relative contributions of these components to the total diet, and (3) the different concentrations of Sr in the dietary components.

If we assume that the Sr isotopes are derived from two sources with different isotopic composition we can treat the analysed samples as a two-component mixing. A mixture of two components, A and B, each with different isotopic compositions but equal concentrations of strontium, yields a straight line in a mixing diagram. However, when the concentrations of strontium are different in component A and B, as is suggested to be the case for terrestrial herbivores relative to marine mammals, the mixing line will be represented by a hyperbola.

Since the $^{87}Sr/^{86}Sr$ ratio of the marine dietary end-member is uniform, and the proportions of marine *vs* terrestrial protein in the diet are known parameters, we can calculate the contribution and the mean isotopic composition of the terrestrial strontium for each sample. If assuming a 1:1 Sr contribution between terrestrial and marine food sources, the equation for estimating the average $^{87}Sr/^{86}Sr$ ratio of the terrestrial food sources (R_t) is:

$$R_t = R_s + (R_s - R_m)/(1 - C_m) \times C_m \quad \text{[Equation 1]}$$

Where R_s is the observed $^{87}Sr/^{86}Sr$ ratio of the measured sample, R_m is the average local marine $^{87}Sr/^{86}Sr$ ratio, and C_m is the proportion of marine components in the diet. However, if assuming a 5:1 Sr contribution between the two food sources, the equation for estimating R_t is:

$$R_t = R_s + (R_s - R_m)/(1 - C_m) \times 0.2C_m/(1 - 0.8C_m) \quad \text{[Equation 2]}$$

We consequently assume that the contributions of Sr from terrestrial food sources on the one hand, and marine food sources on the other, are somewhere in the range between the extremes 1:1 (Eq. 1) and 5:1 (Eq. 2).

Using this model, we can thus estimate the original strontium isotope value of the terrestrial component of the diet. Accordingly it is possible to identify non-local individuals even if they had a mixed marine/terrestrial diet.

3. Material and methods

3.1 Human samples

We analysed tooth enamel of the first molar (M_1), with mineralization initiated around birth and continuing up to an age of ~3-4 years, from nine Resmo individuals, three from each chronological phase (Table 1). The analysed population includes two individuals (subj. 12 and 16), where substantial intra-individual dietary changes have previously been identified, both from the second phase. For these individuals also the second molar (M_2), representing the period between ~2.5 and 6-8 years, was analysed (ages from Hillson 1996:188pp.).

3.2 Faunal reference samples

In order to establish the local terrestrial isotopic range for bio-available strontium on Öland, we included six faunal bone and tooth samples, originating from Resmo and from the Neolithic site Köpingsvik (Fig. 1) on Öland. The terrestrial species included are mountain hare (*Lepus timidus*, n=3), wild boar (*Sus scrofa*, n=2), and roe deer (*Capreolus capreolus*, n=1). Further, we analysed shells from four modern specimen of the land-living white-lipped snail (*Cepaea hortensis*, n=4), collected on uncultivated locations (avoiding contamination from modern fertilizers) in the vicinities of Köpingsvik and Resmo. The $^{87}Sr/^{86}Sr$ ratio for bio-available strontium in the Baltic Sea during the period in question is estimated from previously published prehistoric marine mollusc shells, where 22 shell samples (*Mytilus edulis, Cerastoderma* sp. and *Macoma baltica*) originating from the Baltic Proper and radiocarbon dated to the Neolithic or Bronze Age were included, taking into consideration both the spatial and time dependent variations in the Baltic Sea (Widerlund and Andersson 2011). Further, three marine mammal bone samples of harp seal (*Phoca groenlandica*, n=2) and ringed seal (*Pusa hispida*, n=1) were included.

