Estonian Journal of Archaeology, 2025, 29, 2, 109–137 https://doi.org/10.3176/arch.2025.2.01

Defining the Estonian strontium isoscape for archeological and paleoecological provenance studies

Raivo Suni
raivo.suni@ut.ee
Archemy, Department of Archeology, Institute of History and Archeology, University of Tartu, Jakobi 2, 51005 Tartu, Estonia

Kalle Kirsimäe
kalle.kirsimae@ut.ee
Department of Geology, Institute of Ecology and Earth Sciences, University of Tartu, Ravila 14A, 50411 Tartu, Estonia

Eve Rannamäe
eve.rannamae@ut.ee
Archemy, Department of Archeology, Institute of History and Archeology, University of Tartu, Jakobi 2, 51005 Tartu, Estonia

Lembi Lõugas
lembi.lougas@ut.ee
Archeological Research Collection, Tallinn University, Rüütli 10, 10130 Tallinn, Estonia / Department of Zoology, Institute of Ecology and Earth Sciences, University of Tartu, J. Liivi 2, Tartu 50409, Estonia

Liina Maldre
liina.maldre@ai.ee
Archeological Research Collection, Tallinn University, Rüütli 10, 10130 Tallinn, Estonia

Mari Tõrv
mari.torv@ut.ee
Archemy, Department of Archeology, Institute of History and Archeology, University of Tartu, Jakobi 2, 51005 Tartu, Estonia / Chair of Analytical Chemistry, Institute of Chemistry, University of Tartu, Ravila 14A, 50411 Tartu, Estonia

Aivar Kriiska
aivar.kriiska@ut.ee
Chair of Laboratory Archeology, Institute of History and Archeology, University of Tartu, Jakobi 2, 51005 Tartu, Estonia

Ester Oras
ester.oras@ut.ee
Archemy, Chair of Analytical Chemistry, Institute of Chemistry, University of Tartu, Ravila 14A, 50411 Tartu, Estonia / Chair of Laboratory Archeology, Institute of History and Archeology, University of Tartu, Jakobi 2, 51005 Tartu, Estonia

Received 19 March 2025, accepted 11 July 2025, available online 9 September 2025

ABSTRACT

Strontium isotope analysis has been used in archeology for about 40 years to study the provenance and mobility of ancient humans and animals. The interpretation of strontium isotope compositions in archeological materials requires a reference isotopic baseline map that delineates the geographical variation of bioavailable strontium. This paper introduces the first full map of bioavailable strontium in Estonia, based on the $^{87}Sr/^{86}Sr$ ratio of bioavailable strontium collected from 84 rodents and snails across 38 locations. The results were compared with data that also include larger wild and domestic mammals, to see if their data can be used as a reference in future studies.

The analysis identified two clearly distinct isotopic areas in relation to Estonia's bedrock composition: (1) coastal and central Estonia, including the West Estonian archipelago, where bedrock is composed of Ordovician and Silurian carbonate rocks and characterized by bioavailable $^{87}Sr/^{86}Sr$ ratios between 0.7094 and 0.7147; and (2) southern Estonia, located predominantly on Devonian sandstone bedrock, with $^{87}Sr/^{86}Sr$ ratios of 0.7147–0.7185. The analysis also showed that when stricter statistical methods were applied, the dataset that included larger wild and domestic mammals gave similar results. Hence, in Estonia, our expanded dataset can be cautiously used to provide context in areas where rodent data are missing. The baseline map refines and expands our current knowledge about the distribution of bioavailable strontium in the Baltic Sea region.

KEYWORDS

strontium isotopes, geochemistry, archeology, baseline map, provenance studies.

Introduction

Strontium is a chemical element that is incorporated into living tissues through water and food from the local environment. It has four stable isotopes: three non-radiogenic isotopes ^{84}Sr (ca 0.56%), ^{86}Sr (ca 9.86%), and ^{88}Sr (ca 82.58%), and one radiogenic ^{87}Sr isotope, which forms from the decay of ^{87}Rb (CIAAW). The ratios of these isotopes can vary in rocks, soils, surface, and/or groundwater depending on their origin and geological age, leading to region-specific $^{87}Sr/^{86}Sr$ signatures (Bentley 2006).

Strontium does not fractionate in geological and biological processes, in contrast to light-element stable isotope systems such as carbon, nitrogen, oxygen, and sulfur (Capo et al. 1998; Blum et al. 2000; Price et al. 2002; Rossi et al. 2024). Its isotopic composition is strongly influenced by the composition and age of rocks interacting with fluids at or near the Earth's surface (Faure & Mensing 2005; Rossi et al. 2024). This makes the $^{87}Sr/^{86}Sr$ ratio a valuable tool in provenance studies. Since the half-life of ^{87}Rb is 48.8 billion years (Faure & Mensing 2005), the $^{87}Sr/^{86}Sr$ ratio remains stable over the time periods relevant to archeology (Bowen & West 2008; Holt et al. 2021).

Rocks interact with water during weathering, releasing strontium into water and soil (Price et al. 2002). Through food chains, strontium, which behaves similarly to calcium, is distributed throughout ecosystems and can replace calcium in bone- and shell-forming tissues. Strontium deposited in the organism has no metabolic function (Pors Nielsen 2004; Bentley 2006; Willmes et al. 2018). In addition to strontium redistribution from rocks during weathering, plants can absorb strontium from wet and dry deposition (sea spray, aeolian dust) through their leaves (Snoeck 2014; Schulting et al. 2018; Alonzi et al. 2020; Carling et al. 2020). In agriculture, activities such as irrigation and the use of fertilizers or phytochemicals can significantly alter the strontium isotopic composition of plants and substrate soil (Techer et al. 2017; Aguzzoni et al. 2018). These circumstances must be considered in the analysis and interpretation of strontium isotope ratios.

Strontium isotopes have been widely used for over forty years to study the provenance of archeological materials (Ericson 1985; Price et al. 1994; Bentley 2006). They help in understanding major cultural processes such as migration, diffusion, invasion, colonization, cultural exchange, and trade (Barnard & Wendrich 2008; Gori et al. 2018). The key to strontium isotope analysis is matching an individual's isotopic signatures to the bioavailable strontium at their place of burial (Bentley 2006; Slovak & Paytan 2012). The $^{87}Sr/^{86}Sr$ ratios of mammal (including human) bones and teeth can be traced to the geology of the areas where individuals were born, grew up, and died, as strontium from water and food is incorporated into the skeleton during tissue formation (Price et al. 2002). Typically, these isotopic signals are compared with known reference data or baseline maps that reflect the isotopic ratio of bioavailable strontium at specific locations or regions. To establish this reference framework, locally identified materials (plants, mammals with a small distribution range, water from small water bodies, bedrock, etc.) are often used (Lengfelder et al. 2019; Holt et al. 2021).

In recent years, numerous baseline maps of bioavailable strontium have been created worldwide using various materials, analytical methods, and interpolation techniques (Holt et al. 2021; James et al. 2022). For example, the map for Poland is based on isotopic ratios of bedrock, surface waters, and plants (Zieliński et al. 2021), while Denmark's map primarily used surface water and topsoil (Frei & Frei 2013). In Ireland, the focus was on the strontium isotopic composition of plants (Snoeck et al. 2020), whereas in France and Portugal, plant samples and soil leachate were used (Willmes et al. 2018; James et al. 2022). In several countries, such as the Netherlands (Kootker et al. 2016), Greece (Whelton et al. 2018), Germany (Bentley & Knipper 2005), and Sweden (Sjögren et al. 2009; Price et al. 2018), mammal bones (bone tissue, tooth dentin, or preferably enamel) from archeological sites were a key source for baseline maps.

There is no comprehensive strontium isotope baseline map for Estonia. In neighboring countries, baseline maps have been created for Lithuania using isotopic data from archeological mammal remains (Piličiauskas et al. 2022) and for southern Sweden using surface water, soil leachate, and plant material (Ladegaard-Pedersen et al. 2021). In southern Finland, isotopic data from zooarcheological finds have been analyzed for baseline values, but no baseline map has been produced (Price et al. 2021). Strontium isotope analyses have also been reported for a few mammal finds in Latvia (Petersone-Gordina et al. 2022), but there are no studies of isotopic geography for Latvia.

