Identifying Prehistoric Origin and Mobility: using Strontium analysis and laser ablation on teeth enamel from Viking Age boat-graves XI and XIII from Tuna in Alsike.

Bachelor Thesis (2015) at the Archaeological Research Laboratory, Stockholm University

Author: Elias Ghattas Lama

Supervisor: Kerstin Lidén
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Abstract:
The Viking Age cemetery of Tuna in Alsike from the 9th - 11th century AD is located in the eastern part of middle Sweden and contains inhumation boat graves. Here analysis of Strontium isotopes, using laser ablation method on the tooth enamel of the canine and first molar of two individuals buried in boat-graves XI and XIII have been performed. Comparing Strontium isotope evidence with local strontium ratios and variations indicated that at least one individual, the one in boat-grave XIII, were non-local.

Cover Picture
Grave XI from Tuna in Alsike (Arne 1928) FMI archive.

1. Introduction

1.1 Preface
Traditionally archaeological investigations rely on foreign artefactual and architectural evidences to indicate origin and human mobility. However, today the chemistry of human bone is becoming important means of complementing this type of research.

Studies of ancient DNA and stable isotope analysis of skeletal remains allow archeologists to determine genetic ancestry, past diet, mobility and changes in residence. Also radiogenic isotopic studies of Strontium (Sr) can be used to detect individuals, textiles (Frei 2014) and fauna (Frei & Price 2011) of local or non-local origins.

Radiogenic strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) analysis on ancient human tooth enamel in archaeological research proves useful when evaluating origin and migration and distinguishes between local and nonlocals at prehistorical archaeological sites such as cemeteries. It allows mapping mobility during different life stages at the individual level making it an important “tool kit” for archaeologists (Frei & Price 2012, 103).

Applications of Sr analysis in archaeology to investigate place of origin have been performed in a number of studies on Danish materials. Here, Price et.al (2011) have e.g. conducted strontium isotopic analysis on the skeletal remains found in the round fortress built in AD 980/981 by Harold Bluetooth. Strontium analysis indicated that the buried population in the garrison cemetery by the fortress consisted of individuals of both local and non-local origin, where the nonlocals probably were of a southern Baltic origin, as axes of Slavic types were found in the graves of these non-local individuals (Price et.al 2011, 480,487).

A recent study, also conducted by Price et.al (2015) examined preserved teeth from skeletons from a Viking Age cemetery on the Danish island of Funen, near the town of Galgedil, dating from the 9th to11th cent AD resulting in the identification of nonlocals (male & female) among the buried sample population (Frei et.al 2015, 13-14).
In a similar one at the cemetery of Ndr in Denmark, from the 11\textsuperscript{th} Century AD, Sr isotopic analysis on human tooth enamel was used to distinguish between local and non-locals buried in the cemetery (Price et.al 2013).

The multidisciplinary study on the exceptionally well-preserved bronze aged Egtved Girl from Denmark by K.M Frei et. al. (2015) demonstrated that she originated from a place today outside the country, viz. the Black Forest area in Germany (see also sub-section 2.4).

Varied strontium isotopic studies were also conducted in other parts of the World on both sides of the Atlantic, Near East and North Africa (see list of studies in Slovak & Paytan 2012,756-757) and some of which are mentioned here below.

Price et.al (2013) conducted a multiple-isotope analysis on Spanish and African skeletal remains in Campeche in Mexico dating from the 16\textsuperscript{th} cent AD and the substantial isotopic variations from the migrants and dietary differences have helped map the settlers in the Spanish colony.

Simonetti et.al (2008) analyzed human tooth enamel from the ancient Egyptian colonial site of Tombos located in ancient Nubia (modern-day Sudan) dating from the New Kingdom period (16\textsuperscript{th} cent BC) were the study reported comparable elemental abundances and Sr isotope ratios using laser ablation-MC-ICP-MS (Simonetti et.al 2008, 372).

Richards et.al (2008) studied a fossil third molar tooth from a Neanderthal using laser ablation \textit{in situ} to investigate paleomobility and came to the conclusion this Neanderthal, at the site of Lakonis in Greece, had moved over a wide geographical range (at least 20 km) in his life time (Richards et.al 2008, 1251).

This paper examines skeletal remains, teeth, found in two boat-graves (XI & XIII) from the Viking age cemetry at Tuna in Alsike dated to 9-10\textsuperscript{th} Century AD. In light of the archaeological remains and Runic stones, it appears that Tuna in Alsike Parish was a place that was involved in the political and economic activities in the Viking period. The good preservation conditions at this site further offers suitable material for Strontium isotope analysis.

![Figure 1: The site at Tuna in Alsike Parish (Arne 1934).](image-url)
1.2 Aim and research questions

Previous archaeological research by Stolpe (1895-96) and Arne (1928-31) has concentrated on reporting and dating the findings at the Viking Age cemetery of Tuna in Alsike. Studies by Arvidsson (1999) of light isotopes (carbon and nitrogen as well as trace elements of zinc in bone collagen has been conducted on the skeletal remains as well as DNA samples were extracted from one tooth that is also used in this paper (Kerstin Lidén, 2015 Pers.Comm.).

Isaksson (2005) & (2010) made a lipid analysis of ceramic finds in Tuna but no attempts have been made to reconstruct origin or residential patterns of subjects in the cemetery using strontium analysis thus making the essay first of its kind.

The focus of this essay is on strontium isotopes signatures retrieved from human tooth enamel from skeletal remains of two individuals buried at Tuna in Alsike. The two burials are boat-graves number XI and XIII, dating to the Early Viking Age (800-979 AD). The aim is to use strontium isotope analysis as a mean to study mobility and discuss this with regards to the archeological context.

Strontium isotope data will be obtained using a laser ablation multi collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) on the ancient teeth, at the Vegacentre in Stockholm and to answer the following questions:

- Were the individuals buried in boat-graves XI and XIII in Tuna in Alsike local?
- Can it be to infer any mobility over the two individuals’ life span?
- What could be the purpose of receiving a boat-grave burial in relation to the place of origin?

Since strontium isotope ratios in ancient human dentition can be indicative of geographical origin, it is possible to formulate and test the hypothesis that Strontium enamel ratios that are similar to local Strontium ratios indicate that the analyzed individual originated from the very same place.

The following sections provide the main principles and methods of radiogenic strontium isotope analysis. Section 2 is a discussion about the properties of Strontium isotopes and tooth enamel and is followed in section 3 by a comparison of the different techniques to obtain Strontium isotope values from the enamel. In section 4 the archaeological material is introduced.
2. Theoretical background

2.1 Fundamental considerations for Strontium analysis

Strontium, an alkaline metal, lies in the same group as calcium and magnesium in the periodic table. Strontium has an ionic radius that is similar to that of calcium (see Periodic Table of Elements) and can therefore easily replace calcium in mineral lattices and becomes incorporated into skeletal tissues and the body by means of diet (Figure 3). Besides Strontium concentrates in calcium-bearing minerals such as hydroxyapatite; the same mineral that makes up the tooth enamel (Figure 2) making strontium even more useful to archaeological research (Frei 2012, 1).