3.3 Laboratory procedures

Sample preparations were performed at the Archaeological Research Laboratory, Stockholm University, and at the Laboratory for Isotope Geology (LIG), Swedish Museum of Natural History. Mass spectrometry was conducted at LIG. Bone and tooth samples were ultrasonically pre-cleaned in de-ionized water, and the outermost surface of the samples was mechanically removed to a depth of >0.5 mm for bone and >100 μm for enamel. Approximately 10-20 mg of

bone powder and enamel was obtained through drilling and by means of a disc saw, respectively. Enamel samples were taken c. 2 mm above the cervix, and any adhesive dentine was mechanically removed. The samples were ashed (Grupe et al. 1997; Price et al. 2001) in a muffle furnace at 500°C for 12 h, and the enamel chunks were subsequently pulverized in an agate mortar. The ashed samples were transferred to acid cleaned 15 ml Teflon® vials and dissolved in 4 ml 5 M HNO_3 (all reagents used are Suprapur®), evaporated on a hot plate, and redissolved in 1 ml 6 M HCl. Shell samples of approximately 1-3 mg were sawed out, dissolved in 2.5 ml 1 M acetic acid, centrifuged to separate remnants of silicate and organic material, and evaporated on a hot plate. A few drops of concentrated HNO_3 were added and evaporated in order to dissolve residual particles. The samples were then redissolved in 2 ml 6 M HCl. Strontium was isolated through cation exchange procedures, and samples were mixed with a tantalum activator and loaded onto single Rhenium filaments (Widerlund and Andersson 2006).

The Sr isotopic composition was analysed using thermal ionization mass spectrometry, TIMS, on a Thermo Scientific TRITON® in multiple collector mode. The measured ^{87}Sr intensities were corrected for Rb interference assuming $^{87}Rb/^{85}Rb = 0.38600$. The $^{87}Sr/^{86}Sr$ ratios were reduced assuming exponential fractionation and normalized to $^{88}Sr/^{86}Sr = 8.375209$. Repeated analysis during the course of this work of the standard, SRM 987, gave an $^{87}Sr/^{86}Sr$ ratio of 0.710223±0.000011 (2 s.d., n=10). The reproducibility of the SRM 987 standard was used as the error for the reported samples except if the internal error, $2\sigma_{mean}$, was larger.

4. Results

Results are presented in Tables 1–2 and Fig. 3.

Terrestrial fauna

Terrestrial faunal samples display a range of isotopic compositions from 0.7122 to 0.7174 (mean ± 1s.d. = 0.7144±0.0019, n=6). The highest value, 0.7174, represents a pig from Resmo, and is surprisingly high considering the geology of Öland; it is therefore likely to be domestic and brought into the region by human agency. To import or seasonally move domestic animals into Öland is a rather unproblematic enterprise given the proximity to the mainland. In a study on stable sulphur isotopes, where reference data from wild fauna is more abundant, we have identified a group of samples from domestic animals displaying values deviating from the predicted local range (Linderholm et al., ms.). The specimen with a high $^{87}Sr/^{86}Sr$ ratio can be found within this group. Since both sulphur and strontium isotope data for the sample deviate from wild fauna, we conclude that the animal has probably subsisted on non-local food sources. If excluding this sample, terrestrial faunal values range from 0.7122 to 0.7155 (mean 0.7138±0.0012, n=5). The second analysed pig, originating from Köpingsvik, is interpreted as wild on the basis of stable isotope data (Eriksson et al. 2008; Fornander et al. 2008) and is considered to represent local values. The $^{87}Sr/^{86}Sr$ ratio for this sample falls within the range of the remaining local fauna. The snail shells have $^{87}Sr/^{86}Sr$ values between 0.7109 and 0.7134 (mean 0.7121±0.0010, n=4).

When combining the local terrestrial faunal bone and tooth samples (see above), with data from the shells, the mean $^{87}Sr/^{86}Sr$ value ± 2 s.d. yields a range between 0.7102 and 0.7158 (n=9). Although this estimated range is rather wide, it is in line with what can be expected to be found on Öland, where the Phanerozoic sedimentary rocks are primarily composed of limestone and are covered by sedimentary glacial and postglacial soils partly originating from crystalline mainland regions.

Marine fauna

The $^{87}Sr/^{86}Sr$ ratios for marine mollusc shells (n=22) range from 0.7092 to 0.7096, with a mean of 0.7093±0.00009 (Widerlund and Andersson 2011). The seal bones appear to have elevated $^{87}Sr/^{86}Sr$ ratios, 0.7106–0.7111, compared to the marine molluscs, possibly indicating diagenetic alteration towards the local terrestrial values. They have therefore been excluded from estimation of the local marine range. Accordingly, the estimated marine $^{87}Sr/^{86}Sr$ ratio for Neolithic marine fauna is in the range 0.7091-0.7095.