In Estonia, a few $^{87}Sr/^{86}Sr$ ratios have been published for Bronze Age and pre-Roman burial site finds in northern Estonia (Oras et al. 2016), Viking Age Salme ship burials in Saaremaa (Price et al. 2016; Price et al. 2020), and a pre-Roman burial site in Tallinn (Niinesalu-Moon et al. 2023). Based on these limited data, baseline strontium isotope ratios in northern Estonia are defined to range from 0.7106 to 0.7137 (Oras et al. 2016). Table 1 summarizes the bioavailable strontium isotope data published for Estonia to date. Additionally, Estonia is represented in the European soil database (n = 14, $^{87}Sr/^{86}Sr$ ratio 0.7042–0.7106) (Hoogewerff et al. 2019).

These datasets are geographically limited and provide insufficient information about the variability of bioavailable strontium in Estonia, hindering regional provenance analysis. This study creates the first Estonian bioavailable $^{87}Sr/^{86}Sr$ baseline map covering the whole country, using strontium ratios from animal remains collected from archeological sites across Estonia. This baseline map will significantly aid archeological provenance studies in the future, including the tracking of prehistoric human and animal migrations within the country. Furthermore, the newly created dataset places Estonia within the broader Baltic Sea strontium isotope background, helping to trace prehistoric population dynamics in the region.

In addition to creating the baseline map, this study also tests the usability of data from larger wild and domestic mammals as reference material. Several previous strontium isotope studies have used such data to calculate baseline values (e.g., Marciniak et al. 2017; Price et al. 2019; Piličiauskas et al. 2022; Eckelmann et al. 2024; Penske et al. 2024). However, some researchers are cautious about using data from larger mammals, as their home ranges may span multiple regions with different $^{87}Sr/^{86}Sr$ ratios (Kootker et al. 2016; Blank et al. 2018; Holt et al. 2021). In the case of domestic mammals, a key concern is that they may have been imported from elsewhere, meaning the strontium signal in their tooth enamel reflects the region where they were raised, not necessarily

TABLE 1. Data on $^{87}Sr/^{86}Sr$ ratios published in Estonian archeological studies (n – number of analyzed specimens/individuals; n/a – not analyzed)

Context (publication)	Animals	Humans
Bronze Age and pre-Roman burial site in northern Estonia (Oras et al. 2016)	n = 8 0.7106–0.7159	n = 8 0.7110–0.7196
Salme ship burials (Price et al. 2016)	n = 13 0.7094–0.7199	n = 8 0.7237–0.7324
Salme ship burials (Price et al. 2020)	n = 13 0.7094–0.7308	n = 34 0.7104–0.7393
Pre-Roman burial site in Tallinn (Niinesalu-Moon et al. 2023)	n/a	n = 6 0.7112–0.7126

where they were found (van der Jagt 2012; Madgwick et al. 2019). The results from domestic mammals may also be influenced by imported feed used in their diet (Montgomery 2010). This study also aims to test how much the results from rodents and larger mammals differ, and whether, in the Estonian context, data from larger mammals could be used to estimate baseline values in areas where rodent data are unavailable.

Geological setting of Estonia

Estonia is located on the East European Platform at the southern edge of the Fennoscandian Shield, where crystalline rocks outcrop in Finland, Sweden, Norway, and northwestern Russia (Koistinen et al. 2001; Lahtinen et al. 2023). The Precambrian crystalline rocks underlying the platform's sedimentary cover in Estonia date from the Paleo- to Mesoproterozoic and consist of Svecofennian metamorphic and plutonic formations, as well as anorogenic rapakivi granites that intrude the Svecofennian metamorphic complex (Puura et al. 1997). Structurally, the crystalline bedrock in Estonia is comparable to the Svecofennian Domain of the Fennoscandian Shield in Finland and Sweden (Kirs et al. 2009). This bedrock exhibits a flat, peneplained erosional surface, dipping approximately two to four meters per kilometer to the south. The thickness of the sedimentary cover increases from about 100 meters in northern Estonia to approximately 800 meters in southern and southwestern Estonia (Soesoo et al. 2004), and there are no crystalline basement outcrops on the Estonian mainland.

The sedimentary cover in Estonia consists of Neoproterozoic to Paleozoic deposits from the Baltic Paleobasin (Raukas & Teedumäe 1997). This basin spans the southeastern part of the present Baltic Sea basin and the western portion of the East European Platform. The sedimentary deposits thicken southward and southeastward, ranging from approximately 800 meters in southern Estonia and northern Latvia to about 2500 meters at the southern boundary of the Baltic Paleobasin (Poprawa et al. 1999; Šliaupa & Hoth 2011).

In Estonia, the sedimentary rocks of the Baltic Paleobasin are unmetamorphosed and largely undeformed (Kirsimäe et al. 2020). The sedimentary sequence, which unconformably overlies the crystalline Precambrian basement, begins with Ediacaran sandstones and silty clays. While Ediacaran sediments do not outcrop at the present ground surface, the southward dip of the stratigraphy results in progressively younger beds outcropping in belts of varying width, depending on the thickness of the corresponding units (Fig. 1). Cambrian sediments (539–483 Ma), comprising clay-, silt-, and sandstones, are exposed in a narrow strip along the Gulf of Finland. These are overlain by Ordovician (483–441 Ma) sedimentary rocks, including siltstones, sandstones, black shales, and normal marine limestones (Raukas and Teedumäe 1997). The Silurian (441–416 Ma) succession, outcropping in central and western Estonia, predominantly

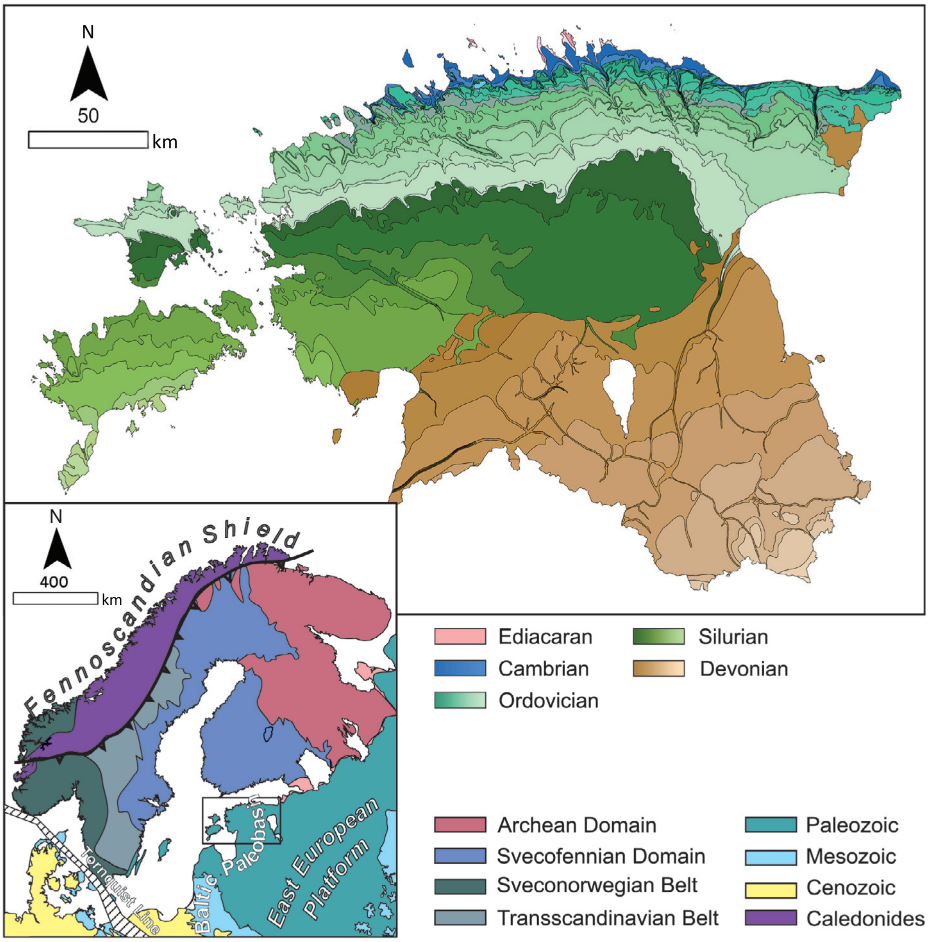

FIG. 1. Geological map of Estonia and its structural position in Fennoscandia. The geological map is from the Estonian Geological Survey (scale 1:400 000; Estonian Land Board's map application).

consists of partially dolomitized shallow marine carbonates (Raukas & Teedumäe 1997; Šliaupa & Hoth 2011). The Devonian (ca 394–372 Ma) deposits in Estonia primarily include shallow marine deltaic sandstones and siltstones, interbedded with lagoonal dolomites and marlstone limestones (Raukas & Teedumäe 1997).

