The Ratio of Strontium Isotopes in Biological Remains (Based on the Materials of the Bronze Age Sites from the Southern Trans-Urals)

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Abstract. This paper presents a statistical assessment of $^{87}Sr/^{86}Sr$ isotope variations for 69 individuals and 32 animals. All materials belong to the Bronze Age of the Southern Trans-Urals (eight archaeological sites). The sample consists of 101 measurements. The samples were obtained from different types of biological materials: bone, enamel, and dentine. We collected two to three samples from the same individual ($n = 22$) or animal ($n = 10$) to compare various tissues. Significant differences in the results of the analysis of human tooth enamel illustrate the sample's actual heterogeneity, i.e. ancient collectives could be formed by incorporating individuals from distant locations. Differences in the results of the analysis of the tooth enamel of people indicate a difference in the origin of individuals within the collective. The relative consistency of the results of bone and enamel analysis was recorded for animals from most of the sites, which indicates local grazing and the absence of long-range exchange.

Keywords: Sr isotopes · Southern Trans-Urals · Bronze Age · Mobility · Sintashta culture · Alakul culture

1 Introduction

Radiogenic Sr isotope analysis is one method to study the forms and scales of human and animal mobility (Bentley 2006; Ventresca Miller et al. 2017, etc.). Despite these profound efforts, sampling, analysis, and interpretation remain topics for discussion and subjects for modification depending on the region and research questions. For instance, much attention is paid to diagenetic processes (Smith et al. 2007; etc.). This work presents new regional data from the southern Urals and assesses the reliability of strontium data obtained from different types of biological samples. This aspect is crucial as the degree of sample heterogeneity may be high due to the variable character of sample specimens and diagenetic processes.

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2 Materials and Methods

The sample consists of 101 measurements of $^{87}Sr/^{86}Sr$ isotope ratios acquired in a cleanroom unit (ISO classes 6 and 7, Zavaritsky Institute of Geology and Geochemistry of the Ural Branch of the Russian Academy of Sciences, Geoanalyst Center for Collective Use, Ekaterinburg). The Sr isotopic composition was measured on a Neptune Plus magnetosector multicollector mass spectrometer with inductively coupled plasma (MC-ICP-MS). Samples from the eight Bronze Age sites were measured (the Sintashta and Alakul culture sites, a sample from the Final Bronze grave (the Sokolok mound)). The sampled sites are the fortified settlement of Stepnoye, Stepnoye-1, Krivoe Ozero, Kulevchi VI, Kamenny Ambar-5, Aleksandro-Nevsky cemeteries, the Sokolok mound, and a settlement at the Vorovskaya Yama ancient mine. The burial grounds of Krivoe Ozero, Kulevchi VI, Kamennyi Ambar-5, and materials from the Vorovskaya Yama mine have been previously published (Vinogradov 2003; Epimakhov 2005; Kulevchi 2020; Ankusheva et al. 2023). All sites are dated to the cal. 20th–16th centuries BCE (Krause et al. 2019; Epimakhov et al. 2021; Chechushkov and Epimakhov 2021; Ankusheva et al. 2022; etc.), and they are located on the forest-steppe and steppe zone frontier and in the northern steppe of the southern Trans-Urals. Geologically, the sample lies within the boundaries of the three structural-formational zones of Urals: Tagil-Magnitogorsk, East Urals, and Trans-Urals (Puchkov 1997), which is supposedly reflected in the $^{87}Sr/^{86}Sr$ ratios.

The samples were obtained from different types of biological materials: bone, enamel, and dentin (Table 1). The collection combines the sampled human remains (mostly adults; $n = 38$) and domestic animals (caprine, cattle, and horses; $n = 21$). We collected two to three samples from the same individual or animal to compare various tissues. Seven human individuals were provided with three sample types (the Kamennyi Ambar-5 cemetery, bone, dentin, and enamel); for the rest, we conducted a bone-enamel pairwise comparison.

Box-and-dot diagrams allow us to characterize the sample in two ways: by species (humans ($n = 69$) and animals ($n = 32$)) and by sample type (bone, dentin, enamel).