Human data

The human samples from Resmo display a range in $^{87}Sr/^{86}Sr$ ratios from 0.7106 to 0.7257 (mean 0.7161±0.0047, n=11). Isotopic ratios for the individuals from the first phase range 0.7128-0.7154. In contrast, considerable variation in the $^{87}Sr/^{86}Sr$ ratios can be seen in subjects dated to the second phase, 0.7106-0.7257. The highest values, 0.7257 (M_1) and 0.7232 (M_2), are displayed by subject 16, whereas subject 12 represent the lowest isotopic ratios, 0.7111 (M_1) and 0.7106 (M_2). Samples from phase three, the Bronze Age, display $^{87}Sr/^{86}Sr$ ratios ranging from 0.7149 to 0.7176. During the third phase, we consequently see approximately the same range of variation in $^{87}Sr/^{86}Sr$ ratios as during phase one, although with higher absolute values.

5. Discussion

Strontium contamination of archaeological bone can be caused by penetrating groundwater. Since enamel is denser than bone, it is considered less susceptible to diagenesis and contamination (Budd et al. 2000; Koch et al. 1997; Kohn et al. 1999). Strontium isotopic data from archaeological bone should thus be regarded with caution, and enamel samples are preferred (Price et al. 2002). Available dental faunal remains are sparse in the Öland material, and therefore we have included bone samples from the assumed local terrestrial and marine fauna in this study. Since contaminants will reflect the $^{87}Sr/^{86}Sr$ ratio of the local geology (Grupe et al. 1997), a local isotopic range for biologically available strontium can be derived from bone samples of local fauna despite the contamination problems. The available data provide ranges for $^{87}Sr/^{86}Sr$ ratios that can be expected in local individuals on Öland, although we admit that the faunal dataset is modest. The two lowest measured ratios are represented by snails. According to Evans et al. (2009), snails may exhibit rainwater/seawater muted signals, particularly in high-rainfall maritime regions, due to the large amount of liquid needed for production of slime. However, the annual precipitation on Öland is one of the lowest in Sweden, why it is questionable whether such muted signals are present among the samples analysed in this study.

Fig. 4 and Table 3 show the observed $^{87}Sr/^{86}Sr$ ratios versus the approximated contributions of marine dietary protein. The predicted local range for bioavailable terrestrial strontium on Öland is marked, along with the predicted marine $^{87}Sr/^{86}Sr$ ratios in the Neolithic Baltic Sea. Since there is a decline in Sr/Ca ratios caused by biopurification, the impact of terrestrial food sources can be over-emphasized in human samples displaying mixed dietary signals. Therefore, two predicted ranges for local values are considered, one assuming a 1:1 (the straight mixing line) and a second assuming a 5:1 (the hyperbolic mixing curve) contribution between terrestrial and marine food sources. Observed values falling outside both ranges are likely to represent a non-local origin, whereas observed values falling within the second, but outside the first, range, are considered inconclusive as regards local or non-local origins. Based on this (Fig. 4), four individuals are clearly outside the predicted local ranges, namely Subjects 16 (represented by two data points, both outside the ranges), 18, 24 and 29, thus indicating a non-local origin. Subjects 2, 6 and 12 (represented by two data points, both inside the ranges) fall within the predicted local range, whereas Subject 15 and 28 fall within the inconclusive range. The non-local individuals increase over time, from one in the first phase, and at least one in the second phase, to at least two in the third phase.

A key issue concerns to what extent changes in observed $^{87}Sr/^{86}Sr$ ratios result from intra-individual variations in the proportions of marine *vs.* terrestrial food sources, or from change of residence. The next step in applying the model is therefore to estimate the original $^{87}Sr/^{86}Sr$ values of the terrestrial dietary component (R_t) for individuals with mixed marine/terrestrial diet. This estimation will be expressed as a span with a maximum and a minimum value, owing to the biopurification process. For samples with both high marine dietary input and$^{87}Sr/^{86}Sr$ ratios outside the local range, there is a relatively larger span than for other samples, as evident in Fig. 5. In contrast to Fig. 4, this graph describes only the terrestrial part of the diet, which means that for individuals with an almost entirely terrestrial diet, such as Subject 24, the estimated and the observed values are in close agreement. The estimated values can also be used to exclude potential sources of bioavailable strontium from various other geographical areas. The most obvious consequences of this estimation concerns Subject 29, where the observed value is seemingly within the local terrestrial range, but when taking into account the 55% marine dietary contribution, the estimated terrestrial strontium isotope ratio is clearly non-local (this was visible also using the mixing lines, Fig. 4). The interpretation of Subject 29 as representing a non-local origin is further strengthened by intra-individual stable sulphur isotope data, implying a mobile lifestyle with at least one change of residence during the course of life (Linderholm et al., ms.). For Subject 15, with a similar observed value, it was not possible to determine if this individual was non-local or not, from the mixing lines alone (Fig. 4). However, using the model, which estimates the original terrestrial strontium isotope ratio, it is obvious that this is a non-local individual too (Fig. 5), whereas the origin of Subject 28 remains inconclusive.

