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RESEARCH

Were metalworkers itinerant? Interdisciplinary analysis of a metalworker's burial at the Krivoe Ozero late Bronze Age cemetery (southern Trans-Urals, Russia)

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Abstract
Diagnosing the mobility of individuals involved in metal production helps to understand practices of metallurgy and related social processes in the southern Trans-Urals during the Late Bronze Age. In this paper, we present a comprehensive analysis of a unique Sintashta culture grave of an elderly male individual, dated to the early 2nd millennium BCE. The grave is notable for evidence of craft specialization in metal production, as indicated by a specific set of artifacts, while the deceased individual possessed unusual physical appearance, which apparently did not cause his social marginalization. The individual's lifetime mobility is suggested by $^{87}Sr/^{86}Sr$ values in his tissues that differ from those typical for the cemetery locus and the presence of non-local copper ore indicates long-distance exchange or import. We assume that craft specialization in metal production could be a factor in individual mobility related to the ore procurement and metal exchange.

Keywords Bronze Age · Northern Eurasia · Sintashta culture · Mobility · Metallurgy · Burial practices · Strontium isotope analysis

Introduction

Copper metallurgy and metal production is often considered one of key factors that caused individual and group mobility during the Bronze Age. This is due to uneven distribution of ore deposits and scarcity of fuel, as well as the need for specialized knowledge and skills. Diffusionist paradigm, epitomized by Childe (1930) and still debated today (Renfrew 1969; Wertime, 1964; 1973; Chernykh 1992) advocates the existence of itinerant metal producers in the Bronze Age who disseminated knowledge about metallurgical technologies and relevant skills and traveled large distances for ore procurement and product exchange (Roberts et al. 2009).

However, regional and chronological variability in organization of Bronze Age metallurgical production have been recognized as varying from the bottom-up organized systems to expeditions attempted by state authorities (Erb-Satullo 2017). Studies of practices of metal production are based on various types of information, including data from settlements, burial grounds and mining sites. Among them, cemeteries allow the study of craft specialization and social contexts related to such specialists. This kind of research is well developed in publications devoted to the Chalcolithic and Bronze Ages of Western and Central Europe (Batora 2002; Jockenhövel 2018; Nessel 2019; Molloy, Mödlinger 2020; Batasova 2021; Nowak et al. 2022).

In the Urals, however, the information potential of graves with evidence for specialization on metal production is realized to lesser extent. The earliest graves with casting molds

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belong to the Yamnaya culture and are dated to the Early Bronze Age during the first half of the 3rd millennium BCE (Chernykh 2005, pp. 29–35, 100). The subsistence system of the Yamnaya population was largely based on mobile pastoralism (Morgunova et al. 2019) that makes differentiation of mobility related to metal production from the general economic activity hardly possible.

For this reason, the focus of our research is on the later period of Ural prehistory, when the scale of expected mobility changes significantly with the origin of settled communities. Archaeological sites of the Sintashta culture (c. 2000 – 1900 cal BCE) are located in the steppes of the southern Trans-Urals. The culture is widely known for a number of features: migration origin (Narasimhan et al. 2019; etc.), the chariot complex, walled nucleated settlements and associated mound cemeteries (Koryakova and Epimakhov 2014). Pastoralism retains its role as the subsistence basis, but herding was limited to the local scale (Stobbe et al. 2016). The Sintashta culture is also associated with the discovery of copper deposits in the southern Trans-Urals and Mugodzhar Range and the beginning of ore smelting in these regions. Evidence of the full cycle of metal production such as fragments of copper ore, metallurgical slag, ruins of forges, nozzles, crucibles, casting molds, ingots, and finished copper products, is widely represented in settlement cultural layers and funerary contexts (Degtyareva 2010; Krause and Koryakova 2013; Vinogradov 2013; Epimakhov and Berseneva 2016). Economic specialization of the whole Sintashta society on metal production is put forward as a hypothesis explaining innovations in settlement architecture and the richness of funeral rites (Vinogradov 1995, 2021). However, large-scale excavations at settlement sites do provide evidence for specialized places of metal production and processing (Grigoriev 2015: 316–321), and the annual scale of metal production hardly overcome the need for local exchange (Chechushkov and Petrov 2021), which contrasts with manifestations of metal production specialization in funeral rites.

There are dozens of Sintashta graves with tools of metal production, but limitations in the data reduce the study's potential (Epimakhov and Berseneva 2016). Firstly, the majority of craft tools are rock-made hammers, pestles, and abrasives, which could be used for various purposes beside metal production. Secondly, most graves are collective tombs with several individuals buried in them, which makes it hard to associate the attributes of metal production with a specific individual. Thirdly, for various reasons, more than half of the graves were looted or borrowed, limiting the analysis. For these reasons, we proposed to limit the attributes of metal specialization to a few categories of eco- and artifacts, including copper ore, pieces of slag, metal ingots and drops, nozzles, and casting molds. Seventeen graves from nine burial grounds met these criteria, with only six containing single individual graves. Slag pieces and casting molds are among the least common finds (two cases of each), while pieces of ore were found in ten cases. Combinations of different categories of finds within the same context are extremely rare (3 out of 17). Of these, the safe association of deceased individuals with metal production attributes was possible only in two cases, allowing for the assumption of their craft specialization as metalworkers.

In this paper, we focus on the study of one of such cases, namely, a well-preserved individual grave in the Krivoe Ozero cemetery in the southern Trans-Urals. We aim to assess the degree of individual mobility of a person who was presumably involved in metal production as a craft specialist. As a result, we may be able to assess the degree of mobility associated with metal production and exchange during the Late Bronze Age in the southern Trans-Urals. Our analysis is based on a complex methodology involving a bioarchaeological study of human remains and mineralogical and geochemical analyses of accompanying artifacts. Firstly, we study the origin of the individual by comparing the $^{87}Sr/^{86}Sr$ ratios in bone tissues of the studied individual with those of the rest of the buried population, as well as data with data on bioavailable strontium. Secondly, craniometric characteristics are considered for assessing the physical appearance of the individual in comparison to the rest of the deceased. Thirdly, a detailed analysis of the funeral rite and the artifact typology helps to reveal differences or similarities of cultural standards to study possible inclusion or marginalization with the Sintashta community. Fourth, XRF, optical and electron microscopy, LA-ICP-MS analysis of ores, slags and metals shed light on the technological practices of extracting raw materials, processing them and manufacturing finished products and assess the associated scale of mobility.

Despite the isolated complex, our results may help to understand the degree of mobility of Sintashta individuals, involved in metal production, and to open an avenue to study industries of other prehistoric periods. For instance, in the subsequent Alakul period, attributes of metallurgy vanish from the burial record, despite the economy, rituals, and technologies remaining similar to the Sintashta period. However, we do not observe the decline of regional metal production, as its leftovers are well presented on the Alakul settlement sites and mine workings (see Degtyareva et al. 2001; Epimakhov 2012; Grigoriev 2015; pp 512–521; Ankusheva et al. 2022, 2024). We can assume that practices of metal production, including possible need for mobility, and associated social relations varied throughout the Bronze Age within a single region rich in local sources of raw materials.