Since the end of the Devonian period, the Estonian territory has experienced very slow but fluctuating uplift and erosion (Kirsimäe et al. 2020). As a result, Late Paleozoic, Mesozoic, and Early Cenozoic sediments are absent in Estonia but can be found in the southern and southwestern regions of the Baltic Paleobasin (Šliaupa & Hoth 2011). The current loose sedimentary cover, which overlies Paleozoic sedimentary rocks, mainly consists of Pleistocene continental glacigenic deposits (including meltwater sediments) and Holocene marine and continental deposits (Raukas & Teedumäe 1997).

Since the Middle Pleistocene, the Estonian area has been repeatedly covered by the Scandinavian Ice Sheet (Kalm 2012). During glacial periods, the area was primarily in zones of glacial erosion or moderate accumulation, resulting in a relatively thin Quaternary sediment cover across much of its territory (Raukas & Teedumäe 1997). In northern and western mainland Estonia, as well as on Saaremaa Island, the Quaternary cover is typically less than 5 meters thick (Fig. 2). The thickness increases to 10–20 meters in central and southwestern Estonia (including Hiiumaa Island) and can locally exceed 20 meters, reaching 50–200 meters, especially in front of the Baltic Klint along the Gulf of Finland, in the central Estonian drumlin fields (e.g., Saadjärve Drumlin Field), on the southeastern uplands of Otepää and Haanja, and within ancient buried valleys (Raukas & Teedumäe 1997).

Approximately 95% of Pleistocene sediments consist of tills, primarily deposited in lodgment settings, and composed of a mixture of locally derived and far-transported materials. However, the proportion of transported bedrock material decreases significantly – falling below 20–30% – within 6–8 kilometers from bedrock lithological contacts. The content of far-transported erratic material in lodgment tills rarely exceeds 5–10%. The proportion and transport distance depend on rock types; resistant varieties of crystalline rocks can be transported over hundreds of kilometers, enriching the tills with more durable clasts (Raukas 1978).

Alongside till, the other most common types of Pleistocene surface deposits are glaciofluvial and glaciolacustrine sediments such as sand and gravel, fine sand and clays (including varved clay). The latter two usually overlie the till,

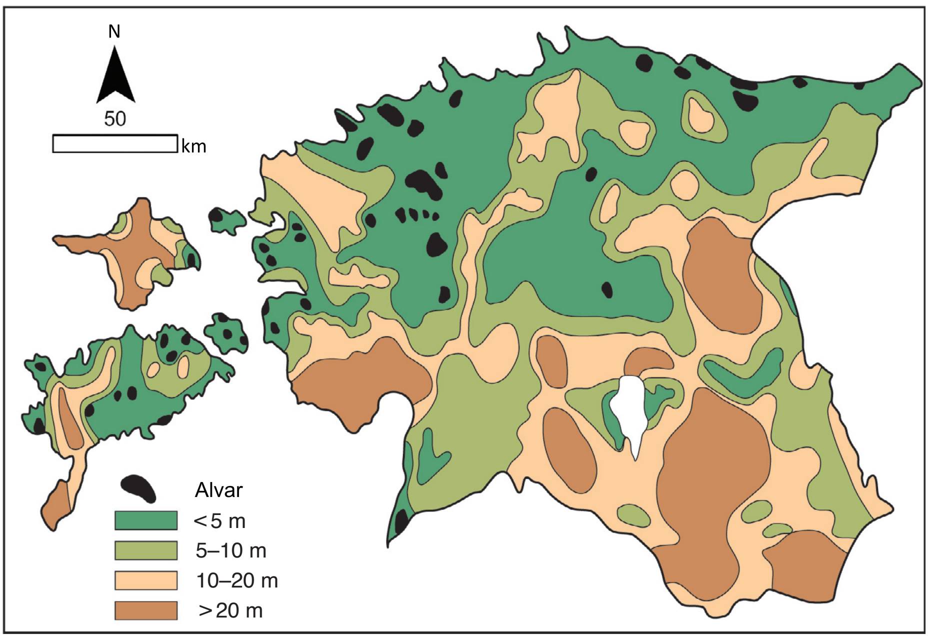

FIG. 2. Thickness of the Estonian Quaternary deposits. The map is adapted from Raukas & Kajak (1997).

smoothing out its surface irregularities (Pirrus 2001). Relatively thin Holocene sediments include: (1) marine sediments formed over the last 12 000 years due to shoreline shifts, characterizing areas that were once underwater; (2) aeolian sediments, reshaped and transported by winds along exposed coastlines; and (3) lake and peat bog sediments (Raukas 1988; Pirrus 2001). The Pleistocene glaciofluvial and glaciolacustrine sediments, along with Holocene sediments (excluding peat bog sediments), are composed mainly of locally reworked material from underlying tills or sedimentary bedrock.

From a strontium isotope chemistry perspective, the composition and origin of rocks transported from Scandinavia to Estonia during the Pleistocene glaciations are significant in the coarse fractions of tills. These rocks mostly originate from southern Finland, where erratics of certain rock types can be traced to specific sources: rapakivi granites from Viipuri, southwestern Finland (Laitila and Vehmaa), and Åland; quartz porphyries from Suursaari, Åland, the Gulf of Bothnia, and the Baltic Sea bottom; and olivine diabase from Satakunta (Viiding 1955; Raukas 1988). The most common erratics are gneisses, migmatized granites, and rapakivi granites of southern Fennoscandian origin (comprising approximately 80%). However, the finer fractions of glaciogenic sediments, which are most susceptible to strontium leaching into the environment, are dominated by locally derived bedrock material (Raukas & Teedumäe 1997).

The composition of surface water and shallow groundwater in Estonia is influenced by glaciogenic rocks and outcropping bedrock sediments (Karise et al. 2004). Given the limited thickness of the glacial deposits in northern and central Estonia, the shallow groundwater in these areas is largely in equilibrium with the composition of bedrock sediments. In southern and southeastern Estonia, it reflects the composition of glaciogenic sediments.

In addition to the geological background, the bioavailable strontium isotope composition can also be locally influenced by marine and anthropogenic effects. The Estonian coastline stretches for about 3800 kilometers (Suursaar et al. 2024). Active exposure to the sea means that sea spray can significantly lower coastal strontium isotopic ratios (Alonzi et al. 2020). Ratios in coastal areas can also be considerably influenced by a higher proportion of fish in the diet (Price & Gestsdóttir 2006). Additionally, the use of artificial fertilizers in Estonia, which dates back to the late 19th century (Nebokat 1882), has had a notable impact. Fertilizer use peaked in the 1980s, with over 100 000 tons of nitrogen fertilizers and more than 60 000 tons of phosphorus fertilizers rich in strontium being applied annually to Estonian fields (Iital et al. 2008).

Analytical material and methods

The dataset for this article consists of (1) newly sampled archeological remains from the archeological research collections of the Tallinn University and the University of Tartu; and (2) previously published data from Estonia (Oras et al. 2016; Price et al. 2016; Price et al. 2020). Both datasets were analyzed using thermal ionization mass spectrometry (TIMS) at the University of North Carolina at Chapel Hill (USA) Isotope Geochemistry Laboratory. Sample preparation for both datasets followed the protocols from the archeological chemistry laboratory at the University of Wisconsin–Madison (Frei & Price 2012; Price et al. 2012; Oras et al. 2016).

SAMPLE SELECTION

The dataset included a total of 182 zooarcheological specimens from 65 distinct geographical points (Fig. 3; Supplementary material). After preliminary data analysis, modern samples (n = 6) were excluded from further analysis because their $^{87}Sr/^{86}Sr$ ratio differed significantly from archeological animal samples in the same area. In addition, we removed the data of four dogs found in the Salme ship burial, as they were associated with foreigners in the same burial and were likely of non-local origin (Price et al. 2020). The removed data are marked as strikethrough entries in Supplementary material.