Some interesting observations regarding chronological patterns can be made from Fig. 5. Apparently, the two earliest individuals display possibly local isotopic ratios, whereas the following three individuals are clearly non-local, although Subject 16 shows clear evidence of change in strontium sources during childhood. These non-local samples further seem to represent at least two different regions of origin. Subject 12, which is also Neolithic, does show a change in strontium sources during childhood, but this change possibly took place within the island, since both the estimated values fall within the local terrestrial range. Among the Bronze Age individuals, only one out of three displays possibly local isotopic values, and the two non-local samples could represent the same region of origin.

This model deals with populations utilizing both marine and terrestrial resources, enabling identification of non-local individuals and estimation of non-local strontium sources. Although a model always includes uncertainties, the simplicity of the present model makes it easy both to apply and to comprehend.

6. Conclusion

We have used a two end-member mixing model to evaluate strontium isotopic data in populations with mixed marine/terrestrial diets. The presented model for estimating the $^{87}Sr/^{86}Sr$ ratio of the terrestrial dietary components have enabled identification of non-local individuals in the Resmo population, as well as estimated $^{87}Sr/^{86}Sr$ ratios of their respective source regions. Among the nine subjects included in this study, at least five have been identified as non-local, representing at least two geologically different regions. Based on the limited data presented here, the frequency of non-locals increased during the Bronze Age, as compared to the Neolithic. This study emphasizes the importance of including stable isotope analyses when approaching $^{87}Sr/^{86}Sr$ in coastal populations, where the diet potentially has been derived from mixed marine and terrestrial sources.