Metalworker's burial in the Krivoe Ozero cemetery: an overview

Environmental settings

The sites of the Sintashta culture, located in the steppe zone of the Southern Urals, are settlements with encapsulated layouts, burial grounds and, probably, mine workings (Koryakova and Epimakhov 2014). The Krivoe Ozero burial ground is located in the Troitsky district of the Chelyabinsk region (Russia) on the right bank of the Uy River (Tobol basin) (N54°00′ E60°40′). The site marks the northern border of the Sintashta ecumene (Fig. 1a). This part of the Southern Trans-Urals is a slightly hilly plain with a gentle incline eastward (Trans-Ural peneplain), 238 m above sea level. The cemetery is located on the first terrace above the floodplain, approximately 2 m above the waterline. The Uy River basin is a conventional border of modern steppe and middle forest-steppe with ribbon and island forests (Levit 2005). The low percentage of forest cover in the territory now is caused by its long-term agricultural use.

The Southern Trans-Urals experience a temperate continental climate characterized by significant fluctuations between summer and winter temperatures. January sees an average monthly temperature of -12 °C, while July averages around +22 °C. Extremes include a January minimum of -35 °C and a July maximum of +40 °C. Annual precipitation remains below 400 mm. Although detailed paleoclimatic data are available for areas located 130–160 km south of the considered region, palynological studies indicate significant humidification beginning around 4000 cal BCE. This increase in humidity notably enhances meadow yield, as supported by botanical macroremains studies conducted within the Stepnoye synchronous settlement (located 22 km

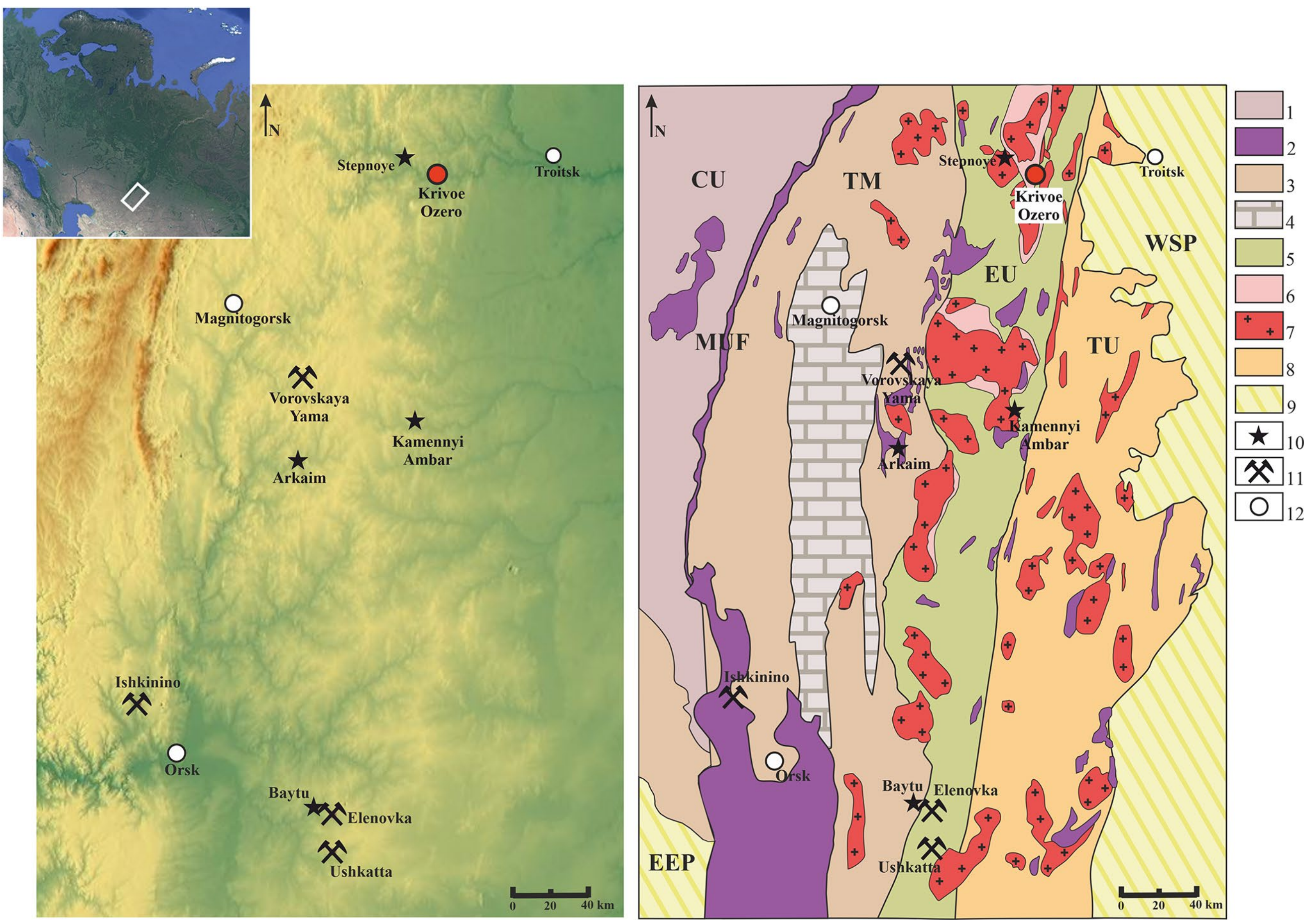


Fig. 1 Location of the Krivoe Ozero burial ground. Left: Geographic map with the location of sites mentioned in the text; Right: scheme of the Southern Urals geological structure (according to Kozlov et al. 2001): 1 – Precambrian and Paleozoic metamorphic complexes; 2 – Paleozoic ophiolite ultramafic-mafic complexes; 3 – Devonian-Carboniferous volcanic-sedimentary complexes; 4 – Carboniferous limestones and volcanogenic-sedimentary complexes; 5 – Paleozoic metamorphic and volcanogenic complexes; 6 – Proterozoic volcanic rocks and granite-gneisses; 7 – Carboniferous-Permian granite intrusions; 8 – Proterozoic-Paleozoic volcanogenic-sedimentary complexes; 9 – Mesozoic-Cenozoic sedimentary complexes; 10 – Bronze Age settlements, 11 – ancient mines, 12 – modern cities. The main structural-formational zones: EEP – East European platform, CU – Central Ural megazone, MUF – Main Ural Fault, TM – Tagil-Magnitogorsk megazone, EU – East Ural megazone, TU – Trans-Ural megazone, WSP – West Siberian platform

to the WNW) in the Uy River basin, where meadow vegetation predominates (Kupriyanova 2023; p. 81–83).