The idea that the variations of the strontium isotopic ratios in archaeological remains and that of surrounding bedrock and soil of one specific geological area can be used to obtain potential geographical origins was proposed already in 1985 by JE Ericson. Ericsson demonstrated that strontium while substituting for calcium in the food chain (Figure 3) is deposited in the hydroxyapatite crystal in human tooth enamel (Ericsson 1985, 503-514 and Frei 2014, 1 and Slovak & Paytan 2011, 744).

The fact that Sr isotopic ratios ($^{87}$Sr/$^{86}$Sr) do not alter throughout the food chain, due to their relative large atomic mass (Slovak & Paytan 2011, 743) and that the age and type of bedrock and their respective soil formation constrain a signature of variations on $^{87}$Sr/$^{86}$Sr in every geological area all this makes Strontium measurable and traceable (Frei 2014, 1). As a result $^{87}$Sr/$^{86}$Sr signatures in human tooth enamel reflect not only the $^{87}$Sr/$^{86}$Sr composition of water, plants, and animals consumed but also $^{87}$Sr/$^{86}$Sr bedrock signatures in a given region (Slovak & Paytan 2011, 744).

Strontium has four naturally occurring isotopes (Fornander et.al 2011, 179), $^{88}$Sr (82.53%), $^{87}$Sr (7.04%), $^{86}$Sr (9.87%), and $^{84}$Sr (0.56%). All of the four occur naturally as isotopes and are stable but not $^{87}$Sr which is partially formed by radioactive decay of rubidium-87 and therefore is variable (Faure 1986 in Frei 2012,1). Thus the strontium isotopic tracer system relies on the use of two of the four $^{87}$Sr and $^{86}$Sr. the ration of $^{87}$Sr/$^{86}$Sr is related to their natural abundance and often lays around 0.7 (7% $^{87}$Sr/ 10% $^{86}$Sr) (Frei 2012,1).

Moreover and in general, very old rocks with high Rb/Sr ratios usually exhibit $^{87}$Sr/$^{86}$Sr signatures above 0.710 while younger rocks can have values that are less than 0.704 (Slovak & Paytan 2011,745). More of this in this regard is discussed in sub-section section 5.3.

2.2 Problems and limitations of Sr analysis

Ericsson pointed out that radiogenic strontium isotope analysis cannot be used to track movement in coastal areas as the inhabitants that relied totally on marine foods would all reflect the marine $^{87}$Sr/$^{86}$Sr value which is very similar in different geographic areas at c. 0.7092 (Ericsson 1985, 507).

However and according to a recent study by Fornander et.al 2015 it is possible to reconstruct ancient mobility to prehistoric populations with mixed marine and terrestrial diets. The
research managed to develop a mathematical formula in order to separate between marine and terrestrial intakes of strontium (Fornander et al., 2015).

Other factors that can affect the local Sr values geological ration are the sea spray effect, already discussed above, and the application of modern fertilizers to an area, atmospheric dust and rainwater (Frei & Price, 2012, 105-106). Also it should be excluded that individuals under investigation did not consume imported food (Slovak & Paytan, 2011, 744-745).

Ericsson (1985) noted that for a successful use of strontium as an indicator of prehistoric mobility there should be sufficient geologic variability between different residence areas so that variation in $^{87}\text{Sr} / ^{86}\text{Sr}$ values can be detected (Ericsson 1985, 510).

It is possible that Sr isotope signature of different geological areas can be similar and as a result set limits to discrimination between areas (Slovak & Paytan, 2011, 744). As a result the geological knowledge of the local bedrock is not enough as background information and should be completed with a measure of bio-available ratios that can be obtained from bone tissue of local small animals, plants and water (Frei, 2014, 1).

Obviously it is a necessary step to established local $^{87}\text{Sr} / ^{86}\text{Sr}$ values for the region or even the site under investigation e.g Tuna in Alsike which can be estimated from geological maps, exposed bedrocks and whole soil in the area of interest. To best capture $^{87}\text{Sr} / ^{86}\text{Sr}$ values it would also mean to measure $^{87}\text{Sr} / ^{86}\text{Sr}$ signatures for small local animals whose diets can reflect average $^{87}\text{Sr} / ^{86}\text{Sr}$ regional values.

This is recommended as it has been shown that $^{87}\text{Sr} / ^{86}\text{Sr}$ signatures in a geological substrate may not reflect bioavailable $^{87}\text{Sr} / ^{86}\text{Sr}$ values in the food chain (Price et al. 2002 and Slovak & Paytan, 2011, 745).

The incorporation of other and additional light and stable isotopic tracers like carbon ($\delta^{13}\text{C}$), nitrogen ($\delta^{15}\text{N}$) and oxygen ($\delta^{18}\text{O}$) may also facilitate the investigation (a multi-isotope approach). Nitrogen and Carbon can be used in identifying past dietary habits as values of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ in human bone collagen and tooth dentine reflect $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures in plants and animals consumed (Price et al. 2015, 8-12 & Nuorala et al. 2015).

Although neither carbon nor nitrogen can be used for migration, studies of oxygen isotope signatures ($\delta^{18}\text{O}$) however can be used to detect ancient migration as $\delta^{18}\text{O}$ values in tooth enamel reflect the $\delta^{18}\text{O}$ in childhood drinking water but which also depends on other factors to be taken in consideration such as temperature, elevation and distance from sea water (Slovak & Paytan, 2011, 746).

Since stable isotopic analysis cannot be carried out on cremated bones (Ericsson 2008, 521), pars petrosal bone that survives cremation seems as a best candidate for strontium analysis indicating an advantage of this technique compared to the others already mentioned above (Harvig et al. 2014, 4).

Finally and despite limitations Sr analysis as a method is useful in discriminating between local and non-local individuals.
2.3 The Tooth Enamel

Enamel in teeth is normally the best preserved of hard tissues, (Figure 2) and archaeological enamel yields in most cases good microscopic sections undistinguishable from fresh (recent) enamel (Hillson 2005,158). The specialized hard tissue that covers the crown is both avascular and acellular and once formed about 97% is mineralized and fossilized (White & Folkens 2005, 130).

![Figure 2: Tooth anatomy as provided by Hillson (2005), page 6.](image)

Bone, on the other hand, is much more prone to diagenetic alteration than enamel due to its high organic matter (almost 30% is collagen), its high porosity and poor crystal-like structure. Beside, after burial the human bone is physically contaminated from the surrounding soil and elements such as quartz, calcite and clay seep into its porous structure (Slovak & Paytan 2011, 747).

The principal inorganic constituent of tooth enamel is calcium phosphate in the form of hydroxyapatite (3Ca$_5$(PO$_4$)$_2$CaX) where X can be a mixture of F, Cl, CO$_2$,OH and very similar to the chemical composition of the mineral apatite Ca$_3$(PO$_4$)$_3$CaX(F,Cl,OH) (Simonetti et.al 2008, 373).

The high content of hydroxyapatite crystals and the absence of collagen makes tooth enamel less exposed to contamination. All this makes tooth enamel one of the best parts of human skeleton with a “locked-in” early signal (Harvig et.al 2014, 1).

Strontium enters into humans from rocks and soil via the vegetation through the food chain (Figure 3). Virtually the entire strontium intake in the human body is deposited in the skeleton, thus the strontium isotope ratio of human tissue should reflect the ratio of their food and also maybe the place where they lived (Price 2013, 312).

