**Isotopic provenancing of the Salme ship burials in pre-Viking Age Estonia**

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*Ship burials are a well-known feature of Scandinavian Viking Age archaeology, but the discovery of 41 individuals buried in two ships in Estonia belongs to the pre-Viking period and is the first of its kind in Europe. The two crews met a violent end around AD 750 and were buried with a variety of richly decorated weapons, tools, gaming pieces and animal bones. The rich grave goods suggest this was a diplomatic delegation protected by a cohort of elite warriors. They were armed with swords of Scandinavian design, possibly from the Stockholm-Mälaren region, and stable isotope analysis is consistent with that being the probable homeland of the crew.*

*Keywords:* Estonia, pre-Viking Age, isotopic analysis, ship burial, grave goods

**SUPPLEMENTARY MATERIAL**

**Isotopic provenancing: principles and procedures**

Enamel powder for isotopic analysis was collected from the teeth by first burring the area to be sampled to remove possible surface contamination and then extracting a cusp or fragment in the case of friable enamel. Any remaining dentine was carefully removed and the sample ground to powder. The powder is weighed and submitted for measurement.

Measurement of $^{87}Sr/^{86}Sr$ in the enamel powder was done in the Geochronology and Isotope Geochemistry Laboratory (Dept. of Geological Sciences, University of North Carolina-Chapel Hill). Samples were dissolved in nitric acid and the strontium fraction purified by ion selective chromatography (Eichrom Sr resin) prior to analysis by TIMS on a VG Sector 54 mass spectrometer run in dynamic mode. Internal precision in the laboratory is consistently around 0.0007% standard error (or $1\sigma$=0.00006 in the ratio of a particular sample). Long-term, repeated measurements of SRM-987 are around 0.710260—an acceptable difference from the recognised value of 0.710250—and raw sample values from individual runs are standardised to the recognised value of SRM-987. Light isotopes of carbon and oxygen in enamel powder were measured simultaneously in the Environmental Isotope Laboratory (Department of Geosciences, University of Arizona) using a Kiel device attached to a Finnigan MAT252 ratio mass spectrometer. Samples are converted to $CO_2$ with dehydrated 70°C phosphoric acid. External precision, as measured by repeated measurements of standard reference materials (NBS-18 & NBS-19) is ±0.08‰ for $\delta^{13}C$ and ±0.1‰ for $\delta^{18}O$.

**Strontium isotopes**

Strontium isotope analysis provides a robust means for examining past mobility. The strontium isotope ratio of $^{87}Sr/^{86}Sr$ varies among different kinds of rocks, based on their age and composition. The heavier isotope ($^{87}Sr$) is formed by the radioactive decay of rubidium-87. Thus, older rocks and sediments with more rubidium have higher $^{87}Sr/^{86}Sr$ values, while younger materials with less rubidium are at the opposite end of the range with lower ratios (e.g. Faure & Mensing 2004). The proportion of $^{87}S$ varies in the

terrestrial ecosystem, but averages around 7 per cent of total strontium; $^{86}Sr$ is about 10 per cent. Their ratio normally varies from about 0.700 in rocks with low Rb to 0.730 and much higher in high-Rb rocks that are billions of years old.

Strontium moves into humans from rocks and sediment through the food chain (Sillen & Kavanagh 1982; Price 1985, 2000) and deposited in the skeleton. The enamel in teeth forms in early childhood and contains the strontium isotope ratio of the food consumed and the local geology from the first years of life. The ratio in the enamel remains largely unchanged during life and after death. In archaeology, enamel is used as a signal of place of birth. If an individual moves to a new location in a different geologic context, or is buried in a new place, the enamel isotope ratio will differ from the new location, allowing the designation of that individual as non-locally born. Most measurements of human enamel fall in the range of 0.705 to 0.725.