Two types of data were used in compiling Estonia's strontium baseline map. The primary dataset consisted of teeth (n = 85) and bones (n = 14) from small mammals, which are commonly used for constructing bioavailable strontium baselines (Bentley 2006; Holt et al. 2021). Rodents are generally considered the most suitable sample material; however, rats (n = 10) were excluded from the primary dataset due to their potential for unintentional human-mediated transport

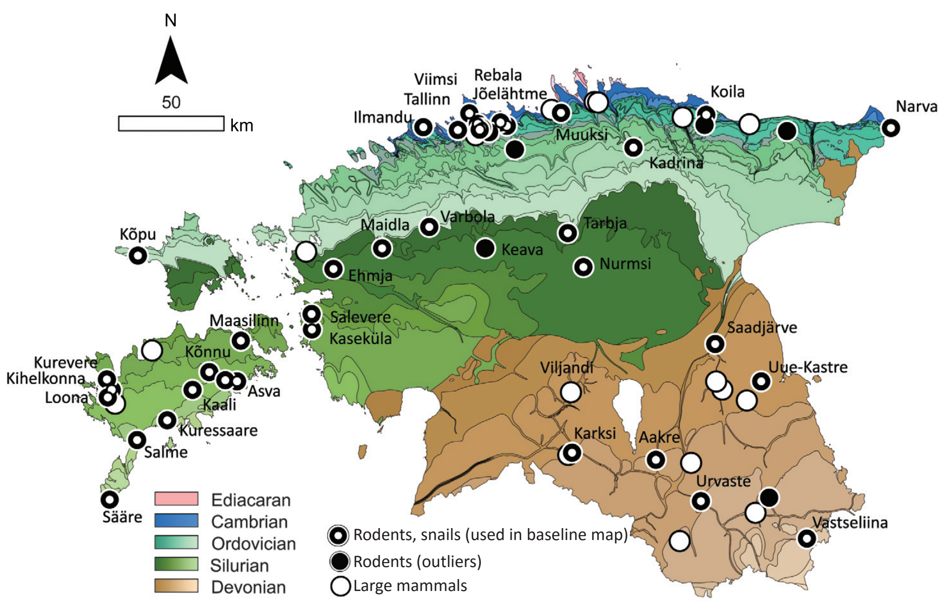

FIG. 3. Geographic distribution of zooarcheological specimens used in the strontium analysis. See the text and Supplementary material for details.

(e.g., through trade) and their frequent reliance on anthropogenic food sources (Perry et al. 2008). Snail shells (n = 9) were included in the primary dataset, with the acknowledgment that they may reflect only a very small habitation area (even a single rock), which can lead to narrow and possibly biased isotope results. In total, the primary dataset used to construct the baseline map included 108 specimens from 44 locations (Supplementary material; Fig. 3).

The secondary dataset consisted of larger wild and domesticated mammal specimens, for which some caution has to be exercised when including them in creating an isotope baseline map. Depending on the species, wild mammals can travel tens or even hundreds of kilometers, making it difficult to detect a clear local signal. Domestic mammal samples may also be influenced by the long-distance acquisition and exchange of livestock (Bentley & Knipper 2005; Kootker et al. 2016). Despite these limitations, we wanted to test if and how samples from larger mammals could be incorporated into building a local strontium baseline map. Our secondary dataset included 64 specimens from 29 locations – sheep/goats (n = 17), hares (n = 10), rats (n = 10), pigs (n = 7), cattle (n = 5), and other mammals (n = 15) – with strontium isotopes measured from teeth (n = 54) and bones (n = 10).

SAMPLING PROTOCOL

The sampling procedure followed previously reported protocols (Frei & Price 2012; Price et al. 2012; Oras et al. 2016). Briefly, teeth and bone fragments were cleaned in ultrapure Milli-Q water using an ultrasonic bath. The water was changed after each wash until it became clear, ensuring that no extra mineral particles were left on the tooth or bone surface. Thereafter, about 8–10 milligrams of tooth enamel or bone was cut using a clean saw-drill.

For small rodent species, the teeth were often too small to obtain pure enamel, as recommended by the laboratory protocol. Thus, the entire tooth was cleaned and sampled (enamel and dentine). The inclusion of dentine in the sample carries some risk, as dentin may somewhat affect the $^{87}Sr/^{86}Sr$ ratio of the sample, altering the signal more toward diagenetic ("local" and/or modern) values. A similar risk exists in the analysis of bones, which are porous and can be "contaminated" with strontium intake from the soil during diagenesis (Rasmussen et al. 2019; Budd et al. 2000). However, since we were particularly interested in the local signal characterizing the find location of the sampled animal remains, potential contamination from diagenesis was not considered a major problem. The analytical material was crushed with a pestle in a mortar and packed in a 2-milliliter plastic vial.

STRONTIUM ANALYSIS

The samples were analyzed in the Isotope Geochemistry Laboratory (Department of Geological Sciences, University of North Carolina at Chapel Hill) using TIMS.

The crushed samples were dissolved in 3.5 M HNO_3 and strontium was purified with Eichrom Sr-Spec resin and analyzed on a VG Sector 54 mass spectrometer run in dynamic mode. Internal precision in the laboratory is consistently around 0.0007% standard error ($1\sigma = 0.00006$ in the ratio of a particular sample).

SPATIAL ANALYSIS

Open-source software Quantum Geographic Information System (QGIS) and ArcGIS, a geographic information system developed by the Environmental Systems Research Institute (U.S.A.), were used to create maps. For each sample location, coordinates were extracted and converted to the Estonian Coordinate System of 1997 (EPSG: 3301). The basemaps used for the data were the bedrock map created by the Estonian Geological Survey (scale 1:400 000), freely available in the Estonian Land Board's spatial data repository, and the Estonian contour map. The final baseline map was created using the Empirical Bayesian Kriging Regression Prediction method (see Gribov & Krivoruchko 2020), which incorporates geological information along with the measured baseline data to estimate the variation in the strontium baseline within the region.

STATISTICAL ANALYSIS

The statistical analysis compared $^{87}Sr/^{86}Sr$ ratios from skeletal remains with the bedrock geology of Estonia. The data were grouped by bedrock stratigraphy and lithology, and outliers were identified using the median absolute deviation (MAD) method with a threshold of 3 (Leys et al. 2013). Statistical analysis was conducted using Microsoft Excel and the R programming language for statistical computing, employing Levene's test and the independent-sample *t*-test to compare different datasets.

Results and discussion

Our datasets are geographically somewhat unevenly distributed (Fig. 3) because they reflect the locations of major excavated archeological sites and inhabited regions (Kriiska et al. 2020). Based on location, local stratigraphy, and lithological characteristics of the Estonian bedrock, the samples were divided into seven groups (Table 2). Within this grouping, the strontium data from Cambrian to Silurian bedrock largely overlap, whereas the data from middle Devonian sandstones–siltstones (D2) show a clear difference (Table 2; Fig. 4). It is also notable that most of the data are widely dispersed, with several outliers.

To identify outliers, the MAD method (threshold 3) was used. Even after removing these outliers, the data in group S1 (lower Silurian dolostones) remained dispersed. Three small rodent tooth samples showed unusually high $^{87}Sr/^{88}Sr$ ratios (0.7166–0.7183). In contrast, all other samples from areas with Ordovician–Silurian limestone–dolostone bedrock had ratios consistently

TABLE 2. Summary of the primary dataset before and after removing outliers (MAD, threshold 3)

	C1 Lower Cambrian sandstones and shales	**C3–O2** Upper Cambrian to lower Ordovician phosphatic sandstones and black shale	**O2** Middle Ordovician limestones	**O3** Upper Ordovician limestones	**S1** Lower Silurian dolostones	**S2–3** Middle to upper Silurian limestones and dolostones	**D2** Middle Devonian sandstones–siltstones with dolostones
Initial ratios of $^{87}Sr/^{86}Sr$							
No. of samples	11	5	19	12	10	36	15
Min	0.7110	0.7130	0.7105	0.7078	0.7121	0.7055	0.7112
Max	0.7156	0.7169	0.7210	0.7197	0.7183	0.7199	0.7205
Range	0.0046	0.0039	0.0105	0.0119	0.0062	0.0144	0.0093
Median	0.7126	0.7130	0.7121	0.7129	0.7148	0.7118	0.7171
Standard deviation	0.0015	0.0017	0.0023	0.0033	0.0023	0.0037	0.0022
3MAD low	0.7090	0.7127	0.7106	0.7087	0.7080	0.7061	0.7147
3MAD high	0.7162	0.7133	0.7136	0.7171	0.7215	0.7175	0.7195
Modified ratios of $^{87}Sr/^{86}Sr$							
Final No. of samples	11	4	15	8	7	27	12
Min	0.7110	0.7129	0.7111	0.7112	0.7121	0.7094	0.7153
Max	0.7156	0.7135	0.7136	0.7156	0.7152	0.7146	0.7185
Range	0.0046	0.0006	0.0025	0.0044	0.0031	0.0052	0.0032
Median	0.7126	0.7130	0.7121	0.7132	0.7125	0.7113	0.7171
Mean	0.7129	0.7131	0.7121	0.7132	0.7134	0.7114	0.7171
Standard deviation	0.0015	0.0003	0.0006	0.0013	0.0014	0.0016	0.0010