The territory of the Southern Trans-Urals is characterized by a complex geological structure, which includes volcanogenic, metamorphic, and sedimentary strata of different ages complicated by numerous intrusive complexes (Fig. 1b). In terms of large geological structures, the territory where the burial ground is located belongs to the East Ural megazone, which is a collage of microcontinental blocks dissected by ophiolitic and island-arc formations (Puchkov 1997). The territory of the burial ground is confined to Early Carboniferous granitoids (Supplementary Files (SF) I).

The Krivoe Ozero burial ground

The burial ground consists of 16 earthen mounds (kurgans) 0.25–0.6 m in height and 12–21 m in diameter. It is assumed that the necropolis was left by the inhabitants of Chernorechye III fortified settlement, which is separated from it by the bed of the Chernaya River (the right tributary of the Uy River). Four mounds consisting of 56 graves were excavated in the 1980s (Vinogradov 2003; Vinogradov et al. 2017). Burial mounds #1 and #2, which belong to a group of mounds along the river's bank, contained the Petrovka culture burials. Two Sintashta mounds #9 and #10, the latter of which had been also re-used for Petrovka graves, were also studied at the edge of the modern river's terrace.

The space under the burial mounds is arranged by emphasizing the center (the largest burial pits and sacrifices of domestic animals) and the periphery (smaller pits, often individual children graves). The Sintashta part of the necropolis includes 41 graves. Large graves (up to 2.3 m by 3.7 m) were deep (in some cases more than 2 m) and had wooden elements. All burials were conducted in accordance with the inhumation rite which is typical for the Sintashta culture; the position of the deceased is flexed to the side with their hands located close to their faces. Northern directions prevail in the orientation of the deceased. The number of people buried within the grave varies: there are individual, double, and collective graves. Children predominate numerically; some of them are buried in the same graves with adults.

The composition of grave goods is determined by age and gender, with the exception of ceramic vessels (Vinogradov 2003; Rykushina 2003; Vinogradov et al. 2017; Epimakhov and Berseneva 2012). The Sintashta finds included 36 metal items made mainly of copper-arsenic alloys (adze, knives, awls, needles, jewelry, rivets, and staples), as well as stone arrowheads and metalworking tools, bone artifacts, faience beads, etc. The chariot complex occupies a special place in the series of artifacts: fragments of carts, parts of horse bridles, and horse sacrifices are found. Bones of cattle, sheep, goats, and dogs, in addition to horses, were found among the sacrificial animals inside and outside the graves.

The metalworker's burial

Burial pit #3 was discovered in the northern part of Burial mound #10 (Vinogradov 2003; Vinogradov et al. 2017). No above-burial structure (typical for large burial pits in Sintashta necropolises) was detected. The dimensions of the pit were 2.65 m × 2.25 m in the upper part and 1.95 m × 1.45 m in the bottom part. The structure is oriented along the NNW-SSE line. The depth, including the mound soil, exceeded 2 m. The stepped structure of the burial pit indicates the presence of an unpreserved wooden ceiling at a height of about 1.4–1.6 m from the bottom. A cluster of five cattle crania and limb bones was discovered at the same depth, near the northern wall. Organic decay at the bottom of the pit allowed the reconstruction of the dimensions of the burial chamber as 1.8 m by 1.4 m) and its structure, including four corner pillars of about 10 cm in diameter with a plank wall-lining to a height of at least 20 cm. The skeleton of the deceased person was discovered at the bottom along the western wall of the chamber. The deceased was laid on the left side with the hands near the face (Fig. 2).

The main features of ritualism and the appearance of the ceramics collection allow the complex to be attributed to the Sintashta culture (Fig. 3). One of the most striking markers of the Sintashta attribution of the ceramic collection is a miniature sharp-ribbed "lamp" vessel with hanging holes (Figs. 2 and 3). We believe that the grave goods but ceramics and sacrificial animals, look like an illustration of the chaîne opératoire of metal production. They include fragments of copper ore, metallurgical slag, as well as whole metal products and their fragments (possibly remelted material).

The complex can rightfully be called unique, since it is the only example of a well-preserved Sintashta individual grave, which provides an opportunity to compare archaeological evidence with mineralogical and isotope data. In case of other discovered metallurgical artifacts, we either do not have such a complete set or cannot associate it with a specific individual due to the large share of collective graves. For example, slag, nozzles and drops of metal were found in the Solntse II burial ground (mound 5, pit 1) (Epimakhov 1996). However, the burial was disturbed many times, as a result it turned out to be impossible to determine the number and composition of those buried. A collective disturbed burial of at least five people was also found in the Sintashta burial ground, which was accompanied by finds of nozzles and casting mold blanks made of talc (Stefanov and Epimakhov 2006). Anthropological materials have now been lost, which precludes the use of many potentially possible analytical procedures.