Enamel has been shown to be resistant to contamination and a reliable indicator of biogenic levels of strontium isotopes (e.g. Budd *et al.* 2000, 2004; Hoppe *et al.* 2003; Schoeninger *et al.* 2003). Strontium isotope analysis as a means of provenancing has been in use for more than 20 years in bioarchaeological research and is described in detail in a number of articles (e.g. Price *et al.* 1994, 2002, 2011; Montgomery *et al.* 2000; Bentley 2006; Montgomery 2010).

**Carbon isotopes in apatite**

The primary factors affecting carbon isotope ratios in skeletal tissues are those associated with dietary input of plants ($C_3$ *versus* $C_4$) with different patterns of photosynthesis (Farquhar *et al.* 1989) and the consumption of marine foods (Tauber 1981). Most paleodiet work involving carbon isotopes has focused on the organic collagen in bone. Carbon is also present in the mineral portion of bone and tooth enamel as carbonate and records the aggregate (protein and carbohydrate) value of individual diet (Sullivan & Krueger 1981; Lee-Thorp *et al.* 1989; Ambrose & Norr 1993; Lee-Thorp 2002). Although there are potential problems with contamination in apatite (e.g. Schoeninger & DeNiro 1982; Hedges 2002), it can nonetheless provide substantial insight into the composition of individual diet.

**Oxygen isotopes in apatite**

Oxygen isotopes have been widely used as a proxy for temperature in many climate and environmental studies and vary geographically in surface water and rainfall (Dansgaard 1964). The oxygen isotope ratio in the skeleton reflects that of body water, and ultimately of drinking water (Luz *et al.* 1984; Luz & Kolodny 1985; Kohn 1996), which in turn predominantly reflects local rainfall. Water from food and atmospheric oxygen are minor, secondary sources. Measured oxygen isotope ratios of body water are enriched relative to those of meteoric water in mammalian species due to the combined fractionation effects of the physiological processes involved in regulating daily water flux (e.g., Nagy 1989).

Oxygen has three isotopes, $^{16}O$ (99.762%), $^{17}O$ (0.038%), and $^{18}O$ (0.2%), all of which are stable and non-radiogenic. Isotope ratios in rainfall are greatly affected by enrichment or depletion of the heavy $^{18}O$ isotope relative to $^{16}O$ in water due to evaporation and precipitation (e.g. Dansgaard 1964). Major factors affecting rainfall $\delta^{18}O$ values are primarily geographic: latitude, elevation, amount of precipitation, and distance from the evaporation source (e.g. an ocean).

Isotope measurements are reported as a ratio of one isotope to another lighter and more common cousin. Like carbon, oxygen isotopes are commonly reported as the per mil difference (‰ or parts per thousand) in the ratio of $^{18}O$ to $^{16}O$ between a sample and a standard. This value is designated as $\delta^{18}O$. This value can be measured in either carbonate $(CO_3)^{-2}$ or phosphate $(PO_4)^{-3}$ ions of apatite in tooth and bone. Phosphate and carbonate produce comparable results. Traditionally, two standard scales have been used to report oxygen isotope ratios by researchers investigating either carbonate (PDB, PeeDee Belemnite) or hydrological systems (VSMOW, Vienna Standard Mean Ocean Water) (Hoefs 2009).

**Isotopic baselines in Sweden**

A distribution map of runestones provides an approximation for the location of human population in Sweden during the Viking Age (Figure S1). Stockholm and Gotland are two areas with substantial Viking settlements closest to Estonia. The island of Gotland is

approximately 200km to the south-west of Saaremaa, while the Stockholm region is roughly 250km to the north-west. There were several large settlements on Gotland during the Vendel and Viking periods. The region around Stockholm and the Mälar Valley directly to the west were also important centres of Viking population. The agricultural lands on the shores and islands of Lake Mälar are some of the richest in Sweden. One estimate suggests there were 4000 farms in *Mälardalen* (the Mälar Valley) during the Viking period and perhaps 40 000 people (Hyenstrand 1982). Another major Viking centre in this part of Middle Sweden was located around Uppsala, 70km north-west of Stockholm.