As mentioned earlier the $^{87}$Sr/$^{86}$Sr of the tooth enamel becomes fixed at the time of enamel mineralization (Copeland et.al 2008, 3187) and different layers of enamel reveal different levels of deposition during the development period of the tooth (Prohaska et.al 2002, 1). Thus ancient human dental enamel can be used to study human mobility. Since dental enamel has a different ontogenesis than skeletal bones, the differences in Sr isotope signature between bone and teeth are therefore an indicator for mobility during the life of an individual.
Since tooth enamel is less prone to digenesis, it is preferably used by archeologists rather than bone which are much more susceptible to. Nevertheless different $^{87}$Sr/$^{86}$Sr values in both the tooth enamel and the bone of the same individual are to an advantage as they may indicate residential change (Slovak & Paytan 2011, 744).

**2.4 Mobility Theory**

Recent research has characterized prehistoric mobility as covering long distances in relative short periods of time. With rapid mobility and apparently being highly dynamic (Frei et.al 2015, 3) and where female subjects were more mobile than male (Price 2015, 11).

A good example of what can be achieved with this kind of analysis is the research to map individual mobility during different life in 2015 by Danish researchers on the well preserved 3,400 years old Bronze Age female (Figure 4) known as the as Egtved Girl (Frei et.al. 2015,1).
The high status, fully dressed, female of 16-18 years old that was laid in an oak coffin and buried under a monumental burrow at Egtved in Denmark. Obviously she did not originate from Egtved but was rather from the regions in the Black Forest in Germany, suggesting inter-chief alliances through inter-marriage with foreign elite females. The multidisciplinary study that was conducted on remains of hair, fingernails and textile also provided evidence for back and forth movement outside of present Denmark (map in Figure 4) prior to her death (Frei et.al 2015,4).

2.5 Boat-grave burials
Mortuary archaeology and burial forms such as boat-graves can indicate status and point to possible origin and even mobility of prehistoric individuals.

Alexander Gramsch (2013) and Fredrik Fahlander (2003) have both pointed out that grave contents and burial forms are closely related to the social status of the interred person before but also after his/her death and that the tomb itself is a “time capsule” that captured specific depositional practices (Fahlander 2003, 86) which could be termed as ritual actions or cult (praxis) (Gramsch & Meier 2013, 194).

Boat-grave traditions were in use around the Lake Mälaren not only during the Migration period but also during the Viking Age. They are characterized by inhumations- where the buried were placed in real boats (see cover picture). This tradition is found in Viking Age cemeteries across the middle of modern Sweden and can be seen as a Scandinavian Nordic phenomenon, although boat burials are found in other countries.

Despite the fact that the boat burials were not found under burrows, these boat graves were considered as tombs of the elite (Arne 1934; Nylen & Schönback 1994; Price,N.S. 2002; Larsson 2007; Gräslund 2011 and Fernstål 2011). Beside their abundant grave goods of silver and bronze, the individuals were accompanied by sacrificed animals like horses (Figure 5) or dogs, which were buried in close vicinity of the boat-graves (Arne 1934 and Nordahl 2001).

Figure 5: Horse skeleton close to Boat Grave XI, a worthy companion in the Afterlife according to Old Norse Mythology (Arne, 1928).
3. Method

To answer the questions within this essay and mentioned in section 1.2 two teeth were selected from two boat-graves from the Tuna in Alsike. The enamels, a canine and a first molar, from the individuals in boat-graves XI and XIII from Tuna cemetery (Figures 8 & 9) will be analyzed at the Vegacentre (Figure 10) where strontium isotope analysis will be performed according to their specific laboratory protocols using laser ablation. The results would be compared to already publish local and available Strontium values of the same region.

The various steps for the Sr analysis, laser ablation and analysis are discussed in this section. One alternative procedure to strontium isotope analysis using laser ablation is the bulk sampling Sr analysis that is also presented here in this section for the purpose of comparison. The theory behind is already discussed in section.2

The analysis is limited to only two individuals from the Tuna cemetery dating to the Viking Age period around 800-1000 AD and which were already disponible at the Archaeological Laboratory at Stockholm University. Availability was the criteria of sample choice.

3.1. Sampling strategies

In the studies by Karin Margarita Frei (2012), Frei & Price (2011), Slovak & Paytan (2011), Copeland et. al (2008 & 2010), Simonetti et.al (2008), Belikov et.al (2012) and Prohaska et.al (2002) fundamental principles, approaches and applications, successes and pitfalls of strontium analysis using either the bulk sampling or laser ablation on human tooth enamel has been discussed in details. Accordingly both methods can be useful in the study of mobility of populations in prehistoric cemeteries.

Furthermore, previous research comparing the use of either the bulk sampling and laser ablation techniques have shown that both yielded almost similar results despite the higher radiogenic values of the Sr in the laser ablation compare to the solution based analysis a thing that would be mentioned later on. However and for the purpose of clarification the bulk sampling and laser ablation techniques will be described below.

3.1.1 Bulk sampling and preparation

Most archaeologists rely on bulk sampling. The bulk sampling technique follows conventional methods summarized below and fully described in Frei and Price (2012). Although mentioned, the bulk sampling technique will not be used in this research.

In order to get as high resolution as possible, samples should be collected across a tooth’s enamel from the buccal, lingual, mesial or distal crown surfaces from the occlusal margin to the cement-enamel junction (CEJ) and indiscriminate of enamel growth phases (Slovak & Paytan 2011, 749).

It also recommended that enamel samples are collected from the layers of tooth enamel that were less susceptible to diagenetic alterations using drilling and that dentine should be avoided (Frei & Price 2012, 109) and (Price et.al 2013, 313).
Once removed these small chips or chunks of tooth enamel from the side of the crown are later ground into a powder using a sterilized mortar and pestle. Enamel samples of up to 5-20 mg should be adequate for further investigation. The resulting \(^{87}\text{Sr}/^{86}\text{Sr}\) enamel values represent a bulk signature formed over a period of several months and/or years of an individual’s childhood or adolescence (Slovak & Paytan 2011, 750).

In Frei and Price (2012) small samples of ca 10 mg of human tooth enamel were separated and pre-cleaned in Milli-Rho-Milli-Q H\(_2\)O. Enamel samples were furthermore cleaned by mechanical abrasion using a Dremel tool, a dental drill, fitted with a sanding bit to extract any possible contamination from the enamel surface in the form of superficial dirt and calculus and also to remove the outermost enamel due to the possibility of contamination by diffusion.

Samples were later dissolved in a 1:1 mixture of 30\% HNO\(_3\) (Seastar) and 30\% \(\text{H}_2\text{O}_2\) (Seastar) and decomposing within 15-30 minutes. Following strontium purification the samples were then dried down on a hot plate at 80\(^{\circ}\)C (Frei & Price 2012, 109).

The dried samples were treated with few drops of 3 N HNO\(_3\) and loaded on glass extraction columns with 0.2-ml stem volume charged with intensively pre-cleaned mesh 50.100 SrSpec\textsuperscript{TM} (Eichkrome Inc.) resin. Strontium was eluted and stripped by ionized water and then dried up again on a hot plate (Frei & Price 2012, 109).

The Strontium samples were then analyzed using solid-source thermal ionization mass spectrometry or TIMS. To do that the samples were dissolved in 2.5 \(\mu\)l of a \(
\text{Ta}_2\text{O}_5\) - \(\text{H}_2\text{PO}_4\) - HF activator solution and loaded onto previously outgassed 99.98\% single rhenium (Frei & Price 2012, 110). These were then measured at 1,250-1,300\(^{\circ}\)C in dynamic multi-collector mode on a VG sector 54 IT mass spectrometer equipped with eight faraday detectors (Frei & Price 2012, 110).