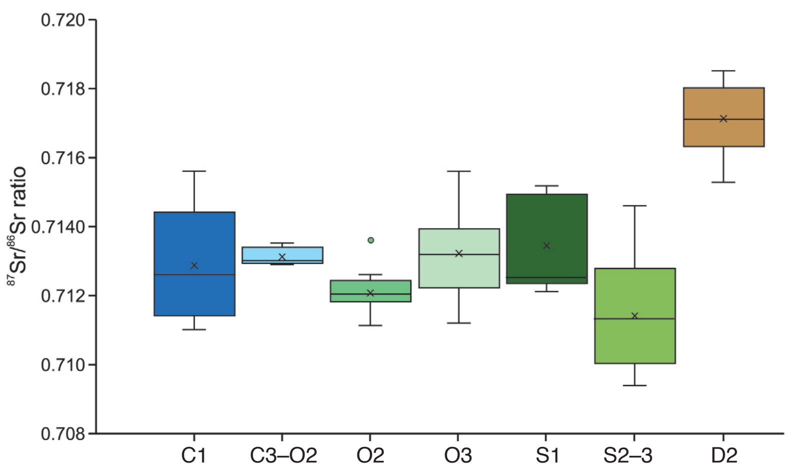

FIG. 4. Boxplot of $^{87}Sr/^{86}Sr$ ratio data by bedrock types after removing outliers, using only the primary dataset.

below 0.7156. These voles were excavated from Keava Hillfort, located in an area where Silurian dolomitized limestones of the Raikküla Regional Stage outcrop.

There could be several reasons for the anomalous rodent data from Keava. The hillfort was in use for more than six centuries and served as an important trade center in northern Estonia during the Viking Age (9–11th century CE) (Lang 2012). It is plausible that in larger prehistoric trade centers, the distribution of imported arable crops contributed to variations in strontium dietary intake (Kootker et al. 2016; Holt et al. 2021). Rodent skeletal remains found in archaeological excavations could also be incidental, originating from modern times (for example, contemporary voles that died in underground tunnels). Furthermore, the hillfort was built on the Keava–Esku marginal esker system, composed of glaciofluvial gravels and sands containing crystalline erratics with strontium isotopic signals typical of Fennoscandian crystalline rocks. Whatever the cause, these three Keava samples are unusual compared to the background strontium ratios and were discarded from further analysis.

Table 2 summarizes the results after excluding the outliers. Trimming the dataset significantly consolidated the data. In some cases, the standard deviation dropped to less than half of its original value, and the data range narrowed to less than one-third of the pre-filtering span. After filtering, 24 results were removed, reducing the number of usable samples from 108 to 84 and the number of mapped sites from 44 to 38 (black dots with white centers in Fig. 3).

According to the statistical analysis (Table 3), most of the bedrock areas have unequal variances. In these cases, Welch's *t*-test was used to compare mean $^{87}Sr/^{86}Sr$ ratios. Statistically, D2 is clearly different ($p < 0.05$), forming its own $^{87}Sr/^{86}Sr$ ratio area. Although there are also statistical differences between different layers of other bedrock types – C1 and S2–3; C3–O2, O2 and S2–3; O2 and O3; S1 and S2–3 – their ratios largely overlap, and they can be considered as one isotopic zone.

The map (Fig. 5) was interpolated in ArcGIS using the Empirical Bayesian Kriging Regression Prediction method. Areas located more than 30 kilometers away from the nearest data points were marked with a dashed line and labelled "No data." The map shows two large zones running northeast to southwest. It is noteworthy that the transition between these zones is aligned along the southwest–northeast-oriented boundary between Silurian limestone–dolostone formations and Devonian sandstone-dominated deposits (see Fig. 1).

Ratios below 0.7147 are typical of Cambrian, Ordovician, and Silurian bedrock areas. On the map, this zone is marked in green, with different intensities indicating strontium isotope sub-ranges. The sub-range with the lowest ratios is concentrated on Saaremaa, Estonia's largest island, where values below 0.7115 are common. This may be due to thinner Quaternary sediments and the stronger direct influence of Silurian carbonate rocks with $^{87}Sr/^{88}Sr$ ratios <0.7090 (Gouldey et al. 2010; Cramer et al. 2011). Mainland Estonia typically has higher $^{87}Sr/^{86}Sr$ ratios in this zone, mostly between 0.7126 and 0.7147, although they can

TABLE 3. Results of the independent sample *t*-tests comparing mean $^{87}Sr/^{86}Sr$ ratios of different bedrock areas (only the primary dataset). Bold results indicate statistically significant differences

	C1	C3–O2	O2	O3	S1	S2–3	D2	
C1	x	0.033 0.0002 0.648	0.004 0.0008 0.128	0.504 0.0003 0.614	0.808 0.006 0.428	0.754 0.0014 **0.015**	0.145 0.0042 **5.8e-07**	*p*-value of Levene's test Mean difference *p*-value of *t*-test
C3–O2		x	0.227 0.0010 **3.3e-04**	0.092 0.0001 0.824	0.161 0.0003 0.546	0.007 0.0017 **2e-05**	0.038 0.0040 **3.9e-09**	
O2			x	0.047 0.0011 **0.048**	0.057 0.0014 **0.040**	2.1e-04 0.0007 0.055	0.054 0.0050 **1.1e-11**	
O3				x	0.781 0.0002 0.748	0.269 0.0018 **0.006**	0.562 0.0039 **1.2e-05**	
S1					x	0.576 0.0020 **0.006**	0.419 0.0037 **1.2e-04**	
S2–3						x	0.038 0.0057 **3.1e-15**	
D2							x	

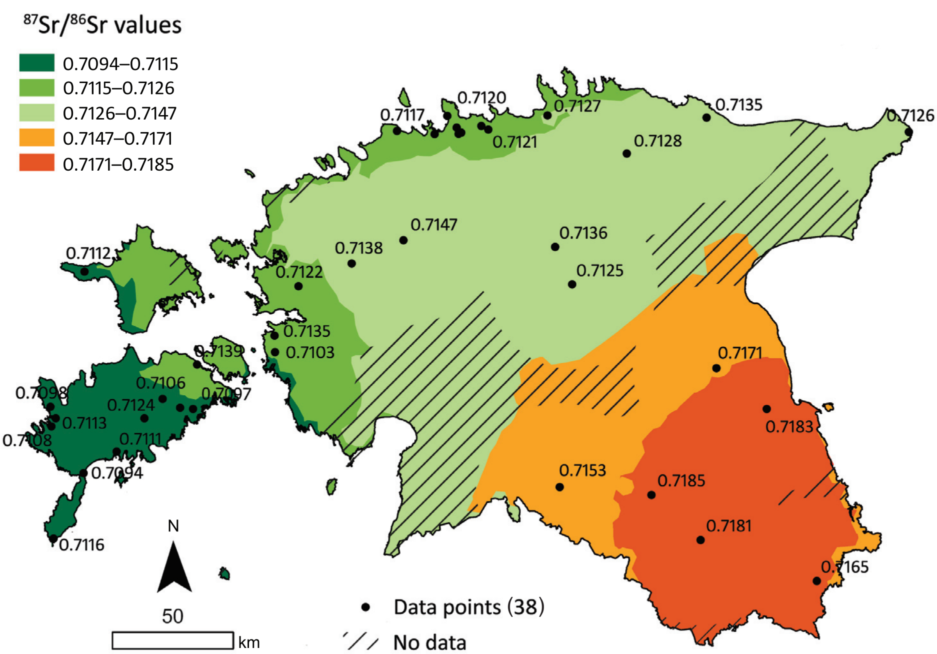

FIG. 5. Bioavailable strontium baseline map of Estonia. The number next to the data point indicates the median measurement result for that area. The hatched areas mark regions located more than 30 km from the nearest data point.

be lower in coastal areas. The second zone is characterized by the Devonian D2 area (marked in red on the map), where ratios exceed 0.7147. In the highlands of southeastern Estonia, Quaternary sediments are much thicker than the national average, and values above 0.7170 are common.

