Preliminary Results of the Strontium Isotopes Analysis in the Framework of the Study of the Mobility of the Bronze Age Population in the Trans-Urals

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Abstract The paper presents preliminary results of studying ancient mobility in the southern Urals by applying the strontium analysis. In total, 70 points were sampled, covering 33.000 km^2. We measured the $^{87}Sr/^{86}Sr$ ratio in 67 samples of water and 57 samples of grass from the same locations. The statistical analysis of the two batches demonstrates their close similarity. The map of values was interpolated with simple kriging based on the 67 samples of water. The map demonstrated the variability in values depending on the geological structure of the region.

Keywords Strontium isotope analysis · Migration · Sintashta · Southern Urals

1 Introduction

The study of mobility in archeology is stimulated from the outside. There are two factors. The first is traditionally high importance of this topic in other disciplines (geography, economics, urban studies, etc.) that lead to the development of a general mobility theory. Sheller and Urry (2006) have even suggested that there is a development of a new methodological paradigm. The second factor is the development of new methods for studying mobility in the past. At the same time, the topic was in the sphere of interest of many scholars, who relied on typology as the primary tool to study mobility and migration. Currently, the range of methods is significantly expanded by applying paleo-DNA and geochemistry (Vandkilde et al. 2015;

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etc.). Some methods are devoted to reconstructing large-scale, long-distance movements. The other methods help to turn to smaller-scale processes, such as individual, seasonal, economic, and other types of mobility. Resolving these issues aims at reconstructing and understanding economic and social phenomena, especially given that most such reconstructions are based on settlement studies, sometimes combined with studies of synchronous funerary sites.

All of the above is directly related to the study of the Trans-Ural Bronze Age (3rd–2nd millennia BCE). This steppe and forest-steppe zones of this area are relatively well studied, and numerous sites (settlements, burial grounds, ancient mines, etc.) have been discovered. Several archaeological cultures have been attributed, and their relative chronologies have been established. The economy based on complex animal herding and other industries, including metal production, is well recognized.

The variability of the geological structure is one of the critical factors for applying the 88Sr/86Sr radiogenic isotope method. The Urals fully meet this criterion. The lack of natural values of strontium isotope variations is an obstacle for mobility studies. On the one hand, the method has been successfully applied in the Urals (Kiseleva et al. 2019; Ankusheva et al. 2021; etc.). On the other hand, researchers have focused on specific loci where natural samples were purposefully collected. The same approach is also typical outside the Urals, but it seems insufficient if we attempt to look at a larger historical picture. Our goal at this stage is to interpolate a base map of the strontium isotopes of the southern Trans-Urals, comparing it to the major geological structures of the region. This involves the development of a sampling methodology and analyzing various samples (rocks, water, mollusk shells, soil, and plants of the same species) gathered at the same location.

2 Materials and Methods

The sampling area lies north of the Ui River, along the border of the Chelyabinsk region of Russia, with the Republic of Kazakhstan in the east. In the west, it enters the Republic of Bashkortostan of Russia. In the south, it touches the Orenburg region of Russia (Fig. 1). For sampling, 70 points were located in the grid at 25 km one from another. Samples were collected within 5-km-radius buffer zones around these 70 points. The sample points were located at the maximum possible distance from industrially active settlements, cultivated fields, and farmland, where fertilizers can serve as a potential source of strontium with a modified isotopic composition (Thomse and Andreasen 2019; Maurer et al. 2012).

The sampling map covers the distribution zone of the Sintashta-Petrovka sites of the southern Trans-Urals. The sampling zones intersect well with the 10-km-radius buffer zones of several Late Bronze Age reference settlements (such as Kamennyi Ambar, Arkaim, Sintashta, Levoberezhnoe, Sarym-Sakly, Stepnoye, Chernorechie). The radius of 10 km was chosen to cover plausible ancient economic activity zones, as the residents of the Sintashta-Petrovka settlements probably needed an area with a radius of at least 4 km for pasturing (Stobbe et al. 2016).