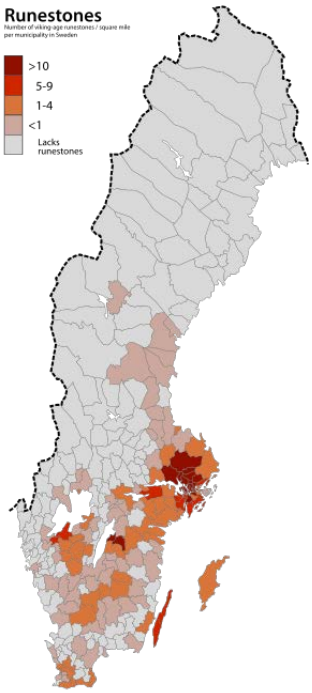


*Figure S1. Distribution of runestones in Sweden. The darker areas have more runestones, the grey areas have none (Sveriges Nationalatlas).*

**Oxygen isotope baselines**

Oxygen isotope ratios vary largely with latitude, temperature and elevation. For that reason there is pronounced variation in $\delta^{18}O$ from south to north in Sweden. Burgman *et al.* (1987) measured $\delta^{18}_{VSMOW}$ in annual precipitation and run-off from a number of sites in Sweden and published a map of estimated ratios for the entire country (Figure S2)

using the seawater standard reference (VSMOW). Values range from −14‰ in the north to −8‰ in the south-west. Slightly more negative $\delta^{18}0$ values should be expected to the east in Estonia. Values for $\delta^{18}O$ in ground waters in Estonia vary from −10.8‰ to −12.8‰ (Punning *et al.* 1987). An annual average for rainwater is assumed to be *c.* −10.4‰ by local scientists (Liina Laumets *pers. comm.*). Although little data exists for Estonia, there is information from Riga in Latvia where average monthly values for modern rainfall range between *c.* −12.0‰ and −7.0‰ over 12 months of the year. These $\delta^{18}O_{VSMOW}$ values correspond to a range in $\delta^{18}O_{PDB}$ in enamel between approximately −9‰ and −5‰ (Chenery *et al*. 2012).

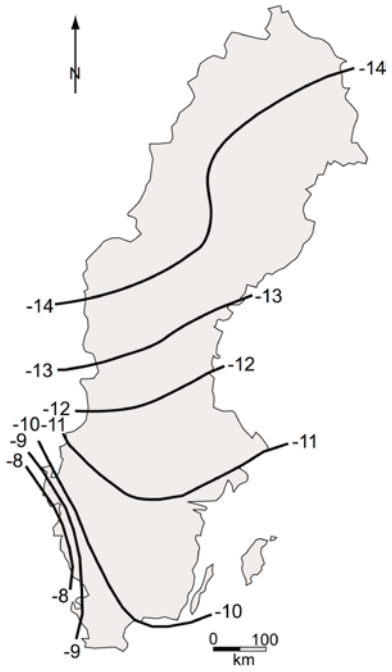


*Figure S2. Oxygen isotope ratios in rainfall in Sweden (Burgman* et al. *1987).*

We have also measured $\delta^{18}O$ in human enamel from Viking Age sites elsewhere in Scandinavia, including the Stockholm area, Birka and Gotland. Some of these data are presented in Table S1. Grødbygård is an Early Medieval cemetery on the Danish island of Bornholm in the southern Baltic. The highest values are seen at Birka and Stockholm in central-eastern Sweden. Birka is on an island in Lake Mälar. Koppersvik is a major Viking settlement on the Swedish island of Gotland. Uppåkra is an important Iron Age centre near Lund in south-western Scania, Sweden. What are particularly notable in Table

S1 are the very similar values between −4.0‰ and −5.0‰ for all of the locales except Stockholm, with a value of −6.4‰. Nearby Birka has an average oxygen isotope ratio of −4.9‰.