While creating the baseline map, several issues emerged that deserve additional commentary. The main factor influencing variability in $^{87}Sr/^{86}Sr$ ratios across Estonia is the geological structure of the sedimentary bedrock. Lower Cambrian and upper Cambrian to lower Ordovician terrigenous sediments (including black shale) outcrop only in a narrow west–east-oriented strip along the Baltic Klint by the shore of the Gulf of Finland, and exert no wider influence. Ordovician and Silurian marine carbonate rocks, however, compose a large and rather uniform complex in northern, western, and southwestern Estonia, with broadly similar strontium isotopic ratios averaging 0.7126–0.7147, though they can be as low as 0.7094. This is close to the strontium isotopic composition of typical ancient marine sedimentary rocks, generally around 0.708–0.709 (Qing et al. 1998; Azmy et al. 1999; Wierzbowski 2013), which largely also corresponds to the current marine $^{87}Sr/^{86}Sr$ ratio (ca 0.7092).

Another important factor that likely affects the bioavailable $^{87}Sr/^{86}Sr$ ratio – especially in coastal areas, where the lowest strontium isotopic ratios are often recorded – is sea spray. This may be the reason why several of the lowest values are from the islands (Saaremaa and Hiiumaa), as well as from northern and western Estonia. When sea waves break, tiny droplets of seawater are thrown into the air and carried inland by the wind. There, they settle onto bodies of water, plants, and the ground. Several studies (Alonzi et al. 2020; Göhring et al. 2023) have shown that marine aerosols can influence the isotopic ratios of plants and the animals that feed on them, shifting these values toward the lower, marine isotopic ratio.

In addition, the Estonian strontium isotope dataset used for the baseline map shows remarkable variability (Table 2). This may be caused by the Quaternary siliciclastic sediments rich in materials derived from the weathering of granitic and gneiss rocks in Fennoscandia. These sediments have increased local soil diversity and broadened the range of strontium isotopic ratios, which might otherwise be relatively narrow considering the homogeneous bedrock structure (Thomsen et al. 2021). The deposition of till during and after the Ice Age has been described by several authors as a significant factor influencing variability in $^{87}Sr/^{86}Sr$ ratios (Widga et al. 2017; Zieliński et al. 2021; Piličiauskas et al. 2022), and this likely applies to Estonia as well.

The $^{87}Sr/^{86}Sr$ ratio can also be influenced by the thickness of Quaternary sediments (Fig. 2). Lower isotope ratios shown on the strontium baseline map are typical of areas where the thickness of Quaternary sediments is <5 meters, and in areas defined as "alvars," where sediment thickness on top of the bedrock is <0.5 meters. These are coastal areas and the Central Estonian Plain. Higher strontium ratios, however, are characteristic of southeastern Estonia, where the sediment thickness often exceeds 20 meters. A thicker Quaternary sediment cover increases the proportion of far-transported Fennoscandian crystalline rock material in different size fractions, potentially carrying $^{87}Sr/^{86}Sr$ ratio signals exceeding 0.73 (Blank et al. 2018; Price et al. 2018).

It should also be considered that the Devonian shallow marine sediments of the Baltic Paleobasin, particularly in Estonia, were deposited in a tidally influenced deltaic setting and are mainly composed of detrital siliciclastic sediments alternating with shales and lagoonal carbonates (Raukas & Teedumäe 1997). These sediments were derived from the erosion of the Caledonian Orogeny (Tänavsuu-Milkeviciene et al. 2009) and hence carry the strontium isotopic signatures of Fennoscandian Shield rocks with high $^{87}Sr/^{86}Sr$ ratios (Blank et al. 2018; Price et al. 2018). This interpretation is further supported by elevated bioavailable strontium isotope ratios reaching 0.7177 in Lithuania, particularly in areas where Devonian sediments are covered by only ca 1–20-meter-thick glacial deposits (Piličiauskas et al. 2022).

Two large areas on the map lack sampling points and are marked with hatching as tentative. Using our baseline map and $^{87}Sr/^{86}Sr$ ratio zones, we can only estimate the strontium isotope ratios for these regions. In the southern part of southwestern Estonia, interpretations should be based on results characteristic of the Devonian (D2) area, while in the northern part, they should be based on results from the Silurian (S2–3) area. In coastal areas, sea spray can shift strontium ratios toward the marine ratio (ca 0.7092). In the northern part of northeastern Estonia, we assume $^{87}Sr/^{86}Sr$ ratios typical of the Ordovician (O3) and Silurian (S1) bedrock.

The baseline map of strontium in Estonia is shown as a contour map, created using the Empirical Bayesian Kriging Regression Prediction method. Some authors have criticized contour maps for making abrupt geological transitions appear too smooth (Adams et al. 2019; Holt et al. 2021). However, Rossi et al. (2024) have noted in response to criticism that geological changes can indeed be sharp and may not be accurately reflected by a contour map, emphasizing the importance of considering each case individually (Rossi et al. 2024). In Estonia, the use of a contour map is justified because glacial erosion and till deposition have mixed sediments and rocks with different strontium isotopic signatures across bedrock boundaries, resulting in gradual transitions in strontium isotopic ratios. Nevertheless, special attention is needed when dealing with data from transition areas between the two zones. In such cases, additional samples – preferably from zooarcheological specimens – should be collected to refine the local strontium signal.

Typically, the strontium isoscape map is useful for distinguishing local and non-local individuals by identifying bioavailable $^{87}Sr/^{86}Sr$ ratios that deviate from the local strontium baseline by more than two standard deviations (Price et al. 2002). However, this is challenging in Estonia due to the high variability of Sr ratios within a single geological background. Using the two-standard-deviation approach, we can easily encounter situations where ratios from the Devonian area overlap with those from Cambrian, Ordovician, and Silurian areas, and vice versa, complicating overall interpretation. Therefore, we recommend combining visual differentiation with statistical methods when analyzing the data.

In addition to the primary dataset, we tested if and to what extent samples from larger wild and domestic mammals (our secondary dataset) could be included in baseline map modeling. Our results showed that larger mammals somewhat influenced the variability of the data; however, stricter outlier detection methods (such as MAD, threshold 2) could be applied. After outlier removal, 132 out of 172 samples remained in our dataset, with the number of sites reduced from 60 to 54.

Under these conditions, the inclusion of larger mammals had minimal impact on data variability while improving geographical coverage. Figure 6 illustrates how maps created using the same ratio scale and interpolation method differ when based on different datasets. The boundaries of value areas that include $^{87}Sr/^{86}Sr$ ratios from larger wild and domestic mammals are marked with gray lines. Overall, the baseline maps show very similar zonation. The only clear difference is on Saaremaa, where the rodent-snail dataset reveals a distinct area with the lowest $^{87}Sr/^{86}Sr$ ratios.

Although the results from different datasets are similar, we recommend taking a more conservative approach by using the baseline map shown in Fig. 5 for Estonia. A sample consisting predominantly of rodents is more standardized: it reflects the strontium isotope ratio within a limited group of species that share similar behaviors and dietary habits (with the exception of snails in our sample), and therefore the results are not significantly biased by diverse metabolic pathways (Price et al. 2002; Grimstead et al. 2017). In addition, rodents typically have smaller home ranges compared to larger mammals, so their isotopic signatures more accurately reflect the local environmental baseline (Holt et al. 2021). Rodents found in archeological contexts are also less likely to have been brought in from elsewhere, which is a common concern with domestic mammals (van der Jagt 2012; Kootker et al. 2016).

Data from other mammals may be used as supporting information in areas where rodent data are unavailable. However, it is essential to ensure that (1) values from larger mammals fall within the defined value ranges of the baseline map; (2) the data are further validated and supported by regional datasets of small mammals; and (3) strict statistical methods are applied to detect outliers.