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Figures

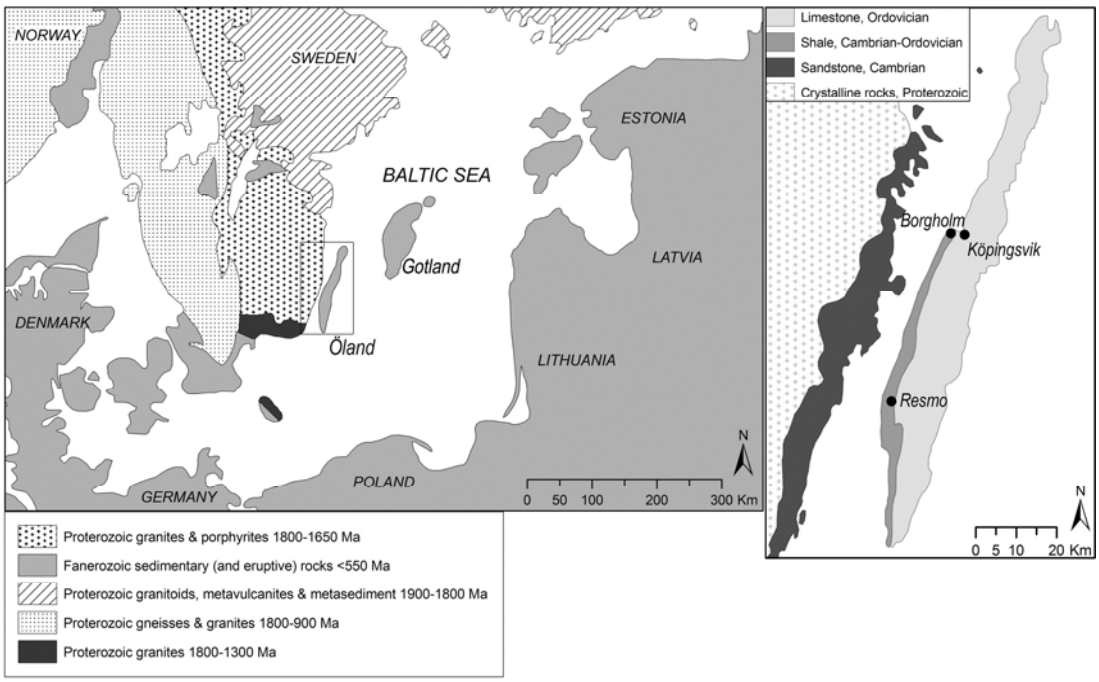

Fig. 1. The geology of the Baltic Sea region and Öland, indicating sites mentioned in the text. Revised after Loberg 1999:386.

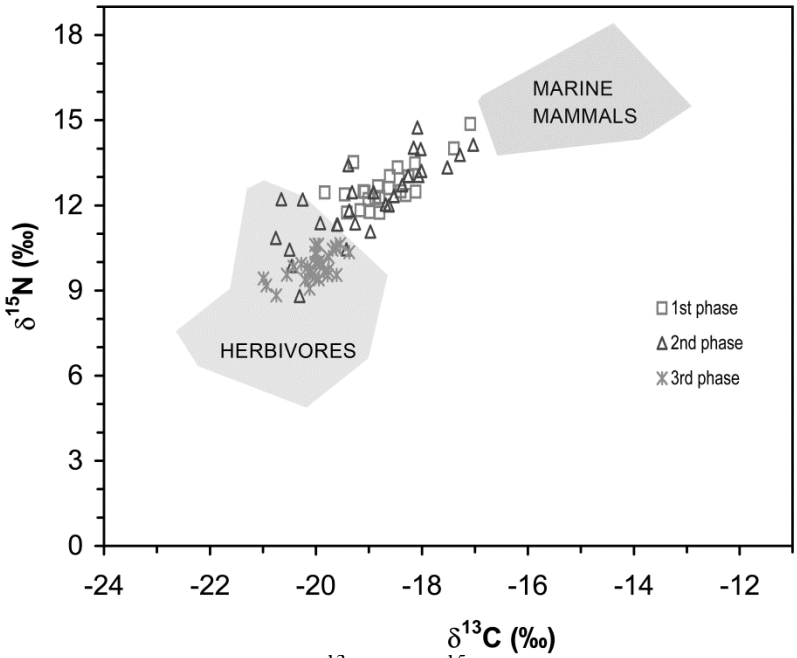

Fig. 2. Human collagen $\delta^{13}C$ and $\delta^{15}N$ values for the the Resmo population (30 individuals, 84 samples), and predicted isotopic ranges for humans subsisting on herbivores or marine mammals (data from Eriksson et al., 2008). Human data indicate a predominantly two-component diet comprised of terrestrial herbivores and marine mammals.