3 Results and Discussion

Three types of samples demonstrate a fundamentally different nature in terms of mean values and heterogeneity, especially pronounced in a human subsample. In this case, groups of bone and enamel samples contain statistical outliers (Fig. 1). They indicate the heterogeneity of the sub-sample, which is not surprising considering combining the results for different sites and structural-formational zones of Urals into a group. A statistically significant difference in bioavailable strontium values was previously diagnosed for the East Urals and Trans-Urals structural-formational zones (Epimakhov et al. 2023). Suppose the presence of outliers has a simple explanation. In that case, the difference in the mean values for bone and enamel requires a separate consideration since we are talking about the same individuals in some cases. The minimum variability is demonstrated by the data on dentin originating from the Kamenny Ambar-5 cemetery, but there are not enough data for interpretation. The strontium isotope measurements

Table 1. Sample description

Site	Culture	Structural-formational zones of Urals	The number of samples			
			Total	Bone	Dentin	Enamel
Aleksandro-Nevsky-1, cemetery	Alakul	TM-EU[a]	10	4 (4/0)[b]		6 (5/1)
Vorovskaya Yama, an ancient copper mine and a settlement	Alakul	TM-EU	14	4 (0/4)		10 (0/10)
Kamennyi Ambar-5, cemetery	Sintashta	EU	29	15 (15/0)	7 (7/0)	7 (7/0)
Krivoe Ozero, cemetery	Sintashta	EU	12	3 (3/0)		9 (9/0)
Kulevchi VI, Cemetery	Alakul	TU	8	4 (4/0)		4 (4/0)
Sokolok burial mounds	Final Bronze Age	TU	1			1 (1/0)
Stepnoye-1, cemetery	Sintashta	EU	13	6 (2/4)		7 (2/5)
Stepnoye, settlement	Sintashta	EU	14	5 (3/2)		9 (3/6)
Total			**101**	**42**	**7**	**53**
Including: *Humans* *Animals*			*69* *32*	*31* *10*	*7* –	*31* *22*

[a] EU—the East Ural megazone; TM—the Tagil-Magnitogorsk megazone; TU—the Transural megazone

[b] In parentheses is the number of measurements of human and animal remains

for animal subsamples produce different results. In this case, the bone values form a wide box with a short whisker, which may indicate sample heterogeneity even without statistical outliers. Enamel sample values are less variable.

A comparison of the different types by sites turned out to be more informative, despite small sample sizes for a number of them (Fig. 2). First, the most contrasting pattern of values fluctuations was recorded for tooth enamel, including within the same site (the settlement of Stepnoye, Krivoe Ozero, and Kulevchi VI cemeteries, to a lesser extent for Vorovskaya Yama). Second, a serious discrepancy in values is more characteristic of human remains, while for animals, we see the relative consistency of the results in the bone and enamel comparison. Third, the observed differences demonstrate the effectiveness of strontium analysis, i.e., the strontium signal in biological samples is associated with the geological zoning, although the nature of this relationship requires further clarification. Finally, several individuals were identified for which samples of different types gave statistically different results. This may be evidence of a difference between the zone of origin and the zone of residence in the last years of life or the result of diagenetic processes.

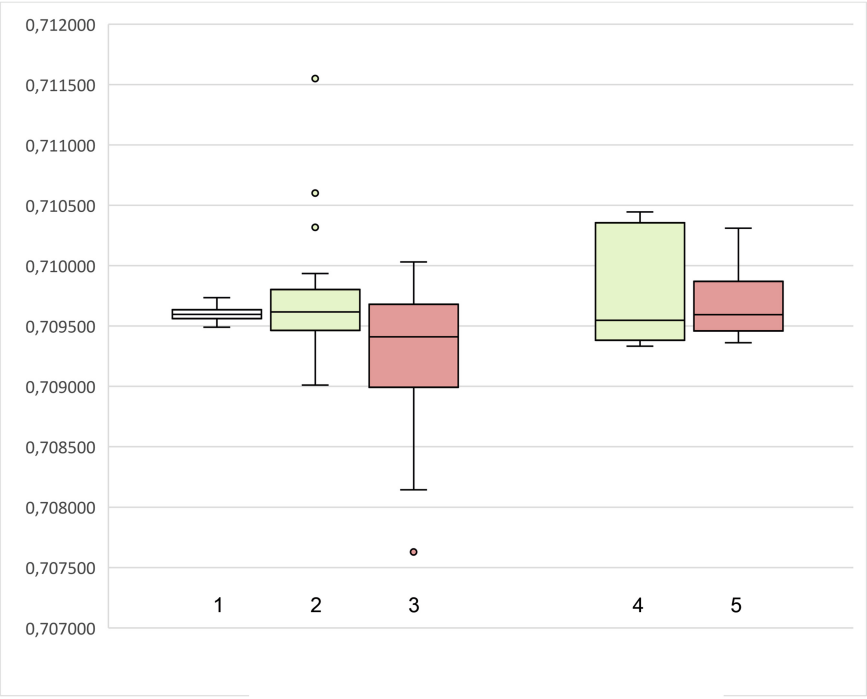

Fig. 1 Box-and-dot diagrams of $^{87}Sr/^{86}Sr$ isotope ratios for different samples: 1–3—human individuals, 4–5—animals. 1—dentin, 2—bone, 3—enamel