**Table S1. Average oxygen isotope ratios in prehistoric human tooth enamel carbonate from selected localities in Denmark (DK) and Sweden (S).**

| Location | n | $\delta^{18}O_{en}$ | ±1 sd |
|---|---|---|---|
| Trelleborg (DK) | 41 | −4.4 | 0.7 |
| Sebbersund (DK) | 7 | −4.0 | 0.5 |
| Galgedil (DK) | 34 | −4.2 | 0.7 |
| Grødbygård (DK) | 36 | −4.9 | 0.6 |
| Kopparsvik (S) | 44 | −4.7 | 1.1 |
| Birka (S) | 29 | −4.9 | 1.1 |
| Stockholm (S) | 3 | −6.4 | 0.3 |

**Strontium isotope baselines**

An essential aspect of strontium isotope analysis involves the determination of the local strontium isotope signal (Price *et al.* 2002). The actual level of strontium isotopes in human tissue may vary from local geology for various reasons. It is necessary to measure *bioavailable* levels of $^{87}Sr/^{86}Sr$ to determine regional and local strontium isotope ratios for comparison with the human remains.

As the archaeological materials found with the Salme ship burials have a distinct Viking affiliation, we have focused on eastern Sweden and Denmark as potential homelands for these individuals. Denmark, Sweden and Norway were the primary homeland of Viking culture. It seems unlikely that Norway might have been the place of origin for the individuals buried on the ships at Salme because of the distance involved and known connections between the Swedish Vikings and the east during the Viking period. In the following pages we present a very brief summary of the geology and strontium isotope sources in the larger region of the Baltic and specifically eastern Sweden and Denmark. The discussion of baseline values concentrates on the island of Gotland and the region around Stockholm as possible homelands of the Salme burials. We then look in more detail at Estonia and the island of Saaremaa.

**The Baltic**

The Baltic Sea, 1600km long and averaging 190km in width, is one of the major bodies of water on earth. The Baltic fills a relatively shallow depression in the earth's surface in northern Europe, bordered by the countries of Denmark, Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Poland and Germany. A major geological division in the region runs along the southern Swedish coast, crosses the Baltic towards Finland and continues through the Gulf of Finland, separating the Fennoscandian (or Baltic) Shield from the East European Platform to the east.

The Fennoscandian Shield in the Scandinavian Peninsula is a region of ancient craton exposed on the surface. Such ancient cratons with a Precambrian basement (>543 mya) were part of the cores of the earliest continental blocks of Archaean Age (>2.4 bya), and contain some of the oldest rocks on earth. These Precambrian crystalline rocks often crop out along the Swedish and Finnish coasts. The Eastern European Platform is characterised by a younger basement of crystalline rocks of Proterozoic age beneath a thick Palaeozoic sedimentary cover (younger than 543 my) that is sometimes found on the surface in the eastern Baltic area, particularly along the coast (Tuuling *et al.* 2011).

There have been several studies of environmental $^{87}Sr/^{86}Sr$ in the Baltic region. There is also some published information on the brackish waters of the Baltic Sea. The waters of the Baltic come from two major drainage regions to the north and to the south (Åberg & Wickman 1987). To the north, most of the waters that flow into the Baltic come off the Precambrian rocks of the Fenno-Scandinavian Shield and have generally high strontium isotope ratios (>0.720). To the south, a large sedimentary basin from northern Germany to the Neva River near Saint Petersburg provides approximately 55 per cent of the waters to the Baltic and a much lower $^{87}Sr/^{86}Sr$ signature. Values reported from the Vistula and Oder average 0.710 (Åberg & Wickman 1987). Andersson *et al*. (1992) measured Sr and Nd isotope ratios in the Baltic to study mixing of waters from river input and the sea. Strontium isotope ratios are generally correlated with salinity in the Baltic waters. Modern $^{87}Sr/^{86}Sr$ values for the southern Baltic Sea waters are slightly

variable and somewhat higher depending on salinity, but usually fall within the range of 0.7092 and 0.7097.