3.1.2 Laser ablation and sample preparation

Laser ablation is an alternative to bulk sampling and is used in this study. It requires far smaller samples than the bulk method making it suitable for the rare and the available specimens of human teeth taken from subjects from the Tuna cemetery at Alsike. This technique is mentioned below and has been described in details in the works of Le Roux et.al (2014), Slovak & Paytan (2011) and Copeland et.al (2008, 2010).

Laser ablation using a multi collector inductively coupled plasma mass spectrometry or LA-MC-ICP-MS is a “state of the art” technique and has many advantages for example there is no requirement for chemical preparations, it produces data rapidly and it is less destructive (no drilling is required) than bulk sampling (Copeland et.al 2008, 3187-3188).

Beside laser ablation (LA) ICP MS methods capture variation in enamel \(^{87}\text{Sr}/^{86}\text{Sr}\) at much finer temporal resolutions than what is achieved using the bulk technique. Since the enamel as described earlier (section 2.3) is composed of different growth layers and the bulk sampling can miss seasonal variations in \(^{87}\text{Sr}/^{86}\text{Sr}\). Furthermore enamel mineralization in human teeth occurs in a multidirectional pattern something that the LA-technique seems to
be able to sample making laser ablation even more sufficiently accurate to investigate geographic origins (Slovak & Paytan 2011, 750-751).

The preparation protocol for sampling using laser ablation is described in details in Le Roux et.al (2014), Copeland et.al (2008, 2010) and in Slovak and Paytan (2011) and follows a general consensus in which a tooth is exposed to both mechanically and chemical pre-cleaning of post-depositional contamination on the surface of the tooth but not identical to the bulk sampling method.

In Copeland et.al (2008) the tooth surface is cleaned manually with a brush and distilled water. The enamel surface is then swabbed with acetone and again swabbed with 0.1 M acetic acid. Then the outer layer of the labial surface of the tooth is gently cleaned by abrasion with a dental drill equipped with a 1mm spherical diamond drill bit and then sonicated for at least 30 minutes in double distilled H2O (Copeland 2008, 3188) or 3 times at least for 5 minutes (Slovak & Paytan 2011,753).

The sequential rinsing or even overnight bathing in the weak acid should remove most diagenetic carbonates in the enamel. One should be careful however how many or how much rinsing is done as each time can cause loss of weight (Slovak & Paytan 2011, 753). After that the sample can be left to dry overnight or can be dried using a desiccator i.e. a hot plate or even in an oven with temperatures below 50°C (Slovak & Paytan 2011, 753).

Before the mass spectrometry analysis, in the bulk sampling method, the strontium in the tooth sample collected has to be separated and purified to reduce mass (isobaric) interference caused by other elements or compounds present in the enamel such as 87Rb or 40Ca 31P 16O, in order to maximize ionization efficiency and stability of the ion beam (Frei & Price 2012, 109) & (Slovak & Paytan 2011, 753).

This is not possible in the laser ablation method i.e. to remove the overlapping between 87Sr and 87Rb (Copeland et.al 2008, 3188). Nevertheless, for the laser ablation technique some corrections should be made to account for the potential contribution of 87Rb on the measured signal of 87Sr. Concerning 40Ca 31P 16O no correction is needed for the Ca polyatomic residuals (Copeland et.al 2008, 3189).

A description of the laser ablation or LA-MC-ICP-MS system instrument and function can be found in Copeland et.al (2008). It is a double- focusing instrument fitted with 12 Faraday detectors, 3 discrete dynode ion counters and 1 channeltron ion counter in a fixed-position collector array.

Unique variable zoom optics manipulated the ion beam to achieve coincidence and alignment of ion beams of interest. Laser ablation byproducts are microscopic ablation pits or microscopic line rasters (Richards et.al 2007,1252).The chamber inside the laser ablation system and where the samples are to be found is flooded with helium which functions as a sweeping gas and mixes with argon using a y-connector prior to injection into the plasma (Copeland et.al 2008, 3188-3189).
3.2 Selection of the human teeth
The selection of the enamel sample is a crucial step in the process of Sr analysis but it can differ among researches. Some do collect material from a single tooth from one individual while other researchers do collect material from multiple teeth and from a single individual.

Using single tooth enamel of one individual and despite the fact that it minimizes the impact on the human skeleton, it underestimates the amount of mobility in ancient populations which could be detected otherwise by sampling several teeth from the same individual.

Conducting a serially sampling of permanent teeth from the same skeleton and comparing the \(^{87}\text{Sr}/^{86}\text{Sr}\) signatures from the various teeth can help archaeologists to detect residential changes during an individual’s childhood (Slovak & Paytan 2011, 748).

Since mandibular and maxillary dentitions have similar enough development rates, strontium isotopic values should not differ from upper or lower teeth if the same crown sides are used, i.e. lingual, buccal, mesial, and distal (Slovak & Paytan 2011, 748).

As already explained in section 2.3 different teeth represent discrete growth periods in an individual’s childhood and adolescence (see below Table 1). Moreover, to provide optimal time differences, the best enamel samples should be taken from the first or the second and third molars and if possible from the premolars (Slovak & Paytan 2011, 747).

Table 1: An approximate timing of dental crown and root formation of human permanent dentition; data compiled from Schour and Masslers (1940) and Smith (1991) and reported in Slovak & Payton (2011), page 747. (Own)

<table>
<thead>
<tr>
<th>Permanent tooth type</th>
<th>Approx. timing of dental crown formation (years old)</th>
<th>Approx. Timing of dental root formation (years old)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First incisor</td>
<td>0.25-5</td>
<td>5-9.5</td>
</tr>
<tr>
<td>Second incisor</td>
<td>0.25-5</td>
<td>5-10.5</td>
</tr>
<tr>
<td>Canine</td>
<td>0.5-4</td>
<td>4-12</td>
</tr>
<tr>
<td>First premolar</td>
<td>2-5</td>
<td>5-12.5</td>
</tr>
<tr>
<td>Second premolar</td>
<td>3-6</td>
<td>6-14</td>
</tr>
<tr>
<td>First molar</td>
<td>0-2.5</td>
<td>2.5-9</td>
</tr>
<tr>
<td>Second molar</td>
<td>3.5-6.5</td>
<td>6.5-14.5</td>
</tr>
<tr>
<td>Third molar</td>
<td>9.5-12</td>
<td>12-20</td>
</tr>
</tbody>
</table>

The first molars begin to form in utero, at weeks 28-32, and are completed at the age of three while the second molars begin to form at the age of three and their crowns are completed when the child is 7 to 8 years (Table 1). While the third molars start to form at ages between 7 and 13 years (Table 1), their crowns are completed at even more different ages, between ages 2 and 16, and where some individuals never develop their third molars at all (White & Folkens 2005, 364).

Third molars, unlike the first and the second, are less affected by maternal strontium isotope signatures compared to the other teeth (Slovak & Paytan 2011, 748) and it is in these molars that archaeologist can detect evidences for residential mobility that could have occurred in early childhood and or adolescence.
But it is also possible to conduct laser ablation on incisors and canines (Dolphin et.al 2005, 880). Canines start to form after birth at the age of 5 months to 4 years old (Table 1).