It is worth looking at such examples in more detail. The bone value of the female individual from the Stepnoye settlement almost does not differ from the rest of the settlement series and the nearby burial ground (enamel and bone samples of people and animals) (Fig. 2: 2–3). Still, it is sharply different in the isotopic signal of tooth enamel. This allows us to draw two conclusions: (1) the influence of diagenetic processes is not traced; (2) the origin of the individual is not related to the Stepnoye micro-district. The sample from the Krivoe Ozero cemetery (Fig. 2: 4) also demonstrates variability, but in this case, it is mainly due to the values from tooth enamel (we only have human samples). One of three paired samples originating from the same individual again illustrates the differences between bone and enamel values. Thus, the conclusions for this series are similar to the previous one, but it is a plausible assumption that the portion of non-local individuals was higher than in the Stepnoye micro-district. The Kulevchi VI cemetery is also heterogeneous, but the situation is different since the enamel signal for five individuals lies in a narrow range of values, while the bone signal differs. From the point of view of formal logic, individuals should have spent the early period of life in similar geological conditions, but just before their deaths, they lived somewhere else. In this case, the burial ground became the resting place for people who were close in origin but lived far from each other. Obviously, this hypothesis requires the test on a sample larger than the eight measurements of the four individuals.

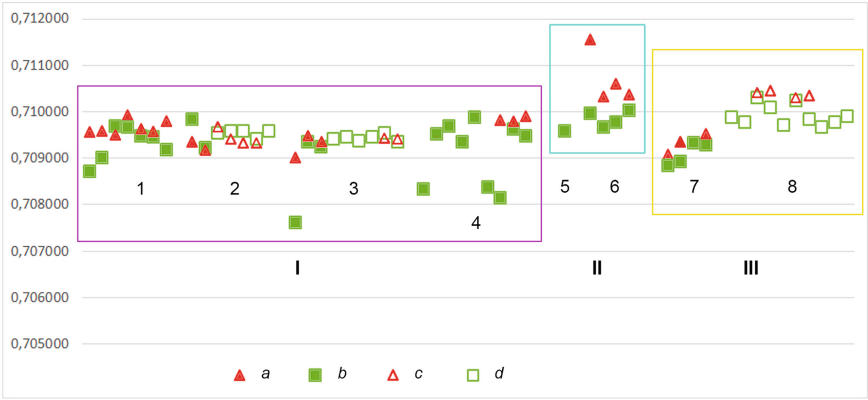

Fig. 2 $^{87}Sr/^{86}Sr$ isotope ratios for different types of biogenic strontium: **a**—human bone, **b**—human tooth enamel, **c**—animal bone, **d**—animal tooth enamel. 1—Kamennyi Ambar-5 cemetery, 2—Stepnoye-1 cemetery, 3—Stepnoye settlement, 4—Krivoe Ozero cemetery, 5—Sokolok kurgan, 6—Kulevchi VI cemetery, 7—Aleksandro-Nevsky cemetery, 8—Vorovskaya Yama mine. I—East Ural megazone, II—Trans-Ural megazone, III—border of Tagil-Magnitogorsk and East Ural megazones

4 Conclusions

The results are the first example of a large-scale project to study mobility using geochemical methods in a region. Despite the relative scarcity, especially for individual sites, it can be concluded that the method was effective. The revealed differences between the values for bone and enamel may reflect changes in areas where individuals lived throughout their lives. In such a case, the bone illustrates the value at the time of the individual's death, while the tooth enamel reflects the value obtained in early life. Indirect confirmation can be data on animals whose life cycle is shorter. The available sample for this category indicates the local grazing of the studied domestic animals and the absence of long-distance exchange. An exception is the specific heterogeneous series of the Vorovskaya Yama mine, which requires separate consideration and reconstruction of the object's functioning model (Ankusheva et al. 2023).

In some cases, the narrow range of values for samples obtained from human bones may be due to diagenetic processes that "leveled out" the $^{87}Sr/^{86}Sr$. However, significant differences in the results of the analysis of human tooth enamel illustrate the sample's actual heterogeneity, i.e., ancient collectives could be formed by incorporating individuals from distant locations. Further testing of this hypothesis requires the multiplication of the series and its comparison to the values of bioavailable strontium.

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