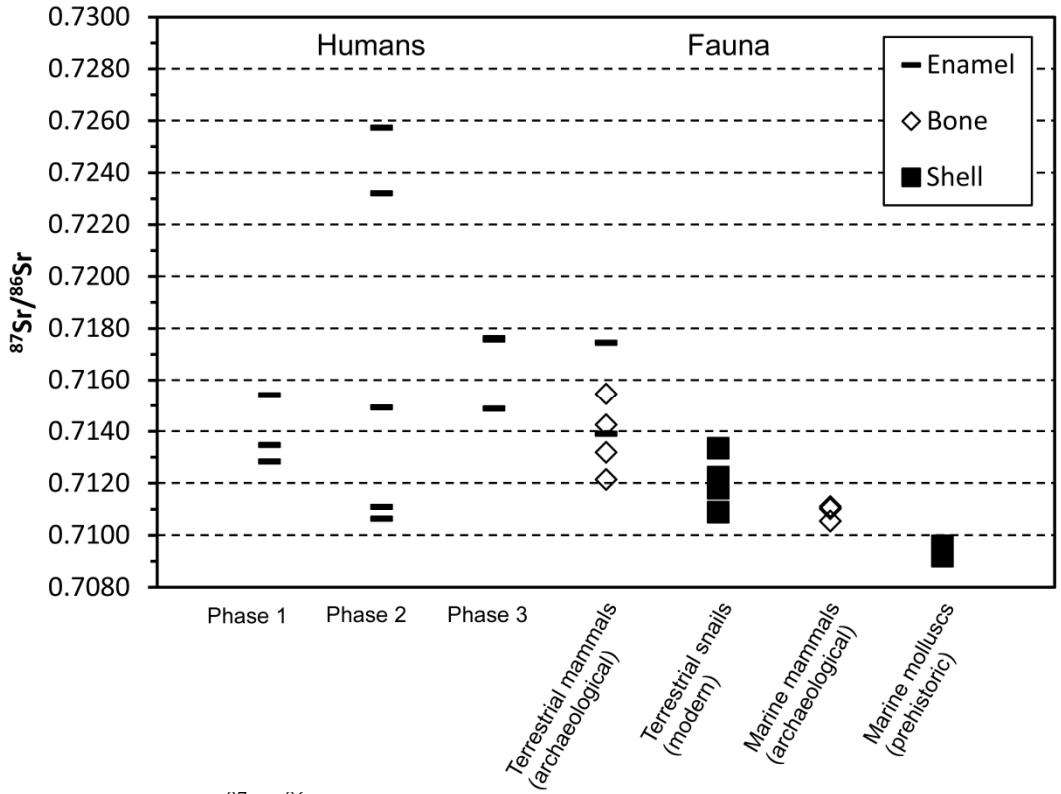

Fig. 3. Measured $^{87}Sr/^{86}Sr$ ratios for human (enamel bioapatite) and faunal samples (enamel, bone, shell) from Öland. Marine mollusc data from Widerlund and Andersson 2011.

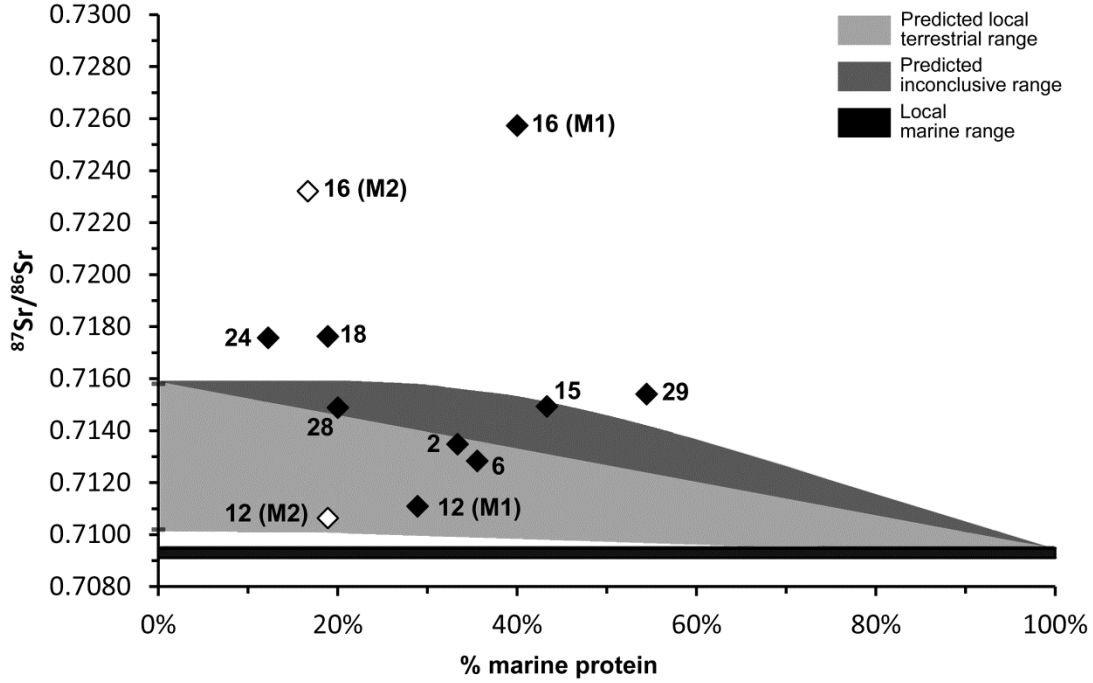

Fig. 4. Observed 87Sr/86Sr ratios for human samples, plotted against proportions of marine protein in the diet based on δ13C data. The shaded areas represent two predicted ranges for local terrestrial values. Based on differences in strontium concentration caused by biopurification, one range assumes a 1:1 (light grey) and a second assuming a 5:1 (dark grey) contribution of strontium between terrestrial and marine food sources. Observed values falling outside both ranges are likely to represent a non-local origin, whereas observed values falling within the second, but outside the first, range, are considered inconclusive as regards local or non-local origins.