Overall, the bioavailable strontium map of Estonia (Fig. 5) aligns with the general understanding of the $^{87}Sr/^{86}Sr$ ratio distribution in the Baltic Sea region. In Finland and Sweden, where granite bedrock is exposed, the isotope ratio is significantly higher (>0.72) (Bäckström & Price 2016; Lahtinen et al. 2021; Price

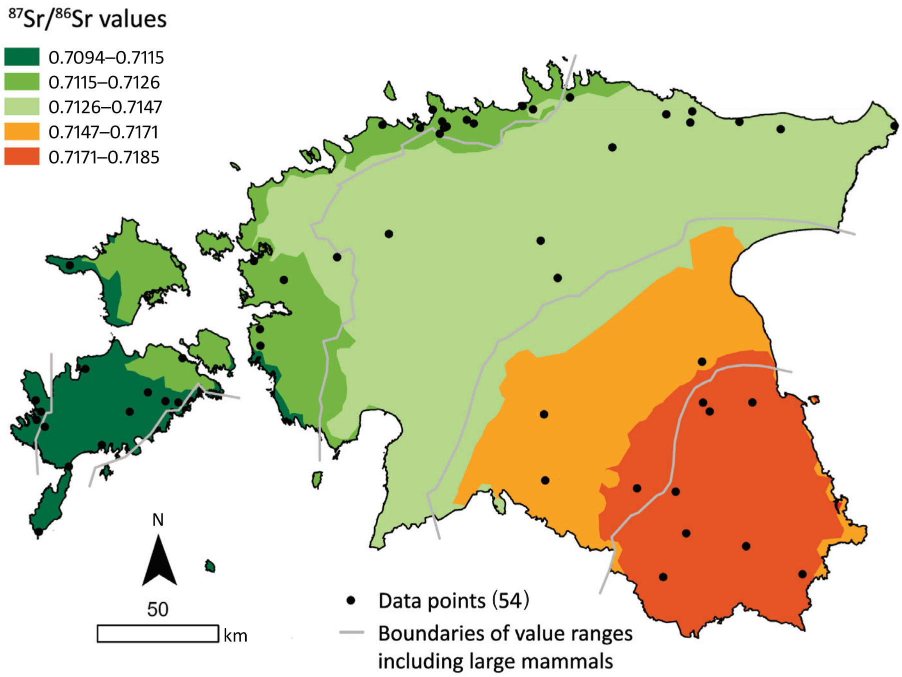

FIG. 6. Estonia's strontium baseline map with gray lines indicating the boundaries of value ranges that include data from larger wild and domestic mammals (n = 132, sites = 54).

et al. 2021; Boethius et al. 2024; Danielisová et al. 2025). For the Baltic Sea islands and archipelagos, the strontium ratio is primarily determined by the bedrock type. Åland, which consists mainly of Precambrian granite bedrock, generally exhibits ratios above 0.72 (Boethius et al. 2024). Gotland, with carbonate bedrock formed during the Ordovician and Silurian periods, has a $^{87}Sr/^{86}Sr$ ratio of 0.71–0.713 (Ahlström & Price 2021), similar to that of the Estonian islands and coastline. The strontium isotope ratio in the Devonian bedrock region of Lithuania (0.7155–0.717) (Piličiauskas et al. 2022) is similar to that of the Devonian area in Estonia.

Although no comprehensive strontium baseline map exists for Latvia, isotopic ratios (0.712–0.714) measured in mammal bones from the Riga area near the Gulf of Riga (Petersone-Gordina et al. 2022) are similar to those of the Estonian coastal region. Additionally, Price et al. (2020) analyzed $^{87}Sr/^{86}Sr$ in three snail shells from Grobiņa in western Latvia, reporting an average ±1 s.d. of 0.707429 ± 0.00008, which can serve as a baseline for the area. Unfortunately, comprehensive data for areas east of Estonia are lacking. Currently, only a few ratios (ca 0.717) are available from Staraya Ladoga (Price et al. 2020), located 125 kilometers east of St. Petersburg. For St. Petersburg, it is assumed that its similar bedrock composition allows the use of data from northern Estonia (Gutsmiedl-Schümann et al. 2020).

Conclusions

To interpret strontium isotope data for past migrations of humans and animals, regional maps of local bioavailable strontium are essential. This paper presents the first comprehensive map of bioavailable $^{87}Sr/^{86}Sr$ ratios for Estonia. The study demonstrates that Estonia's geological structure is reflected in the strontium ratios, with significant differences between Devonian and other bedrock formations.

Our results indicate that Estonia's strontium isoscape can be divided into at least two main zones, based on 84 zooarcheological specimens from 38 sites: (1) coastal and central Estonia, including the western islands, underlain by Ordovician and Silurian carbonate bedrock; and (2) southern Estonia, predominantly underlain by Devonian sandstone.

Variations within these zones further refine the baseline map. For example, Saaremaa, Estonia's largest island, generally exhibits the lowest strontium ratios, whereas the highest ratios are found in the highlands of southeastern Estonia. Similar results were observed when analyzing not only small rodent specimens but also larger wild and domestic mammals.

The baseline map provides valuable insights into mobility patterns in Estonian and eastern Baltic archeological contexts, helping to distinguish between local and non-local individuals and animals, and allowing for indirect assumptions about their origins. When using this strontium isotope baseline map in future research, it is essential to consider the variability of isotope ratios across different geological formations. Conclusions should be based not only on average values but also on their variability. Since living organisms absorb strontium through water and food, the possible origin of their food sources must also be taken into account when interpreting the results. Some areas on the map lack data for baseline projection, and a more detailed description of these regions will require additional analysis.

This research is the first of its kind in Estonia and serves as a valuable tool for further provenance analyses of archeological and ecological materials. It also provides a foundation for future studies aimed at refining the strontium isotope baseline map.

DATA AVAILABILITY STATEMENT

All the data used for the analyses presented in this article are provided in Supplementary material.

ACKNOWLEDGMENTS

This work was supported by the Estonian Research Council (grants PSG 492 and PRG 2026) and the Estonian Ministry of Education and Research (TK215). The isotope analyses of animal remains used in the study were conducted as part of the ASTRA project PER ASPERA at the

University of Tartu (acquisition and modernization of educational and research infrastructure, sub-activity research infrastructure, archeology indoor and outdoor laboratory; responsible executor Aivar Kriiska). We are grateful to the University of North Carolina at Chapel Hill Isotope Geochemistry Laboratory for their constructive collaboration, and to the archeological research collections of the Tallinn University and the University of Tartu for providing access to their osteological collections. The osteological research was conducted using the NATARC core facility, funded by the Estonian Research Council (TT14). Special thanks go to Silvia-Kristiin Kask, Sandra Sammler, and Vasso Gkountroumpi for their valuable input during sampling and documenting the study material. We are also grateful to Andres Vindi and Liivi Varul for their help with collecting modern samples, Marika Mägi and Maris Niinesalu-Moon for providing mammal samples from the Viidumäe context, and Hando-Laur Habicht for initial consultation regarding map interpolation. The publication costs of this article were partially covered by the Estonian Academy of Sciences.

SUPPLEMENTARY ONLINE DATA

Supplementary online data to this article can be found at https://doi.org/10.3176/arch.2025.2.S01.

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Eesti strontsiumi aluskaardi loomine arheoloogilisteks ja paleoökoloogilisteks päritolu-uuringuteks

Raivo Suni, Kalle Kirsimäe, Eve Rannamäe, Lembi Lõugas, Liina Maldre, Mari Tõrv, Aivar Kriiska ja Ester Oras

RESÜMEE

Strontsium on keemiline element, mis satub elusorganismidesse toidu ja vee kaudu. Kuna strontsiumil on kaltsiumiga sarnane valents ja ioonraadius, võib see mineraalides, sh luukude moodustavas hüdroksüülapatiidis, asendada kaltsiumi.

Looduslikul strontsiumil on neli stabiilset isotoopi, millest ^{87}Sr on radiogeenne: see tekib ^{87}Rb lagunemisel. Lähtekivimite murenemisel satub strontsium vette ja pinnasesse, kust see kandub otse või taimede kaudu toiduahelasse. Lisaks võib strontsium sattuda toiduahelasse mitmesuguste aerosoolide, sademete, tolmu ja väetiste kaudu. Neid on oluline arvestada strontsiumi isotoopväärtuste tõlgendamisel.