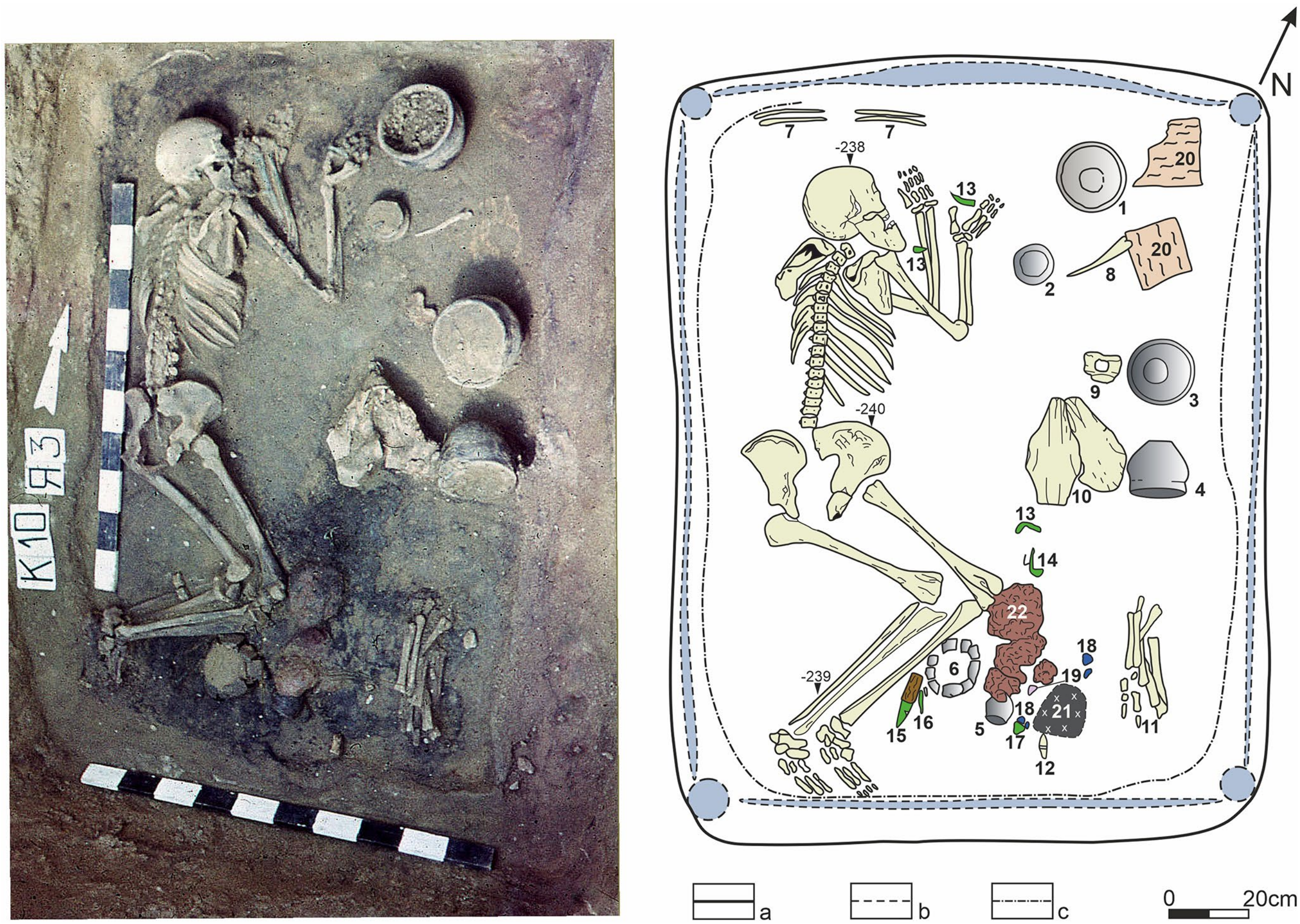


Fig. 2 Grave of a metalworker in the Krivoe Ozero burial ground (mound #10, pit #3). Photo and plan of finds at the bottom of the pit: 1–6 – ceramic vessels # 1–6 (depth −235); 7 – small cattle rib bones (depth −229/-230 cm); 8 – small cattle limb bone (depth of -232 cm); 9 – cattle vertebrae (depth of -235 cm); 10 – small cattle crania (depth of -235 cm); 11 – small cattle limb bones; 12 – bone disc; 13 – fragments of bronze bracelets (depth of -230/-240 cm); 14 – three metal staples (depth of -238 cm); 15 – copper knife-dagger with the remains of a wooden handle (depth of -235 cm); 16 – bronze awl (depth of -235 cm); 17 – copper ore (depth of -235 cm); 18 – metallurgical slag (depth of -235 cm); 19 – bowl (depth of -235 cm); 20 – organic decay (depth of -232 cm); 21 – carbonaceous (?) spot (depth of -235 cm); 22 – lumps of ceramic mass (depth of -235 cm). a – boundary of the burial pit at the level of -230 cm; b – grey-blue organic decay (remains of the wooden structure of the pit, presumably boards and pillars); c – dark gray decay (organic covering of the pit)

Bio-anthropological assessment

Based on the morphological characteristics (SFII-4), the individual is confidently identified as a male aged over 50 years old. The bones of the postcranial skeleton have a well-developed relief and wide shoulders, which suggests significant physical stress on the upper limbs, while the leg bones are moderately developed. The individual's height was about 164–167 cm. Pathologies are recorded in the form of traces of hormonal disorders on the skull and lower jaw, perforation on humeral heads, wear of the articular parts of the lumbar vertebrae, and adhesion of the fifth vertebra and the sacrum. The skull is characterized by general maturization, dolichocrania, a high cranium, and a large facial skeleton moderately profiled horizontally with a strongly protruding nose (Fig. 4). The individual has widely spread cheek bones. Hormonal imbalances caused the development of acromegaly. However, based on morphological characteristics, the skull stands out against the background of other materials from the burial ground and the culture in general (Rykushina 2003; Kitov et al. 2018).

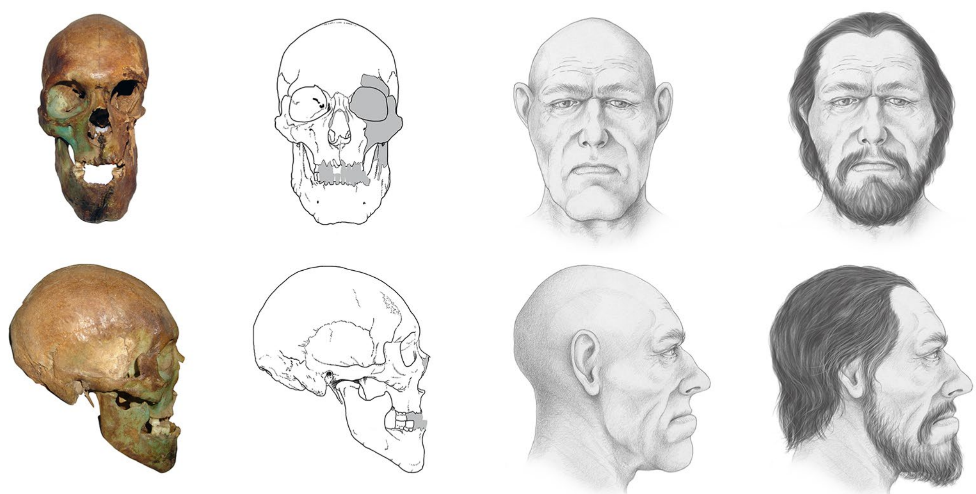
Analytical data

We have results of radiocarbon dating, isotope analyses, geological, mineralogical and metallographic analyses of artifacts and ecofacts from the grave. Aspects of methodologies and initial data are presented in the Supplementary files (SF-II).

Radiocarbon dating of the metalworker's grave includes one new measurement made using collagen from a cattle cranium (IGAN$_{AMS}$-10547, 3470 ± 25). The range of calibrated

Fig. 3 Ceramic vessels from burial #3 of mound #10 in the Krivoe Ozero burial ground. 1 – Vessel # 1; 2 – vessel # 2; 3 – Vessel # 5; 4 – Vessel # 6; 5 – Vessel # 3; 6 – Vessel # 4

Fig. 4 Skull of the male from grave #3, mound #10 in the Krivoe Ozero burial ground (reconstructed elements are marked in gray) and the graphic reconstruction of the face (reconstruction by D.V. Pozdnyakov)



values results (1881–1696 BCE, 95.4%) in a relatively late spectrum within the previously established chronology of the other grave of the cemetery (SF Table 1). However, a single-phase model of the chronology of mound #10 based on four datings (SF Table 2; Fig. 5) does not suggest the presence of statistical outliers, but demonstrates a high level of agreement and convergence. Thus, the hypothesis that the grave dates back to the 2000 – 1800 BCE can be considered reliable.