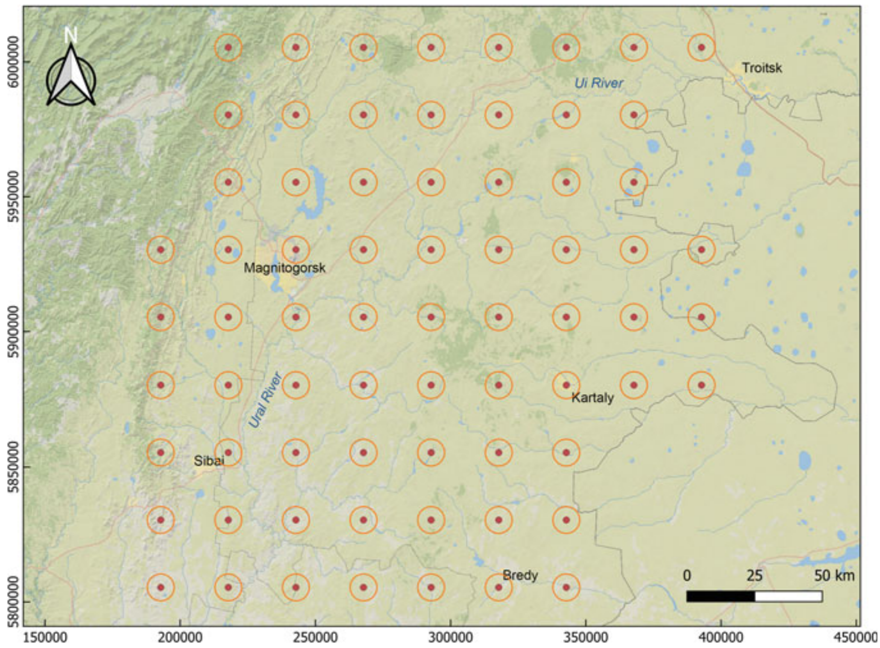

Fig. 1 Map of the study area and sampling area (UTM zone 41)

To date, samples from two series have been studied: the samples of water (n = 67) and the samples of wild plants (*Artemísia absínthium*) (n = 57), allowing for preliminary conclusions.

The analysis corresponds to the following research stages: (1) determination of strontium isotopic values in samples, (2) statistical analysis, (3) strontium map interpolation, and (4) analysis of the strontium spatial distribution.

Measurements of strontium were carried out in a cleanroom unit (classes 6 and 7 of the ISO, the Center for collective use "Geoanalyst," the Ural Branch of the Russian Academy of Sciences, Ekaterinburg). Plant samples were air-dried, ground in an electric mill, and carbonized for 12 h (Maurer et al. 2012). Water samples were preserved with concentrated nitric acid and, after filtering and determining the strontium content, were sent directly to the chromatographic separation of Sr, which was carried out on SR resin (TrisKem) according to the one-stage scheme (Muynck et al. 2009; Kasyanova et al. 2019).

The $^{88}Sr/^{86}Sr$ isotope composition was measured on a Neptune Plus magneto-sector multi-collector mass spectrometer with inductively coupled plasma (MC-ICP-MS). Mass discrimination was corrected using a combination of bracketing and normalization according to the exponential law: $^{88}Sr/^{86}Sr = 8.375209$ (Nier 1938). The results were further bracketed using the NIST SRM 987 strontium carbonate isotope standard by an average deviation from the reference value of 0.710245 (according to the GeoReM database, http://georem.mpch-mainz.gwdg.de/) for every two samples taken between NIST SRM 987 measurements. To control measurements of the strontium isotope composition, the NIST SRM 987 isotope standard was regularly measured over a long time (during 2019–2020): $^{87}Sr/^{86}Sr = 0.71025$, 2SD = 0.00012 (104 measurements in two parallels). The uncertainty under conditions of intralaboratory reproducibility (2σ) for NIST SRM-987 was ±0.003%.

3 Results and Discussion

3.1 *Statistical Analysis of Sample Values from Water and Plant Samples*

The batch of water samples consists of 67 values. The range of values is 0.008571 at min = 0.707308, max = 0.715879. The stem-and-leaves plot is bell-shaped, single-peaked, and has a slight upward inclination, close to being normally distributed. Therefore, the numerical series can be statistically examined and characterized in terms of mean values for subsequent comparison with other types of samples. The water sample is characterized by the following statistical values: mean is 0.709525, SD is 0.001018, SE (95%) = 0.000492, i.e., the mean value lies in the range from 0.709279 to 0.709771 (0.709525 ± 0.000492) at the 95% confidence level.

The batch of plant samples consists of 57 values. The range of values is 0.00321 at min = 0.707972, max = 0.711182. The stem-and-leaves plot is bell-shaped and single-peaked, close to being normally distributed. The grass sample is characterized by the following statistical values: mean is 0.709602, SD = 0.000532, SE (95%) = 0.709460, i.e., the average value lies in the range from 0.709460 to 0.709743 (0.709602 ± 0.709460) at the 95% confidence level.