**Denmark**

Denmark is characterised by a relatively young and rather homogeneous 'basement' geology. About 50 per cent of the country is constructed of Late Cretaceous–Early Tertiary carbonate platforms, the other 50 per cent by marine clastic sediments, all covered by more or less thick sequences of diverse glaciogenic sediments deposited during the two last Ice Ages. The Quaternary glaciogenic sediments are composed, among other things, of various weathered Precambrian granitoids (gneiss and granite). Almost everywhere in Denmark, glacial deposits are the source of strontium isotopes for plants, animals and people. There is very little bedrock exposure anywhere in the country. Baseline strontium isotope data from Denmark has been published (Frei & Frei 2011; Frei & Price 2012). Frei and Price (2012) present strontium isotope ratios from samples of modern mice, snails and archaeological fauna. The $^{87}Sr/^{86}Sr$ values for faunal samples range from 0.70717 to 0.71185, with an average of 0.70919 (s.d. = 0.0011). These values increase slightly from west to east, but in general terms the geology and the strontium isotope ratios in this heavily glaciated region are largely homogeneous.

**Sweden**

Sweden's geology is rather complex, but generally can be divided into three main components: Precambrian crystalline rocks (which are part of the Baltic or Fennoscandian Shield and include the oldest rocks found on the European continent), the remains of a younger sedimentary rock cover, and the formation of the Caledonides during an ancient mountain building episode in the Mesozoic, *c*. 400 mya.

The oldest rocks in Sweden are Archaean (>2500 million years old), but these only occur in the northernmost part of the country. Most of the northern and central parts of Sweden are composed of Precambrian rocks belonging to the Fennoscandian Shield, an ancient craton of mantle rock with generally high strontium isotope ratios. This rock is covered in places by glacial moraine, but is exposed intermittently to frequently on the

surface. Further to the south, Phanerozoic sedimentary rocks rest upon the Precambrian shield. They are less than 545 million years old and cover large parts of Skåne, the islands of Öland and Gotland, the Östgöta and Närke plains, the Västgöta mountains, the area around Lake Siljan in Dalarna and areas along the Caledonian front in northern Sweden.

The youngest rocks in Sweden are from the Tertiary, formed about 55 million years ago. They occur in the most southerly and south-western parts of Skåne. Quaternary deposits formed during and after the latest glaciation (when Sweden was completely covered by an ice sheet) partially cover this bedrock. Southernmost Sweden is a glaciated landscape much like the neighbouring areas of Denmark, and strontium isotope ratios should be similar as well.

There is a growing body of baseline $^{87}Sr/^{86}Sr$ values from central and southern Sweden (Figure S3). The Swedish Geological Service has measured $^{87}Sr/^{86}Sr$ across the country and reports very high rock values from most of the area, generally greater than 0.722. There is some information from environmental studies. For example, Åberg *et al.* (1990) sampled soil and water from five different locations (none in the south-west) and reported values higher than 0.715 at all five sites, often above 0.725. Most of the Fennoscandian Shield across Sweden exhibits similar high values for $^{87}Sr/^{86}Sr$. We have some baseline data from the greater Stockholm region. The site of Birka in the Mälar Valley west of modern Stockholm was a major Viking centre and gateway to the east. Samples of five archaeological rodents from Birka averaged 0.7256, while 29 human enamel samples provided a mean of 0.7207±0.0073 with a range from 0.7103 to 0.7343, values that include a number of non-local individuals. We also have several other human samples of Viking age from central Sweden, including three from Uppsala with a mean of 0.7260 and three from the medieval cemetery of Helgeandsholmen in Stockholm. One of the three from Stockholm appears to be non-local with a value of 0.711, while the other two are similar with an average of 0.7206. In general, human and faunal values from much of central Sweden appear to have $^{87}Sr/^{86}Sr$ values between 0.720 and 0.726.