There are few measurements of δ^{15}N and δ^{13}C isotopes values conducted for other mounds of the burial ground ($n=5$) and collagen from human bones was mainly analyzed. The quality of the analyzes is confirmed by the C/N ratio (3.14–3.19), corresponding to the standard (DeNiro 1985; Ambrose 1990), as well as the similarity with previously obtained regional data from the Bronze Age. The considered individual (SF Table 3) has no noticeable differences from the rest of the series of this burial ground (Fig. 6) and from other previously studied series of the Southern Trans-Urals of the 2nd millennium BCE (Hanks et al. 2018; Epimakhov et al. 2023c). The δ^{15}N and δ^{13}C data set for the southern Trans-Urals indicates the predominance of a meat and dairy diet of the population living in the region during the Bronze Age. The same diet confidently applies to the

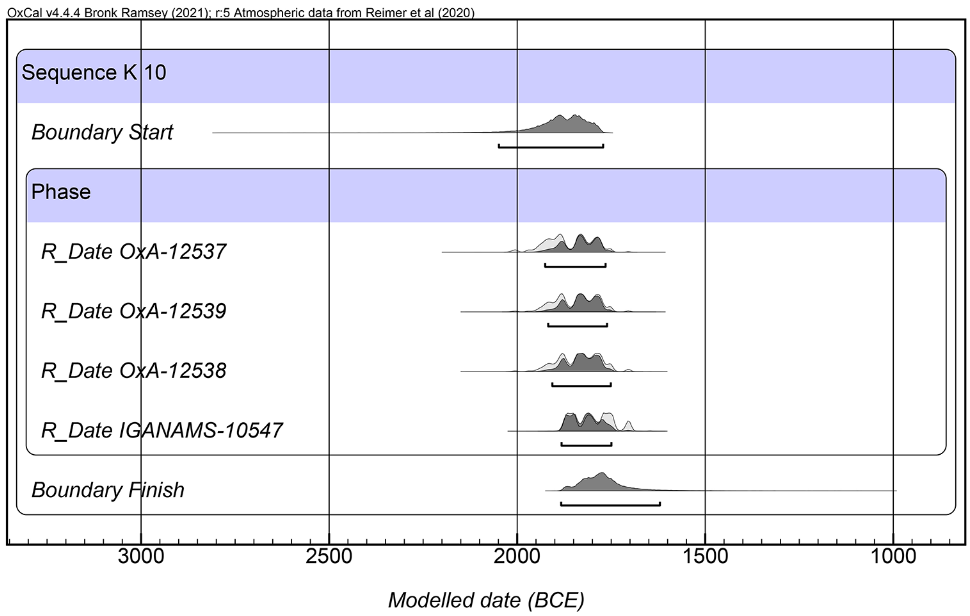


Fig. 5 The radiocarbon chronological model of mound #10 of the Krivoe Ozero burial ground

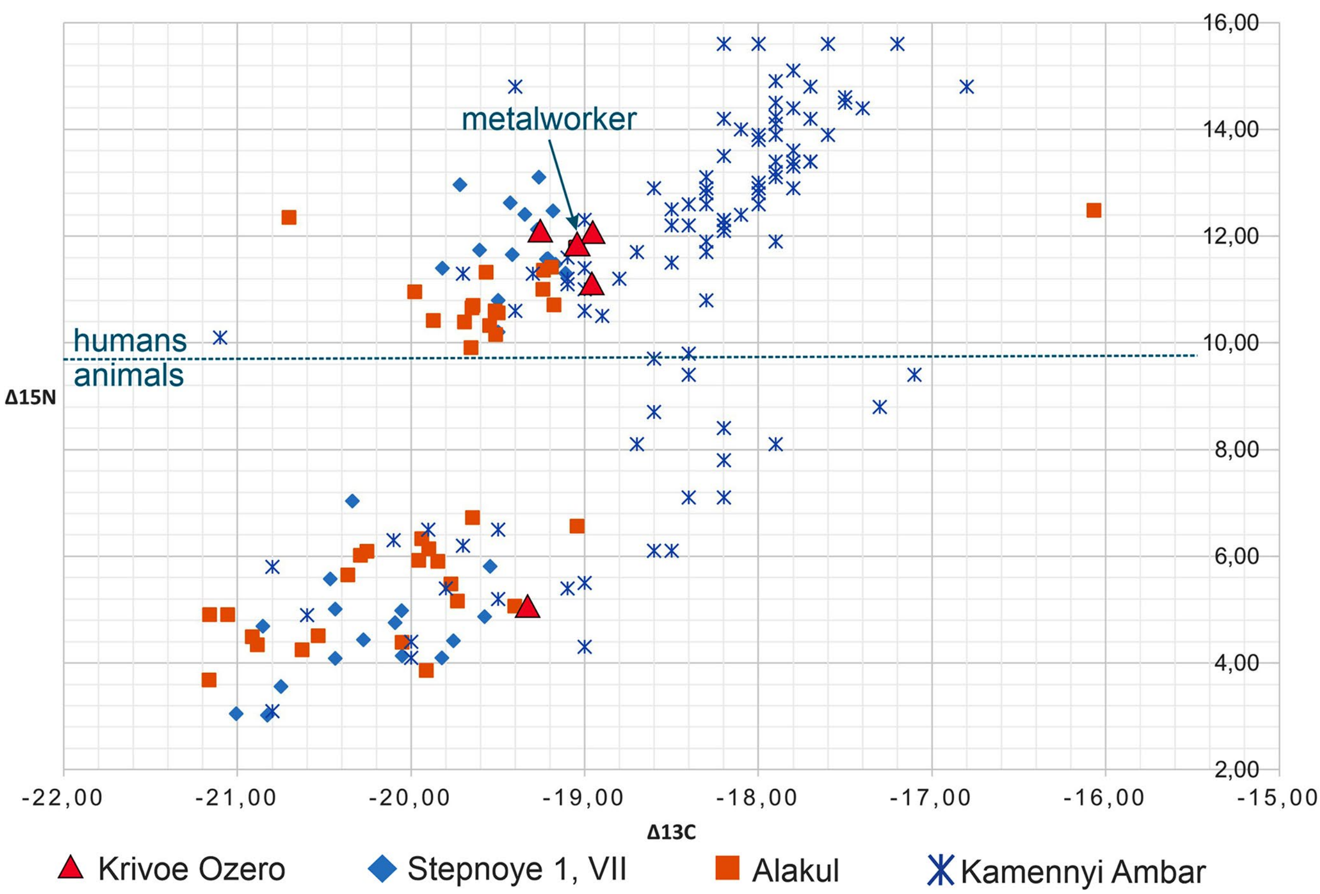


Fig. 6 $\delta^{15}N$ and $\delta^{13}C$ isotopes values in bone collagen of humans and animals from Bronze Age burial grounds in the Trans-Urals (According to: Hanks et al. 2018; Epimakhov et al. 2023c; Vasyuchkov et al. 2024 in press)

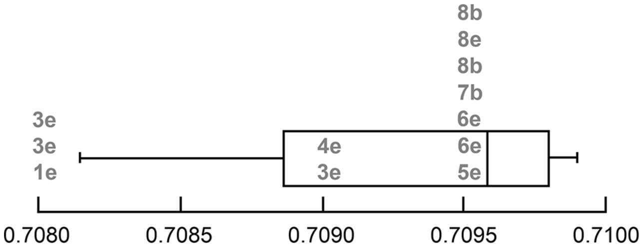


Fig. 7 Combined steam-and-leave and box diagrams with sample types marked ("e" for enamel and "b" for bone)

studied individual. The coincidence of the C and N isotopes values with other individuals of the Krivoe Ozero burial ground may indirectly indicate that they all lived for a long period in a climatic zone with the same level of moisture (Svyatko 2016).