Arheoloogiliste materjalide päritolu-uuringutes kasutatakse $^{87}Sr/^{86}Sr$ suhet, mis on teatud piirkonna kivimite iseloomulik tunnus. Kivimite murenemisel ja leostumisel kandub strontsium pinnasesse ja vette ning sealt elusorganismidesse. Toitainete ringluses osalevat strontsiumi nimetatakse bioloogiliselt omastatavaks ehk bioomastatavaks strontsiumiks.

Arheoloogilise materjali päritolu tuvastamiseks on vaja võrdlusandmestikku, mis peegeldab bioomastatava strontsiumi isotoopsuhet erineva geoloogilise ehitusega geograafilistes punktides. Enamasti on selline võrdlusandmestik esitatud kaardina. Kaardi loomiseks kasutatakse tavaliselt paikse iseloomuga või piiratud elukohaareaaliga bioloogilist materjali, mille bioomastatava strontsiumi tase võetakse piirkonna baas- ehk referentsväärtuseks. Sageli on parimaks lokaalset bioomastatavat strontsiumi markeerivaks materjaliks väikese levikupiirkonnaga loomad (pisiimetajad, teod jt). Referentsväärtuste defineerimiseks kõrvutatakse loomade väärtusi nende levikupiirkonna geoloogilise ehitusega.

Viimastel aastakümnetel on maailmas loodud mitmeid strontsiumi aluskaarte. Meile lähematest riikidest on aluskaardid olemas Leedu, Rootsi lõunaosa, Poola ja Taani kohta. Mõningat võrdlusandmestikku, mida ei ole interpoleeritud kaardiks, on ka Soome lõunaosa ja piiratult Läti kohta.

Eesti võrdlusandmestik on seni olnud üsna piiratud ja juhuslik (tabel 1). Mõningaid referentsväärtusi on avaldatud uurimustes, mis käsitlevad Põhja-Eesti pronksiaegsete ja eelrooma rauaaegsete maetute päritolu (2016) ning Salme laevmatuste (2016, 2020) ja Tallinnas Pärnu mnt 41 päästekaevamistel (2023) eelrooma rauaaegsest matmispaigast leitud inimsäilmete päritolu.

Käesolevas artiklis esitatakse esimest korda kogu Eestit hõlmav bioomastatava strontsiumi võrdlusandmestik (lisamaterjal) ja interpoleeritud aluskaart (joonis 5), mida on edaspidi võimalik kasutada arheoloogilise materjali päritolu uurimiseks.

Kaardi loomisel oli lähtekohaks Eesti aluskorra ehitus (joonis 1), milles eristatakse seitset tinglikku üksust: (1) Alam-Kambriumi liivakivid ja savikivimid (C1), (2) Ülem-Kambriumi kuni Alam-Ordoviitsiumi fosforiit, liivakivid ja graptoliitargilliit (C3–O2), (3) Kesk-Ordoviitsiumi lubjakivid (O2), (4) Ülem-Ordoviitsiumi lubjakivid (O3), (5) Alam-Siluri dolokivid (S1), (6) Kesk- kuni Ülem-Siluri lubjakivid ja dolokivid (S2–3) ja (7) Kesk-Devoni liivakivid-aleuriidid dolokividega (D2).

Kivimitüüpe kõrvutati erinevatelt arheoloogilistelt kaevamistelt kogutud loomaluude apatiidis talletunud $^{87}Sr/^{86}Sr$ suhtega (vt lisamaterjal). Aluskaardi loomiseks kasutati üksnes näriliste ja tigude strontsiumi väärtusi. Statistiliste erandite väljasõelumise järel (kasutatud meetod: MAD, künnis 3) sai kaardi interpoleerimiseks kasutada 84 looma andmeid 38 geograafilisest punktist.

Näriliste ja tigude tulemusi võrreldi valimiga, kuhu olid lisatud ka suuremad imetajad (sekundaarne valim). Võrdluse eesmärk oli välja selgitada, mil määral on võimalik strontsiumi isotoopuuringutes referentsina kasutada ulukite ja koduloomade andmestikku. Nende puhul kasutati erandite leidmiseks rangemaid tingimusi (MAD, künnis 2). Võrdlusandmestiku moodustasid 132 looma andmed 54 erinevast Eesti geograafilisest punktist.

Analüüsi tulemusena eristub Eestis kaks selget strontsiumi isotoopide väärtustsooni (joonis 5). Ühe tsooni moodustavad Kambriumi, Ordoviitsiumi ja Siluri aluspõhja kivimid Põhja-, Lääne- ja Kesk-Eestis koos rannikualadega ($^{87}Sr/^{86}Sr$ suhe 0,7094–0,7147) ning teise Lõuna-Eesti Devoni liivakivide avamus ($^{87}Sr/^{86}Sr$ suhe 0,7147–0,7185).

Kahe andmekogu võrdlus näitab, et suuremate imetajate lisamine valimisse Eesti puhul tulemust märkimisväärselt ei mõjutanud: mõlemal juhul joonistusid välja sarnased väärtustsoonid (joonis 6). Erisused ilmnesid vaid rannikualal, kus näriliste andmete põhjal oli võimalik iseseisva isotsoonina eristada Saaremaad ($^{87}Sr/^{86}Sr$ suhe sageli alla 0,7115). Vaatamata tulemuste sarnasusele soovitame Eesti päritolu-uuringutes kasutada joonisel 5 esitatud aluskaarti. Teiste loomade andmete kasutus on põhjendatud olukorras, kus näriliste andmeid ei ole võimalik kasutada.

Strontsiumi aluskaart kinnitab ja avardab senist arusaama bioomastatava $^{87}Sr/^{86}Sr$ suhte jaotusest Läänemere piirkonnas. Soomes ja Rootsis, kus paljandub graniitne aluspõhi, on isotoopide suhe oluliselt kõrgem (>0,72). Läänemere saarte ja saarestike puhul määravad strontsiumi suhte nende aluskorra ja/või aluspõhja kivimid. Ahvenamaal, mis on graniitse aluskorraga, on strontsiumi isotoopide suhe üle 0,72. Gotlandi aluspõhjale on iseloomulikud Ordoviitsiumi ja Siluri karbonaatsed kivimid ning selle $^{87}Sr/^{86}Sr$ suhe (0,71–0,713) on sarnane Eesti saarte ja rannikualade väärtustega. Leedu Devoni liivakivide avamusel mõõdetud strontsiumi isotoopide suhe (0,7155–0,717) on sarnane Devoni setendite avamusel mõõdetud väärtustega Eestis.

Kuigi Lätis puudub Sr-isotoopsuhte baasjoone kaart, on sealsete arheoloogiliste loomaluude isotoopväärtused (0,712–0,714) Riia piirkonnas Riia lahe lähedal (Petersone-Gordina jt 2022) sarnased Eesti rannikuala väärtustega. Lisaks analüüsisid Price jt (2020) Grobiņas Lääne-Lätis kolme teokarpi, mille keskmine ±1 s.d. oli 0,707429 ± 0,00008 piirkonna baasväärtusena.

Bioomastatava strontsiumi andmestik Eestiga piirnevatelt idapoolsetelt aladelt praktiliselt puudub. Praegu on teada ainult mõned väärtused ($^{87}Sr/^{86}Sr$ suhe ligikaudu 0,717) Staraja Ladogast, mis asub 125 km Peterburist ida pool, kuid Peterburi puhul eeldatakse, et selle aluspõhjakivimite samasugune koostis võimaldab kasutada Põhja-Eesti andmeid.

Bioomastatava strontsiumi aluskaart aitab mõista arheoloogilist materjali Eesti ja Ida-Baltikumi arheoloogilises kontekstis. See võimaldab eristada kohalikke ja sisserännanud inimesi ja loomi ning teha kaudseid oletusi nende päritolu kohta nii Eesti-siseselt kui ka naabermaade kontekstis. Tulemuste tõlgendamisel tuleb hinnata nii mõõtmistulemusi kui ka nende varieeruvust. Kuna elusorganismid omandavad strontsiumi vee ja toidu kaudu, tuleb tulemuste tõlgendamisel arvestada ka nende toiduallikate võimalikku päritolu.

Uuring on Eestis esimene omataoline ning pakub väärtusliku tööriista arheoloogiliste ja ökoloogiliste materjalide edasiseks analüüsiks. See loob hea pinnase järgnevatele uuringutele, mille eesmärk võiks olla strontsiumi isotoopide aluskaardi täpsustamine.