Although most researches select samples from the first, second and if available the third permanent molars (Slovak & Paytan 2011, 747) there is a tendency to use first the premolars P3 or P4 as they form in childhood but well after weaning. This means that the enamel of e.g the first permanent molar contains the isotopic composition that was incorporated from two to five years of age (Table 1).

Concluding this section it should be mentioned that collecting samples for strontium isotopic analysis utilizing either method involves the permanent removal of enamel from ancient specimens that are entirely consumed during purifications and mass spectrometry.

Therefore archaeologists minimize the impact of the analysis on the archaeological material by sampling, for example, teeth that are no longer embedded in the alveolar bone and to avoid sampling intact teeth if fragmentary ones are available for the study.

Also enamel of teeth that exhibit pathological lesions, cultural modifications or diagnostic markers should not be used as these features in the teeth can be used to detect signs related to health, diet, growth and socio-cultural practices among ancient humans (Slovak & Paytan 2011, 750-752).
4. Archaeological setting and material

In the Mälaren Valley, during the Viking Age, inhumation boat graves cemeteries with men, women and children became started to occur more often. Boat-grave cemeteries were found in Vendel, Valsgärde, Gamla Uppsala, Tuna in Badelunda, Norsa, Fittja, Árby and in Tuna in Aliseke.

Alsike in Uppland a region to the south of Uppsala (see map in Figure 6) is an area with rich cultural and archaeological heritage with many prehistoric cemeteries. It used to be a region with large farms with elite status in the Viking period and was also central to communication and trade routes in the middle Ages (Isaksson 2005, 4).

The Tuna village to the south of Alsike lies on a small hill facing west Lake Mälaren and lies about 15 meters above present Baltic Sea level. The village is already mentioned in historical documents from the 14\textsuperscript{th} century and it belonged to the St. Clair cloister in Stockholm. The village is, surrounded by level fields and was, during the Iron Age on the northern shore of a shallow bay penetrating deep into the landscape east of the site (Isaksson 2005, 5).

![Figure 6: Map of Tuna in Alsike with the burial site marked with a red circle (Fornsök 2015).](image)

4.1 The Tuna cemetery

The cemetery excavated on three occasions: in 1895-96 by Hjalmar Stolpe in 1928 and in1931 by T.J. Arne had at least 14 graves of which 10-13 are boat burials. 17 individuals have been identified; both men and women and even children were buried and unlike many other cemeteries where only men or only women got real boats as a burial form. Most of the boat-graves have been dated to the Viking Age except for two which date back to the 6\textsuperscript{th}
century AD but they were chamber graves (Isaksson 2010, 8-9). Individuals buried in boat-graves in the cemetery most probably belonged to the top level in the social hierarchy (Isaksson 2010, 9) and although they cannot represent the whole population in Tuna, but the choice of burial form, the sacrificed animals (Figure 5) and abundance of grave goods leads into that direction.

The archaeologist Ture- J. Arne and physician Nils- Åberg discovered in 1928 four graves, two boat graves with male or female. In boat-grave XI (see cover picture & sub-section 4.2) was a man and in boat grave XII that was a double grave containing either two men or two women. A child was interred in boat grave XIII (sub-section 4.3), and in grave XIV there was a male in a coffin, not a boat-grave.

Of interest to this study is boat-grave XIII (sub-section 4.3). It was excavated by Arne in 1928 and contained the remains of a child and the burial dated to 800 AD. Of interest is also boat-grave XI (sub-section 4.2), which was excavated by Arne in 1928 and that contained a male adult dated to 950-1050 AD (Arvidsson 1999, 9). Documentation of the collected skeletal material and teeth is mentioned in sub-section 4.4.

4.2 Boat-grave XI
The burial had a NW-SE orientation and was excavated by Arne in 1928. The boat was 6-6.5 m long and about 140 cm of remains of the wooden boat has been found. Inside the boat, there were skeletal remains of a male with SE body orientation laid on his side in hocker position (Figure 7).

Grave goods were abundant and included iron nails, probably belonging to the boat, a rounded fibula of bronze, that belonged to the belt of the deceased, a big iron knife 54 cm long was situated next to his right arm side, a comb made of animal bone, a whetstone made from slate rock and iron arrows, iron rings, iron cleats, game stones, a carved pointed horn from a deer, a spindle stone and a strike-a-light stone (Arne 1934, 39-41).

Beside the human skeletal, skeletal remains of a whole horse buried north east of the boat-grave was found (Figure 5 & Figur 7) and also skeletal remains of a dog and birds were found inside the boat-grave, most probably sacrificial offers (Arne 1934, 39).

Figure 7: Skeleton remains of human, animal and bird in boat grave XI (Arne 1934).
4.3 Boat-grave XIII
In 1928, Arne excavated the boat-grave but this grave was not as well preserved as boat-grave XI. The remains of the boat, some skeletal remain, like the pelvis and the broken lower jaw of a young adult, and a 12 cm long horse tooth were identified. The grave goods were many: a bronze fibula, a comb from animal bone, a silver brooch, silver thread, whetstone of slate, a strike-a-light stone and a 6 cm grinding stone (Arne 1934, 45-47).

4.4 Documentation of selected teeth from boat-graves XI and XIII:
All teeth material derives from a late Viking period boat-grave cemetery at the village of Tuna and which was already available at the Archaeological Research Laboratory at Stockholm University. The teeth material of the selected individuals from boat-graves XI and XIII had already been used in previous research but not involving Sr analysis.

The subject from boat-grave XI has already a known bulk measurements of C, N and S (Arvidsson 1999) and the tooth from the subject from boat-grave XIII has some degree of destructiveness at its root due to previous DNA analysis (Lidén 2015 pers.comm).

Several photos of skeletal remains from boat graves XI and XIII that show parts of mandibular and maxillary bones with teeth was taken in order to document all the teeth from these two graves with the purpose to evaluate them just before and after the strontium analysis.

The left side of the mandibular of the subject from boat grave XI was photographed (Figure 8), where the thick body (ramus), some implanted teeth and alveoli are visible. The mental protuberance, the mental spines, the mandibular foramen, the mental foramen, the oblique line, the masseteric fossa and the angle (angulus mandibular) can also be seen.

Following teeth were identified: the left permanent mandibular canine LC\textsubscript{1} or 33 using the World Dental Federation system (black arrow in Figure 8), FDI (tooth enamel attrition is noted on top of its crow), two rounded permanent left premolars, Pm\textsubscript{1} & Pm\textsubscript{2}, or 34 and 35 using FDI and also two permanent left molars, M\textsubscript{1} & M\textsubscript{2}, or 36 and 37 using FDI.

A total of five teeth on the left side of the mandibula were found in good shape with no sign of abrasion or tooth loss. The third molar was not developed. The amount of attrition on both molars suggests that the age of the interred person was between 25 to 35 years old (White & Folkens 2005, 369). The teeth were over all in good condition.
The fragmented right side maxilla of the individual from boat grave XIII was holding 2 teeth and one lose tooth with marks of two holes drilled in its root (Figure 9). Organic material was extracted from the root for an earlier investigation of a DNA (Lidén, 2015 pers comm). Empty alveoli holes are seen; also visible is the incisive foramen, the palatine process, transversal suture (most probably indicating a young adult), the palatine bone and the frontal process.