The *^{87}Sr/^{86}Sr ratios* in the enamel of permanent teeth M1, M2, P1 are associated with the initial stages of life (up to 7 years) (Knipper 2017), while the constantly renewed bone and dentin incorporate local Sr isotope ratios, thus reflecting an isotopic signature at the place of death or the diagenetic impact (Hillson 1996; Price et al. 2002; Bentley 2006; Somerville and Beasley 2023). Twelve tooth enamel and bone specimens originating from nine skeletons from the Krivoe Ozero burial ground were sampled for Sr isotope analysis (SF Table 2, Table 4). The ratios of strontium isotopes in the tooth enamel M1, P1, I1, C of eight studied individuals, including a metalworker, should reflect the geochemical features of the region of birth and the first years of life, another one (tooth enamel M2) – 2–7 years of life (Knipper 2017; p. 85–86). All complexes belong to the Sintashta culture with the exception of the Petrovka grave from mound #1 (# 22–1951).

The small sample size ($n = 12$) confines us to some general observations: median: 0.70958; mean: 0.70933, standard deviation: 0.00065. When analyzing the entire set of enamel values, the sample shows heterogeneity (Fig. 7): a long tail on the left and a peak on the right on the Steam-and-Leave plot and a wide confidence interval of the mean value (from 0.70891 to 0.70974 ($\bar{x} = 0.70933 \pm 0.00041$ at 95% CL)). The difference between the lower and upper limits of the confidence interval is 0.0013, which significantly exceeds the previously formulated criterion $n < 0.001$ marking the origin of the organism from one region for the territory of the steppe Trans-Urals (Epimakhov et al. 2023b). These observations allow dividing the enamel values into two groups based on the median of the entire sample. The first group includes three low values in the range from 0.70814 to 0.70838, and the second group includes six high values in the range from 0.70935 to 0.70989. Despite the small sample size, the means of each group differ statistically from each other. Their difference is $n > 0.001$, which indicates two different regions of origin of the selected groups of the studied individuals (Fig. 8A).

The first group includes two males aged over 50 years old (there is no information on the third person). The individual we are interested in belongs to this group. His bone measurement coincides with the interval of the second group similar to other values for this type of sample. The discrepancy for one individual may be explained both by the difference in the place of origin and burial and diagenetic processes that affected the isotope ratio in the bone tissue.

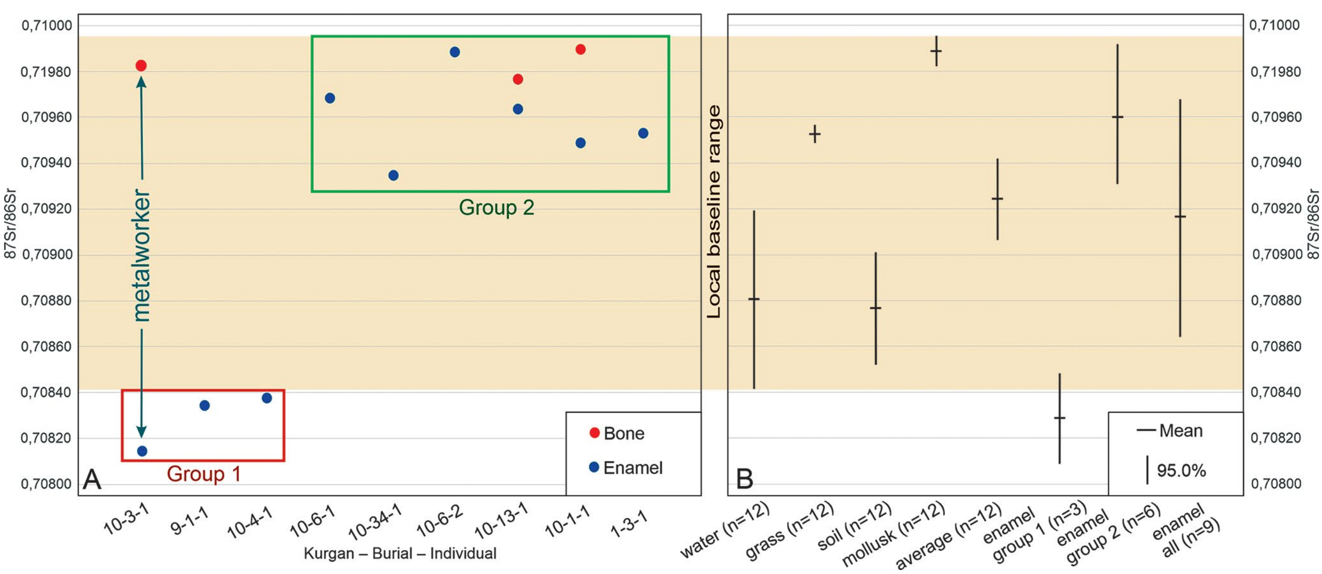


Fig. 8 ^{87}Sr/^{86}Sr values in background and archaeological samples of Krivoe Ozero microdistrict: **A** – ^{87}Sr/^{86}Sr values in enamel and bones of individuals buried in the burial ground; **B** – mean values with a confidence interval (at 95%) calculated for different types of background samples and enamel of the individuals (the confidence intervals which do not intersect stay for statistically significant ($p \leq 0.05$) differences between mean values)

Comparison with local baseline values helps to determine the regions of origin of each group of individuals.This data derived from interpolated maps of bioavailable Sr values for the southern Trans-Urals, covering more than 46,000 sq. km. The surveyed zone covers four large structural-formational zones of the Urals: Central Ural, Tagil-Magnitogorsk, East Ural, and Trans-Ural (Puchkov 1997). According to the maps, zones of increased $^{87}Sr/^{86}Sr$ values are confined to ancient metamorphic strata (average: 0.7106), and low values (0.7091 ± 0.002) – to younger volcanic-sedimentary complexes (Chechushkov et al. 2023; Epimakhov et al. 2023b).