The two batches have similar characteristics, and a comparison with the *t*-test shows no statistically significant difference between the means ($t = 0.513298$, $p = 0.608664$). This may indicate a slight local variability in the measured values of two different types of samples. To test this hypothesis, we compare the difference between the measured values of pairs of samples obtained within the same buffer zone. Thus, the difference varies from −0.002073 to 0.005164, with an average value of 0.000008 and a standard deviation of 0.000898. This average difference is insignificant because close to the two-sigma deviation of the measured values (0.000007). Visual analysis of the mapped values also confirms the similarities of local measurements of plant and water samples.

3.2 *Mapping of Strontium Values*

The resulting map of the distribution of strontium isotopes in the water samples shows a spatial pattern: values increase from west to east, with the highest values in the

Trans-Ural0 peneplain zone (Fig. 2). The identified distribution in the 87Sr/86Sr ratios coincides with four large structural-formational zones of the Trans-Urals, which differ from each other in the genesis, age, and composition of the constituent rocks.

In the west, the sampling grid covers the Central Ural megazone, composed of metamorphosed deposits of the Upper Precambrian—Lower Paleozoic ages (Fig. 2) (Puchkov 2000). The range of rocks includes catagenetically altered sedimentary sequences and highly metamorphosed crystalline complexes. The megazone was sampled at only two locations on the edge of the sampling area (Fig. 2), so expanding the grid to the west is necessary. The Magnitogorsk megazone is formed by Paleozoic island-arc volcanic-sedimentary formations lying to the east. Low values of $^{87}Sr/^{86}Sr$ characterize the zone. A high $^{87}Sr/^{86}Sr$ value in the NW corner of the grid needs additional study.

Further east, the grid overlays the East Ural megazone, a collage of microcontinental blocks dissected by ophiolite and island arc formations. Ultramafic complexes, granite intrusions, volcanic-sedimentary sequences, and metamorphic complexes contribute to the complex geological structure of the zone. The zone is characterized by the highest values of $^{87}Sr/^{86}Sr$. The eastern boundary of the sampling area lies within the Trans-Ural megazone. This megazone is composed of Carboniferous paleoisland-arc calc-alkaline formations. The megazone has been tested by a few

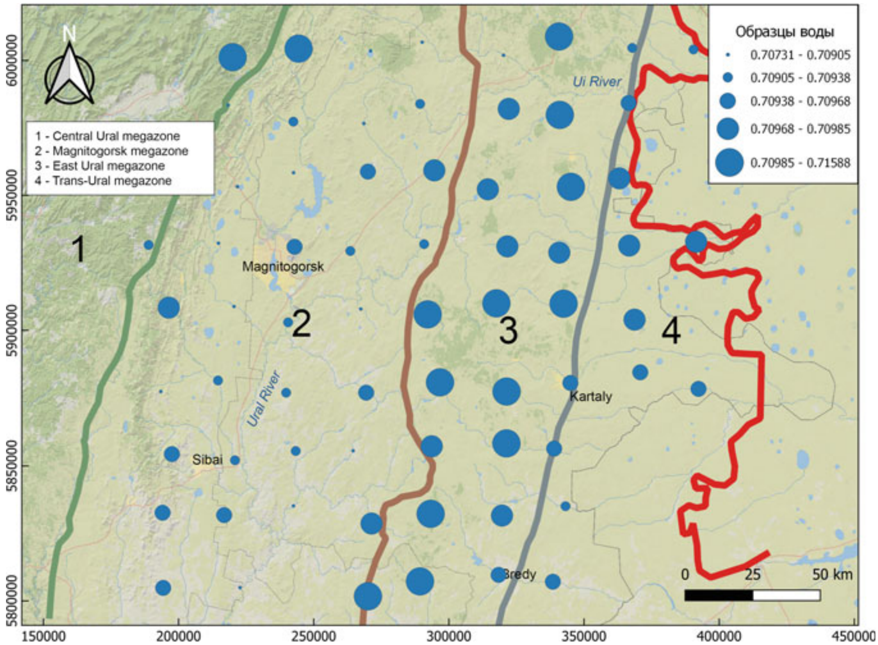

Fig. 2 Map of $^{87}Sr/^{86}Sr$ isotope distribution based on water samples with geological structural-formational zones of the study area

points and needs further sample expansion. So far, the Trans-Ural megazone demonstrates average values of $^{87}Sr/^{86}Sr$. Given the complex geological structure and the broadest range of rocks in the study area, a positive result is the low differentiation of the identified anomalies. Due to this, the described technique demonstrates its suitability for studying sublatitudinal migrations of the ancient population within the Southern Trans-Urals.