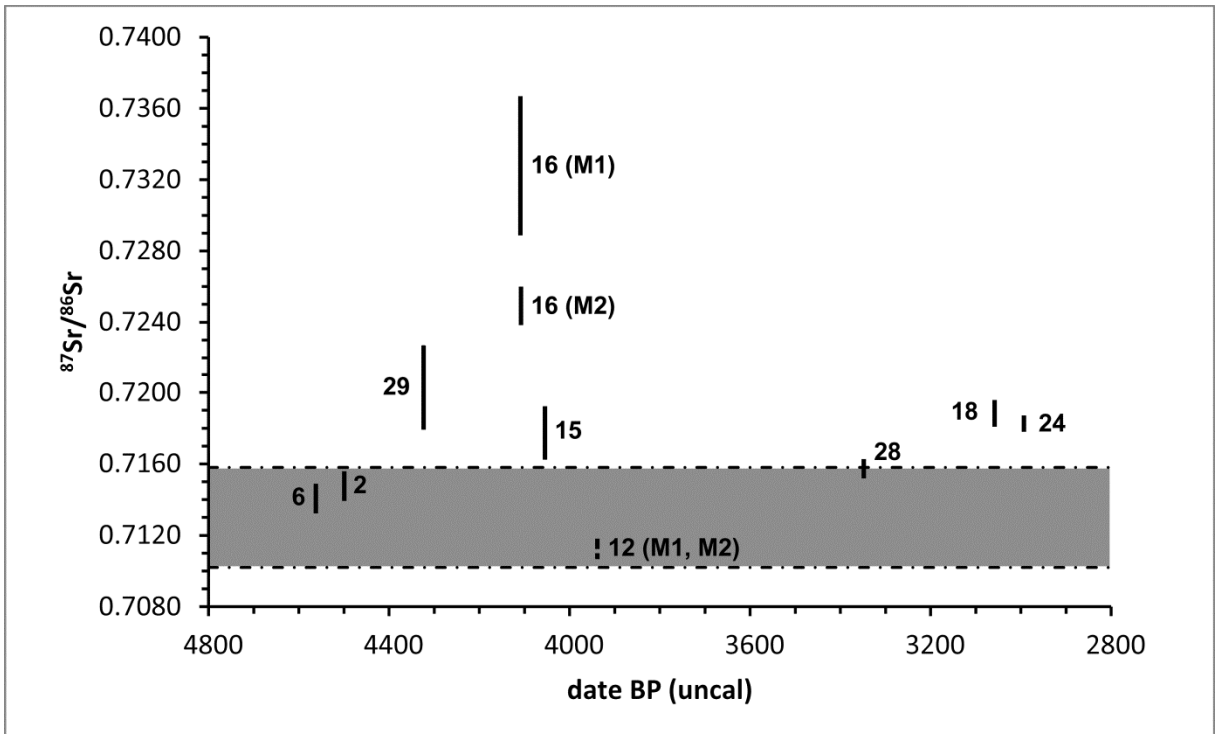

Fig. 5. Estimated $^{87}Sr/^{86}Sr$ (R_t) of the terrestrial food components for each sample plotted against radiocarbon date. The estimated ratio is expressed as a span with a maximum and a minimum value, owing to the biopurification process.

Tables

Table 1. Radiocarbon dates together with $^{87}Sr/^{86}Sr$, $\delta^{13}C$ and $\delta^{15}N$ data for the Resmo humans included in this study (^{14}C, $\delta^{13}C$ and $\delta^{15}N$ data from Eriksson et al. 2008). The error for $^{87}Sr/^{86}Sr$ is 0.00002, and the error for $\delta^{13}C$ and $\delta^{15}N$ is 0.15‰.