Local background values within the Krivoe Ozero burial ground (within a radius of 5–7 km) were calculated for different types of bioavailable samples (SF Table 5). A sample of 12 interpolated values shows a significant scatter for water and soil, and to a lesser extent for wild grasses and mollusk shells (Fig. 8B). The statistically significant heterogeneity of the background values is apparently explained by the fact that the Krivoe Ozero site is located on the border of two geological regions associated with Carboniferous-Permian granite intrusions in the north and Paleozoic metamorphic and volcanogenic complexes in the south. The location of the extreme northern sampling line of our map in the immediate vicinity of the Uy river valley also contributed to the heterogeneity of the background results, which affected the reliability of the interpolation.

To clarify the local interval, we calculated the mean with a confidence interval for the entire background sample and compared it with the means of the entire sample of people and the two groups of values separately (Fig. 8B). The resulting graph shows an incomplete intersection of the average confidence interval with archaeological group 2 (main) and a significant difference from group 1. Even if we expand the possible local interval at the extreme points of the 95% confidence intervals with the minimum value at water and the maximum at the shellfish interval (Fig. 8B), the first group individuals still fall beyond these limits. This allows to suggest that the origin of the metalworker (mound #10, pit #3) and a charioteer (mound #9, pit #1) (Anthony and Vinogradov 1995; Chechushkov and Epimakhov 2018) are not associated with their burial place, unlike the other buried individuals.

The question of their origin can be resolved only within the framework of the obtained $^{87}Sr/^{86}Sr$ ratio interpolation map, which entirely covers the Trans-Ural part of the Sintashta ecumene (Fig. 9). The range of values for the buried group we are interested in, including the metalworker (from 0.70814 to 0.70838), tends to the values of the Tagil-Magnitogorsk geological megazone. Regions of similar values are located 100–150 km west and southwest of the burial ground (Epimakhov et al. 2023b; Fig. 9). The limited scale of the interpolated map of bioavailable strontium allows the clarification of the region only by the additional data analysis.

Mineralogical and geochemical study of metallurgy attributes

Optical and electron microscopy, LA-ICP-MS, used for studying the attributes of metallurgy and metal products gave essential results for the final conclusions (SF II.3). In a small fragment of ore (2 cm × 3 cm), the main mineral is malachite, while accessory minerals are tourmaline, quartz, pyrite, goethite, rutile, chalcopyrite, acanthite, iodargyrite (Fig. 10; SF III.3). Tourmaline is an accessory mineral for porphyry gold-copper deposits (Sillitoe 2010). Possible sources of such ore are currently unknown in the vicinity of the burial ground and the main area where other Sintashta settlements were distributed. Local deposits, the exploitation of which is proven in the Bronze Age, contain ores of a different composition (Ankusheva et al. 2022; Zaykov et al. 2005).

Metallurgical slags are represented by four fragments of 1–2 cm dense non-porous slag cakes (Fig. 11). All samples are similar in mineralogical and geochemical characteristics and belong to the olivine sulfide-containing type (Ankushev et al. 2021). Metal inclusions in the slag are represented by drops of arsenic bronze with impurities of Fe, Ni, and rarely S (SF III-3, Table 6). Relict inclusions are represented by grains of Cr-rich-spinels and partly melted fragments of serpentinites. The amount of metal in the slag is extremely small; some samples had no traces of metal; others contained single droplets up to 80 microns in size.

The previously studied wide sample of metallurgical slags from the Sintashta settlements is characterized by stable morphological and mineralogical-geochemical features. These are generally fragments of dense slag cakes with an edge formed above the metal ingot. The bulk of the slag consists of olivine (zoned prismatic and skeletal crystals (Grigoriev 2015; Ankushev et al. 2021). Fragments of slag cakes from the studied burial are only distinguished by a slightly larger amount of sulfides. The mineralogical and geochemical features of the Sintashta slags suggest that the sources of ore and alloying additives were associated with deposits belonging to ultramafic massifs (Grigoriev et al. 2005; Ankushev et al. 2021).

Metal products (Fig. 12) can be attributed to the Sintashta culture by their morphology and technological features. Their manufacturing process involved single-sided casting followed by forging finishing (SF III-3). The composition of the knife (Fig. 12a) consists of copper with As, Fe, and Ag impurities; the awl (Fig. 12d) is made of arsenic bronze. The composition of the bracelet is characterized by arsenic