The following teeth from boat-grave XIII were documented: the right deciduous second premolar, Pd2 or 15 using FDI was identified. The right permanent first molar, M1 or 16 were found in the maxilla alveolar hole. The permanent first molar M1 or 17 from the right side of the mandibular was identified and provided lose (black arrow in Figure 9). Minimal tooth attrition was noticed and no signs of abrasion or tooth loss were seen. The teeth were in good condition. The child was, based on the dental development, about 8 years old when he or she died (Table 1).

Sex determination from the skeletal remains, the left side mandibular of the person in boat grave XI, indicated that the person was a male. The mandibular angle was sharp and sticking out as expected in males. The Margo inferior was thick and the mandibular trigon was groove. It was impossible to determine the sex and age of the other person in boat grave XIII however the transversal suture should suggest a sub-adult.

For the purpose of this essay it has been chosen that the first permanent molar tooth from the subject in boat-grave XIII should be analyzed, since this was already provided as lose tooth. Also for the same purpose, the canine of the subject from boat-grave XI, which is in good preservation conditions and where the enamel was not worn out, was chosen for analysis (black arrow in Figure 8 & Table 1). Both teeth have been documented using photography before laser ablation.
5. Laboratory Analysis

Previous sections has dealt with theoretical implications for a sequential LA--MC-ICP-MS analysis and its application on a single tooth from each individual from boat-graves XI and XIII from Tuna cemetery at Alside in Uppland, Sweden. This section reviews the preparation protocols for Sr analysis and provides general information on mass spectrometric analysis.

The analytical procedures and protocols given below in section 5.1, some of which are already mentioned in details in both Copeland et.al 2008 and Le Roux 2014 were used during the acquisition of the LA-MC-ICP-MS strontium isotope data and which are presented in section 6.

Instrumentation and laboratory facilities used for this essay and described below were housed either at the Archaeological Research Laboratory at Stockholm University and at the Vegacentre at the Swedish Museum of National History (Figure 10). A laser unit, ESI NWR 193 ArF coupled to Nu plasma (III) MC-ICP-MS at the Vegacentre was used to conduct Sr analysis on the teeth from Tuna cemetery.

5.1 Laboratory Procedures

After extraction of the canine tooth from the mandibula, both teeth were ultrasonic treated in deionized water twice for 2 minutes and then both teeth were washed with deionized water and left to dry overnight in a desiccator at the Archaeological Research Laboratory to remove any surface contamination.

Further pre-cleaning was conducted at the Vegacentre. This time both teeth were wiped with acetone. After marking the surface and after choosing the side of the enamel for the selected teeth both were attached with a blue substance to a sample holder taken from chamber of the laser apparatus to prevent motion during the ablation.

No mechanical pre-cleaning was needed and in opposition to what was recommended in both the bulk sampling and laser ablation procedures mentioned in sections 3.1.1 & 3.1.2, since all the samples were pre- ablated prior to the measuring ablation.

5.2 Instrumentation: mechanism of interaction & mass spectrometry

The mechanism of enamel laser ablation is described in details in Belikov et.al (2012). It’s essential tool, the laser, a fine electron beam that can be used to scan surfaces and sections of teeth specimens which are placed inside the specimen chamber.

Each intra-tooth laser value of strontium was determined with a 650-900 micro milliliter linear laser scans with wavelength of 193 nm across the all the enamel surface even on curved enamel surface with quantified and variable vertical change from tip of the enamel to cervix of the enamel avoiding dentine area of the teeth.

The laser focus for each scan line was set at an appropriate position and in the middle of each line scan (the incremental growth lines or striae of Retzius). The procedure for the analysis employed used the 193 nm laser ablation units. Sampling time per line scan was almost 140
seconds for both teeth. This was done, lines and not laser pits, in order to provide a credible spatial resolution for the tested teeth.

The canine tooth sample from boat-grave XI was scanned for a total of 32 lines while the molar tooth sample from boat-grave XII was scanned for a total of 18 lines with initial space between the first 4 lines of 400 micro milliliters and then 200 nm respectively. Both teeth were scanned starting from the tip of the enamel to its cervix and avoiding the dentine.

All laser ablation analysis were performed with helium gas as the chamber sweep gas and subsequently mixed with nitrogen which was introduced in order to reduce oxide formation. Both corrections for instrumental mass fractionation and correction for Rubidium interference were performed. All LA-MC-ICP-MS data was monitored and analyzed by the Nu plasma Time Resolved Analysis (TRA) software. Each tooth needed approximately one hour of analysis.

Figure 10: Laser Unit coupled to MC-ICP-MS at the Vegacentre at the Swedish Museum of National History (Author, 2015).

5.3 Strontium isotopic ratios for Sweden

The basic principles in strontium isotopic analysis are straightforward and involve comparison of the isotopic ratios in human tooth enamel with local levels from the place of where the individuals were found. Due to the absence of a significant and thorough study and the lack of time to establish local terrestrial isotopic range for bio-available strontium in Tuna in Alike, this paper will depend on local ratios that have been provided by Sjögren et.al (2009) and the Swedish Geological Service and mentioned in Price et.al (2012).

Sjögren et.al (2009) and Price et.al (2012) provide rough estimates of strontium ratio values and data of humans and faunal samples of some geological regions in Sweden. The following Sr ratios (Figure 11) are taken from Price et.al (2012) is helpful and taken into consideration for a discussion of the origins of the two individuals in boat-graves XI and XIII and presented in section. 7.
According to Price, Sweden’s geology although complex can be divided into three main rock componential regions. The northern and central region of Sweden which is composed of Precambrian ancient rocks (545 million years), is characterized by high strontium isotopic ratios generally greater than 0.722 (Figure 11). The southern, west southern part of Sweden and the west coast, is formed by the youngest rocks in Sweden (55 million years) have Sr isotopic ratios that range between 0.711 to a 0.714. The southernmost region of Sweden has similar Sr isotope values to that of Denmark with values lower than 0.710 (Price et.al 2012, 100).

The Eastern region and the eastern coast of Sweden, the red square in Figure 11, have similarly enough Sr ratios while the site of Birka, an important Viking center, exhibited Sr values that ranging from 0.703 to 0.733 with a mean of 0.714 representing a range of origins within the Birka cemeteries populations according to Price (Price et.al 2012,100). Noticed should however be taken here that we expect that the interred at Birka are non-locals exhibiting to the region, non-local values. Gotland in the Baltic Sea on the other hand showed Sr isotopic ratios closer to the bioavailable marine Sr isotopic values, i.e. 0.7092 (Figure 11).

Figure 11: Averaged strontium isotope ratios from human and archeological faunal (in parentheses) samples from southern and central Sweden. Tuna in Alsike is within the red squared area in the map (Price et al, 2012 Danish Journal of Archaeology).
6. Results

6.1. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios

The tooth enamel from the skeletal remains from boat-graves XI and XIII at Tuna cemetery in Alsike were well preserved due to the particular burial practice and soil quality something that also allowed for age and sex evaluation.

All $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were successfully measured for all the lines scanned of each tooth, the canine from boat-grave XI and the first molar from boat-grave XIII. The values of both teeth are shown below in tables 2 and 3 with respective graphs in Figure 12 and Figure 13.