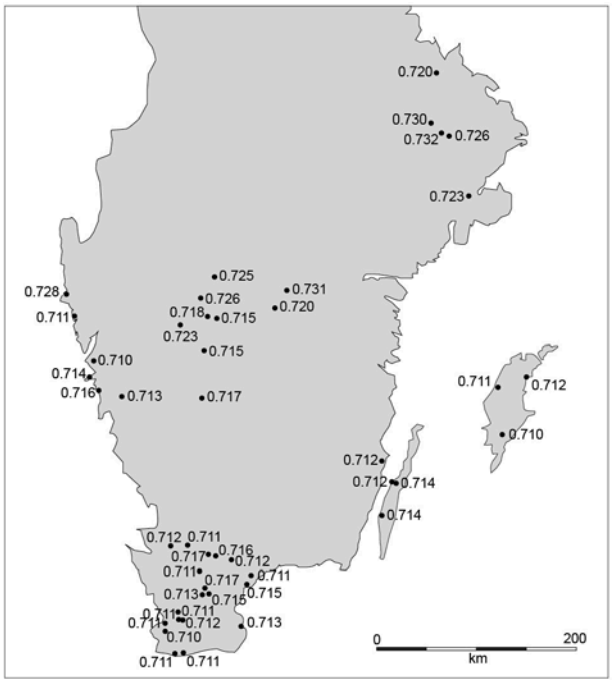


*Figure S3. Averaged strontium isotope ratios from human and archaeological fauna samples from southern and central Sweden.*

There are a few exceptions to the generally high values found across much of Sweden. The south-west corner of the south-western province of Scania has a geology and strontium isotope ratios similar to Denmark, around 0.708–0.711. The south-eastern island of Öland has a distinctive geology, and faunal samples from archaeological sites on the island had an average $^{87}Sr/^{86}Sr$ value of 0.7144. One hundred and six samples of human enamel from the island averaged 0.7160±-0.008, including a number of non-local individuals. Gotland, an important centre of trade in the middle of the Baltic during the Viking period, is another important exception. Most of the island is composed of Silurian limestone, covered by glacial deposits of till and outwash. $^{87}Sr/^{86}Sr$ values in Silurian limestones on Gotland have been measured and show a very narrow range from 0.7084–0.7085 (Azmy *et al.* 1999). Archaeological materials have also been analysed. From Gotland we have around 140 samples, of which 11 are archaeological faunal. These 11 baseline samples of hare, fox, dog, hedgehog and beaver from several sites around the island have an average $^{87}Sr/^{86}Sr$ value of 0.7112. Human samples from Gotland, which

include a high proportion of non-local individuals, average 0.7135±0.0057 with a range from 0.7083 to 0.7389.

There are significant differences among several areas of relevance for the Salme burials. The baseline range of values in Denmark and south-westernmost Sweden falls between 0.708 and 0.711 in the glacial moraine landscape that covers that region. It is clear that the older rocks of the Fennoscandian Shield across most of Sweden result in higher $^{87}Sr/^{86}Sr$ values. The Stockholm region, on the very old Fennoscandian Shield, exhibits $^{87}Sr/^{86}Sr$ values generally >0.715 and often >0.720. The Swedish island of Gotland has a different geology with late Pleistocene glacial deposits on top of Silurian bedrock and equally distinctive $^{87}Sr/^{86}Sr$ values around 0.711 to 0.713. A list of mean $^{87}Sr/^{86}Sr$ values at several Iron Age and Viking Age sites in Denmark and Sweden (Table S2) provides some indication of local ratios, although these human values may include non-local individuals.

**Table S2. Average strontium isotope ratios in prehistoric human tooth enamel from selected localities in Denmark (DK) and Sweden (S).**

| Location | n | $^{87}Sr/^{86}Sr$ | ±1 sd |
|---|---|---|---|
| Trelleborg (DK) | 49 | 0.7116 | 0.0020 |
| Sebbersund (DK) | 19 | 0.7104 | 0.0010 |
| Galgedil (DK) | 38 | 0.7105 | 0.0012 |
| Grødbygård (DK) | 38 | 0.7140 | 0.0018 |
| Kopparsvik (S) | 131 | 0.7135 | 0.0057 |
| Birka (S) | 10 | 0.7174 | 0.0070 |
| Stockholm (S) | 3 | 0.7175 | 0.0054 |
| Uppäkra (S) | 10 | 0.7132 | 0.0024 |

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