	Individual	Element	Enamel $^{87}Sr/^{86}Sr$	Dentine collagen $\delta^{13}C$ (‰)	Dentine collagen $\delta^{15}N$ (‰)	^{14}C age (BP)
Phase 1	Subject 2	M1 tooth	0.71348	–18.9	11.7	4500±45
	Subject 6	M1 tooth	0.71284	–18.8	12.7	4565±50
	Subject 29	M1 tooth	0.71542	–17.1	14.9	4325±40
Phase 2	Subject 12	M1 tooth	0.71109	–19.4	10.5	3940±45
	Subject 12	M2 tooth	0.71064	–20.3	8.8	3940±45
	Subject 15	M1 tooth	0.71493	–18.1	14.7	4055±35
	Subject 16	M1 tooth	0.72573	–18.4	12.7	4110±35
	Subject 16	M2 tooth	0.72321	–20.5	9.9	4110±35
Phase 1	Subject 18	M1 tooth	0.71763	–20.3	9.9	3060±30
	Subject 24	M1 tooth	0.71757	–20.9	9.2	2995±30
	Subject 28	M1 tooth	0.71489	–20.2	9.8	3350±30

Table 2. $^{87}Sr/^{86}Sr$ (enamel/bone bioapatite, carbonate shells) and $\delta^{13}C$ and $\delta^{15}N$ (bone/dentine collagen) data for faunal samples (stable isotope data from Eriksson et al. 2008). The error for $^{87}Sr/^{86}Sr$ is 0.00002, and the error for $\delta^{13}C$ and $\delta^{15}N$ is 0.15‰. RES/ShRES=Resmo, KOP=Köpingsvik, ShBOR=Borgholm.

Sample ID	Species	Element	Bone/enamel / shell $^{87}Sr/^{86}Sr$	Bone/dentine collagen $\delta^{13}C$ (‰)	Bone/dentine collagen $\delta^{15}N$ (‰)
RES 125	Lepus timidus	femur	0.71215	–21.8	7.4
RES 161	Lepus timidus	humerus	0.71426	–22.4	6.2
RES 162	Lepus timidus	humerus	0.71546	–21.2	4.9
KOP 116	Capr. capreolus	phalanx	0.71319	–23.4	4.5
KOP 156	Sus scrofa	molar tooth	0.71391	–21.1	4.3
RES 126	Sus scrofa	M2 tooth	0.71744	–21.7	7.5
ShBOR 01	Cepaea hortensis	shell	0.71181	–	–
ShBOR 02	Cepaea hortensis	shell	0.71335	–	–
ShRES 01	Cepaea hortensis	shell	0.71224	–	–
ShRES 02	Cepaea hortensis	shell	0.71089	–	–
KOP 093	P. groenlandica	femur	0.71110	–16.0	13.3
KOP 096	P. groenlandica	temporal	0.71102	–16.9	13.0
KOP 180	Pusa hispida	humerus	0.71055	–17.4	11.2

Table 3. Estimated $^{87}Sr/^{86}Sr$ ratios of the terrestrial food components (R_t) for the Resmo human enamel samples, calculated using Equations 1 and 2 of the model, and assuming a marine $^{87}Sr/^{86}Sr$ end value (R_m) of 0.70932. The proportions of marine protein in the diet (C_m) are calculated using dentine collagen $\delta^{13}C$ data from each tooth (Eriksson et al. 2008).

	Individual	Tooth	Observed $^{87}Sr/^{86}Sr$ (R_s)	$\delta^{13}C$ (‰)	Marine contribution to diet (C_m)	Estimated $^{87}Sr/^{86}Sr$ of terrestrial food components (R_t)
Phase 1	Subject 2	M1	0.71348	–19.0	33.3%	0.7140–0.7156
	Subject 6	M1	0.71284	–18.8	35.6%	0.7134–0.7148
	Subject 29	M1	0.71541	–17.1	54.4%	0.7180–0.7227
Phase 2	Subject 12	M1	0.71109	–19.4	28.9%	0.7113–0.7118
	Subject 12	M2	0.71064	–20.3	18.9%	0.7107–0.7109
	Subject 15	M1	0.71493	–18.1	43.3%	0.7162–0.7192
	Subject 16	M1	0.72573	–18.4	40.0%	0.7289–0.7367
	Subject 16	M2	0.72321	–20.5	16.7%	0.7239–0.7260
Phase 3	Subject 18	M1	0.71763	–20.3	18.9%	0.7181–0.7196
	Subject 24	M1	0.71757	–20.9	12.2%	0.7178–0.7187
	Subject 28	M1	0.71488	–20.2	20.0%	0.7152–0.7163