First lines of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios indicate last stages of mineralization of the enamel while the last lines the very beginning of enamel mineralization for each tooth from the individuals in each respective boat-grave.

Table 2: Sr isotopic data from canine tooth enamel taken from boat-grave XI and as provided by Vegacentre, 2015.

<table>
<thead>
<tr>
<th>line number</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$</th>
<th>internal precision 2SE</th>
<th>external precision 2SD*</th>
<th>total Sr (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.72131</td>
<td>0.00033</td>
<td>0.00044</td>
<td>0.66</td>
</tr>
<tr>
<td>2</td>
<td>0.72174</td>
<td>0.00033</td>
<td>0.00044</td>
<td>0.63</td>
</tr>
<tr>
<td>3</td>
<td>0.72083</td>
<td>0.00026</td>
<td>0.00035</td>
<td>0.74</td>
</tr>
<tr>
<td>4</td>
<td>0.72085</td>
<td>0.00022</td>
<td>0.00030</td>
<td>0.82</td>
</tr>
<tr>
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<td>0.00028</td>
<td>0.00038</td>
<td>0.90</td>
</tr>
<tr>
<td>6</td>
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<td>0.00022</td>
<td>0.00030</td>
<td>0.91</td>
</tr>
<tr>
<td>7</td>
<td>0.72064</td>
<td>0.00020</td>
<td>0.00027</td>
<td>0.96</td>
</tr>
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<td>0.00030</td>
<td>0.99</td>
</tr>
<tr>
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<td>0.00023</td>
<td>0.00031</td>
<td>0.97</td>
</tr>
<tr>
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</tr>
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<td>0.00035</td>
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</tr>
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</tr>
<tr>
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<td>0.00024</td>
<td>0.00032</td>
<td>1.33</td>
</tr>
<tr>
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<td>0.00031</td>
<td>1.22</td>
</tr>
<tr>
<td>15</td>
<td>0.72070</td>
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<td>0.00034</td>
<td>1.12</td>
</tr>
<tr>
<td>16</td>
<td>0.72099</td>
<td>0.00024</td>
<td>0.00032</td>
<td>1.17</td>
</tr>
<tr>
<td>17</td>
<td>0.72143</td>
<td>0.00027</td>
<td>0.00037</td>
<td>1.10</td>
</tr>
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<td>0.00044</td>
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</tr>
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<td>0.00035</td>
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</tr>
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<td>0.00030</td>
<td>1.43</td>
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</tr>
<tr>
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<td>0.72155</td>
<td>0.00025</td>
<td>0.00034</td>
<td>1.32</td>
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<td>1.20</td>
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</tr>
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<td>0.00027</td>
<td>1.37</td>
</tr>
<tr>
<td>32</td>
<td>0.72260</td>
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<td>0.00027</td>
<td>1.15</td>
</tr>
</tbody>
</table>
Figure 12: $^{87}\text{Sr}/^{86}\text{Sr}$ values for canine tooth enamel from boat-grave XI and as provided by Vegacentre, 2015.

Table 3: Sr isotopic data from first molar tooth enamel from boat-grave XIII as provided by Vegacentre, 2015.
While the values of baseline strontium in the region of Tuna in Alsike and its surrounding areas are shown in Figure 11 & Table 4 and discussed in section 5.3.

Table 4: Baseline $^{87}\text{Sr}/^{86}\text{Sr}$ samples from Tuna in Alsike as reported by Price et al (2012). See also Figure 11.

<table>
<thead>
<tr>
<th>Site</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$ values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tierp</td>
<td>0.7201</td>
</tr>
<tr>
<td>Björklinge</td>
<td>0.7321</td>
</tr>
<tr>
<td>Uppsala</td>
<td>0.7263</td>
</tr>
<tr>
<td>Birka</td>
<td>0.7174</td>
</tr>
<tr>
<td>Stockholm</td>
<td>0.7175</td>
</tr>
</tbody>
</table>

6.2 General observations

There are several things to be noted from these $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and respective graphs:

First, the 32 $^{87}\text{Sr}/^{86}\text{Sr}$ values obtained from scanning the canine tooth from boat-grave XI all display a somehow regularly varying $^{87}\text{Sr}/^{86}\text{Sr}$ values ranging from lowest 0.71894 to highest 0.7312 (see Table 5) maybe indicating seasonal changes in the course of life of the analyzed individual (Figure 12).

Table 5: Average $^{87}\text{Sr}/^{86}\text{Sr}$ of selected individuals in Tuna in Alsike.

<table>
<thead>
<tr>
<th>Boat Grave Nr.</th>
<th>Highest $^{87}\text{Sr}/^{86}\text{Sr}$</th>
<th>Lowest $^{87}\text{Sr}/^{86}\text{Sr}$</th>
<th>Median $^{87}\text{Sr}/^{86}\text{Sr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAXIIC</td>
<td>0.72312</td>
<td>0.71894</td>
<td>0.72103</td>
</tr>
<tr>
<td>TAXIIIM</td>
<td>0.72227</td>
<td>0.71548</td>
<td>0.71888</td>
</tr>
</tbody>
</table>
Second, the \( ^{87}\text{Sr}^{86}\text{Sr} \) values of the first molar from boat-grave XIII are less uniform (Figure 13) showing breaks and falls in the range of minimum 0.7155 to highest 0.7223 (see Table 5). There are also very well marked dips in the curves of this individual around the same values as the individual buried in boat grave XI, values that seem to end in a much lower value than that for the individual in boat grave XI (see red rectangle in Figure 14). This could be suggestive of a shift in the diet and might indicate a change of residence in the later stages of the mineralization of the first molar of the individual in boat grave XIII (Figures 13 & 14).

Third, the Sr values show a broad similarity in the early stages of the mineralization of both teeth of the individuals whereas there is a significant difference in the values at the later end stages of mineralization of the teeth (Figure 14).

Fourth, and despite certain discrepancies in the Sr isotopic ratios both fall within the range of baseline bioavailable values from the Alsike region (see Table 5). This could mean that the individuals in boat-graves XI and XIII may be locals to the region where they were buried or from other areas with similar isotopic values. The candidate areas are shown in Figure 11 and Table 4.

![Figure 14: \( ^{87}\text{Sr}^{86}\text{Sr} \) values from boat graves XI (TAXIC: blue) and XIII (TAXIIM: yellow) showing drastic drop at the end of mineralization of the tooth enamel of the first molar and as provided by Vegacentre, 2015 (red rectangle).]
7. Discussion

The absolute $^{87}\text{Sr} / ^{86}\text{Sr}$ values and the variability of the values differ between the selected individuals from boat-graves XI and XIII and as can be seen in Tables 2-3 and Figures 12-13. Consequently the observed and potential differences will be the focus of the subsequent discussion. Strictly speaking and at this stage of the discussion it could be deduced that at least one individual, the one from boat-grave XI, seems to be of local origin.

7.1 $^{87}\text{Sr} / ^{86}\text{Sr}$ ratios

Results of $^{87}\text{Sr} / ^{86}\text{Sr}$ analysis show a good fit with previously recorded values from the nearby areas. This otherwise good correspondence of $^{87}\text{Sr} / ^{86}\text{Sr}$ ratios of the both samples indicates local origins. However, the individual in boat-grave XIII showed a large difference in $^{87}\text{Sr} / ^{86}\text{Sr}$ values from early childhood to later in life, also in comparison with the individual from boat-grave XI (Figure 14). This fact could be used to investigate a change of residence, but it could also be due to a change towards a higher intake of marine foods probably salmon fish (Nuorala et al. 2015, 8,10) that could have lowered the terrestrial $^{87}\text{Sr} / ^{86}\text{Sr}$ values toward the marine value of 0.7902 (Price et al. 2015, 10).