The map of bioavailable strontium is interpolated with the use of geostatistical methods. Fundamentally, geostatistical methods proceed from the idea of obtaining values of unknown points by interpolating data from known points. Kriging is one of the interpolation methods widely used in topography, cartography, and geology. This method is based on the assumption that at least some spatial variations can be modeled using spatial autocorrelation (the tendency for similar values of spatially close objects, in this case, the measured values of Sr isotopes) (Oliver 1990). During interpolation, the algorithm selects a weighted average of the sample values with minimum variance (Armstrong 1998, p. 88). Kriging techniques can describe and model spatial structural patterns, predict unmeasured point values, and measure the uncertainty associated with a predicted value at unmeasured locations. The method is also suitable for determining unknown values if there is a directional bias in the data. As a result, a surface model can be represented by two-dimensional maps or three-dimensional models.

We applied normal kriging (kriging with an unknown mean) with a linear variogram. The choice of interpolation method seems to be justified since we can assume that our data possess two fundamental characteristics: autocorrelation and spatial bias. The cell size of the interpolated map is 5 km by 5 km (Fig. 3).

4 Conclusions

As a result, it has been found that the distribution of strontium isotope values from the water and plant samples have similar spatial patterns. The statistical differences between mean values are insignificant. A map of strontium isotope values was interpolated for an area of 33,000 km^2 based on 67 water samples (Fig. 3). According to this map, there is a general trend of increasing values from the west to the east. The zone of high values is located submeridionally, apparently confined to the East Ural megazone. The zone of low values inclines towards the Magnitogorsk megazone. A significant expansion of the survey area is necessary to specify isotopic values of other tectonic zones, covered with only a few sampling points (the Central Ural and Transural megazones, the West Siberian Plate). In addition, the map revealed the need to supplement the number of analyzes within the boundaries of the surveyed area in cases where the interpolation is based on single analyzes or near the boundary of geological structures.

Despite the intermediate nature of our results, it can be stated that the data meet our expectations and can be used to diagnose the local versus non-local origin of biological organisms. In the next stage of our work, we aim to measure strontium isotope

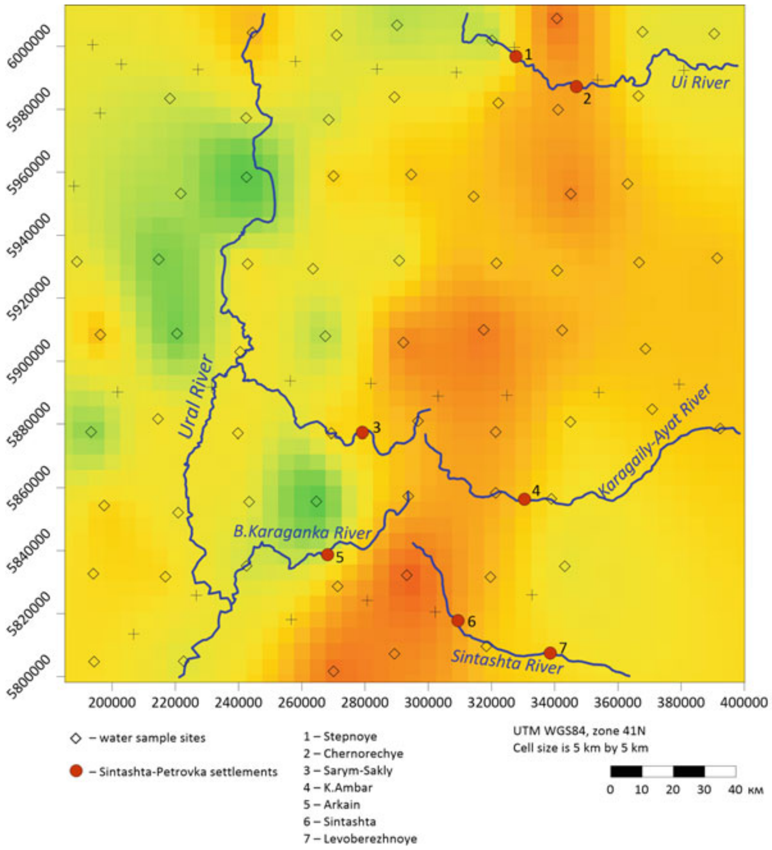

Fig. 3 Interpolated map of $^{87}Sr/^{86}Sr$ isotope based on water samples

values of samples originating from the Late Bronze Age sites, thereby determining the degree of mobility of people and animals.

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