Given the character of the site and the burial forms or customs, one could expect that the population at Tuna in Alsike during the late Viking Age, was not a homogenous one but socially stratified society. That the variability of $^{87}\text{Sr} / ^{86}\text{Sr}$ values among the selected individuals could be due to diversity in diet should not be a surprise.

How this should be interpreted from the archaeological material? Burial of elites in real boats occurred in the Mälaren region around 800-1000 AD. It was a burial practice among elites (see section 4.1) and of symbolic significance that included sacrificed horses (Figure 5) and/or dogs deposited as whole skeletons and placed next to the buried individual and as seen also in Figure 7.

Elites in the Viking Age period, as noted by lipid analysis on ceramics performed by Isaksson’s (2005) on pottery shreds from Tuna in Alsike did consume rich food. His research found traces of animal fat, vegetable oil and fish oil and assumed meat consumption on daily basis thus indicating a rich and mixed diet (Isaksson 2005, 41-43). This could be the case for the individual in the boat-grave XIII.

Although previous stable isotopic analysis showed that the individuals buried depended on terrestrial food rather than sea food (Arvidsson 1999, 35) and that Tuna in Alsike was an inland settlement does not exclude the possibility that certain people there could have consumed marine food and probably more than others in the population during the Viking Age.

A fact that was later confirmed by Isaksson in 2005 which his research at Tuna in Alsike showed that many buried in boat-graves did consume fish (Isaksson 2005, 9). Accordingly 8 out of 12 individuals buried at Tuna cemetery had a diet dominated by fish both Hermansson (1998) and in Isaksson (2005) pp.39-40 mentioned this.
Archeological evidence may allow a narrow interpretation however none of these boat-graves were simple graves as discussed in sections 4.2 and 4.3. Due to the many grave goods and the sacrificial animals it is probable there was also a variability in the diet, as these boat-graves were graves of individuals while alive had enjoyed a high status among the population of Tuna in Alsike in the Viking Age.

**7.2 Boat-graves XI and XIII**

None of the artifacts in both boat-graves and as described earlier in sections 4.2 and 4.3 pointed towards a non-local or specific geographical area as place of origin beside the boats and the grave goods were likely locally produced. Further, the grave goods were typical of what is expected to be found in male burials in the region of Tuna in Alsike such as the start-a-light stone (Price 2002, 121). The fact remains that the selected boat-graves however belonged to individuals had a high rank among the Viking population at Tuna in Alsike.

To summarize, the strontium differs from what would be expected from a costal dweller, which should be around 0.7092 (see section 2.2). These two individuals lived in Tuna in Alsike or nearby during the early period of tooth formation (approximately 500 days) and between the ages of 2 and 8 years of age for both teeth. Whereas one individual, the one in boat-grave XIII, had spent the time of the latest tooth formation period somewhere else or at least have had a deviating diet that produced deviating Sr values.

The lack of a baseline map of bioavailable strontium values across Sweden in the region to determine local isotope ratios would have been necessary to be able to provide a better resolution of the mobility within the area (Price et.al 2015, 10).

Both individuals, XI and XIII, were locals at some time. However it is necessary to keep in mind that the non-local designation does not necessarily means a specific distance or place of origin and that the determination of place of origin can be an impossible task. The place of the non-local may not have been as distant as might be imagined.

Beside it is advisable, also depending on availability and costs of analysis to incorporate comparisons of strontium isotope signatures in both tooth enamel and bone collagen from the same individual. Strontium values in bone samples of same individual can reflect the latest place of residence, for example.

Unlike tooth enamel which is formed early and does not alter its chemical composition, the human bone remodels trough an individual’s life time and at different rates and types of mineralization. The diaphysis e.g. of the tibia or femur can take decades to reshape. These rates of turnover for different bones can be used to detect places of residence (last and latest) and due to the fact that strontium turnover in bone does take time (Slovak & Paytan 2011, 748).

Finally this study underlines key utility of strontium analysis as to be able to do an identification of local and non-local origins (Price et.al 2015, 11).
Also and beside the importance of Strontium analysis in investigating a local or foreign presence this paper showed the effectiveness of laser ablation. Laser ablation allows for easy, rapid and controlled analysis of Strontium isotopic data from tooth enamel and it has revealed to be less destructive than other alternative methods such as bulk sampling (Figure 15).

Figure 15: First molar from boat grave XIII shows no change in the tooth enamel after laser ablation.
8. Conclusion

The aim of this essay has been to detect the presence of nonlocals in the prehistoric cemetery at Tuna in Alsike and as a sign of interaction and mobility, which was accomplished, and questions raised were also answered. This pilot study used laser ablation mass spectrometry on tooth enamel and obtained strontium isotopic data. The method proved its potential to the archaeological research and proved robust means in determining past mobility.

Strontium isotopes, which show no fractionation up the food chain, represent the rocks from which groundwater pass. These isotopes vary with the geology from region to region so it is possible to provide a fingerprint for different rock types. Since the distribution of rocks is usually well mapped in most countries then can the geology of these countries consequently provide a key to study mobility of its prehistoric people.

Strontium in humans is found in bones and teeth however tooth enamel and not collagen (in bones) was analysed as it is denser and is considered less susceptible to diagenesis and contamination. Since teeth and the tooth enamel are formed during childhood and because they are not subject to tissue turnover they offer the possibility of comparing inorganic components such as strontium, having a “locked-in” signature.

Skeletal remains from a burial site at Tuna in Alsike dating to the Viking era were available at Archaeological Research Laboratory at Stockholm University. Tooth enamel from two boat-graves XI and XIII were subjected to strontium analysis by laser ablation at the Vegacentre at the Swedish Museum of National History.

The tooth enamel of the first molar (M1) of the individual in boat-grave XIII and from the left mandibular canine of the subject from boat-grave XI were used. These teeth were chosen as mineralization began around and after birth and continued up to age of 3-4 years respectively.

Isotopic data for strontium was successfully obtained, and showed significant variations but it followed, in one individual (from boat-grave XI), closely the local isotopic terrestrial trend of the Tuna in Alsike region with surroundings thus suggesting a local origin. One interesting observation was that the strongly decreasing \(^{87}\text{Sr}/^{86}\text{Sr}\) values of the subject in boat-grave XIII could have indicated change or mix in diet or different (non-local) geography already in early childhood.

Further investigation of light and stable isotopic analysis such as carbon, nitrogen and oxygen in the subjects’ bone collagen is recommended, a standard practice in the study of past diet that can shed more light on their origin and past mobility.

To sum up, strontium isotope analysis suggested a local origin in one of the individuals (boat-grave XI) and a non-local origin to the other (boat-grave XIII). The fact that both individuals received a boat burial and that their graves were rich in grave goods and with horse sacrifices leads also to conclude that the subjects, in this case, both enjoyed a high status in life and when dead were consequently buried according to Old Norse Mythology and Viking elite burial practices which could include a boat-grave.
References