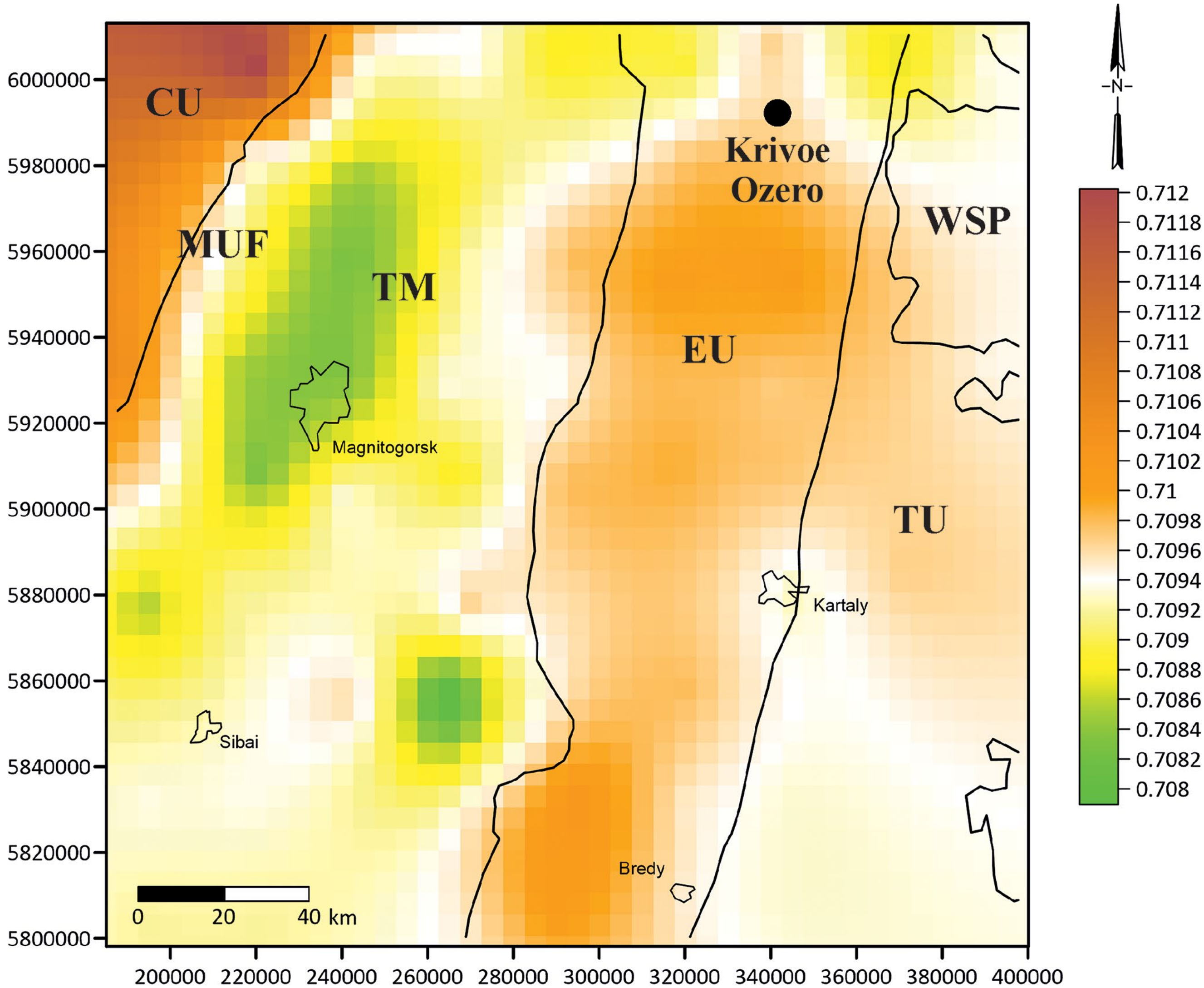


Fig. 9 Map of the interpolated values of bioavailable strontium in Trans-Urals (Epimakhov et al. 2023a). The main structural-formational zones: CU – Central Ural megazone, MUF – Main Ural Fault, TM – Tagil-Magnitogorsk megazone, EU – East Ural megazone, TU – Trans-Ural megazone, WSP – West Siberian platform

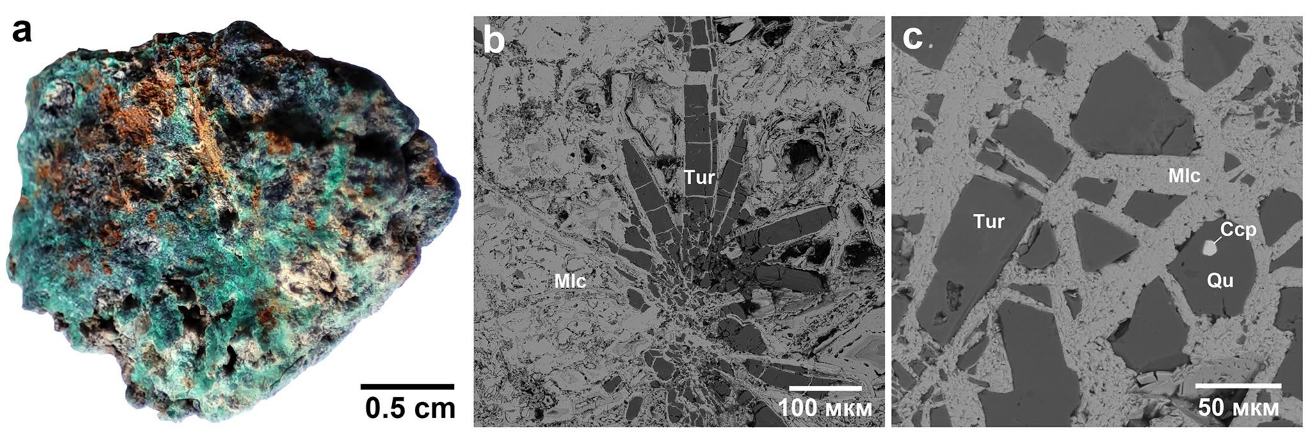


Fig. 10 Fragment of copper ore from grave #3, mound #10 in the Krivoe Ozero burial ground. **a** – general view, **b** – radiate-fibrous intergrowth of tourmaline crystals (Tur) in malachite (Mlc); **c** – quartz grains (Qu) with inclusions of chalcopyrite (Ccp), fragments of tourmaline crystals (Tur) in malachite (Mlc). **b**, **c** – BSE imag

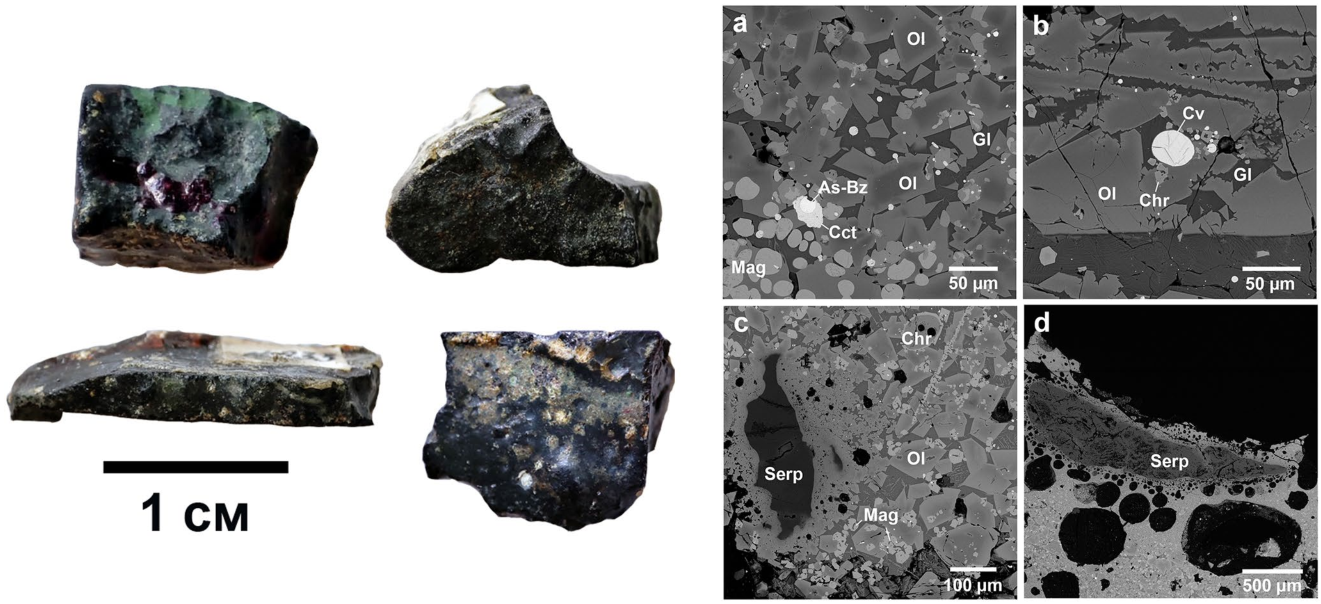


Fig. 11 Fragments of slag cakes from burial #3, mound #10 in the Krivoe Ozero burial ground. Mineralogy of slag: **a** – zoned olivine crystals, magnetite globules and a droplet of arsenic bronze with a sulfide “shirt” in the glass matrix; **b** – skeletal olivine crystals, covellite droplet and relic grain of Cr-rich-spinel in a glass matrix; **c** – relics of serpentinite and Cr-rich-spinel in slag; **d** – relic of serpentinite with inclusions of Ni-Co-copper chlorides. BSE images

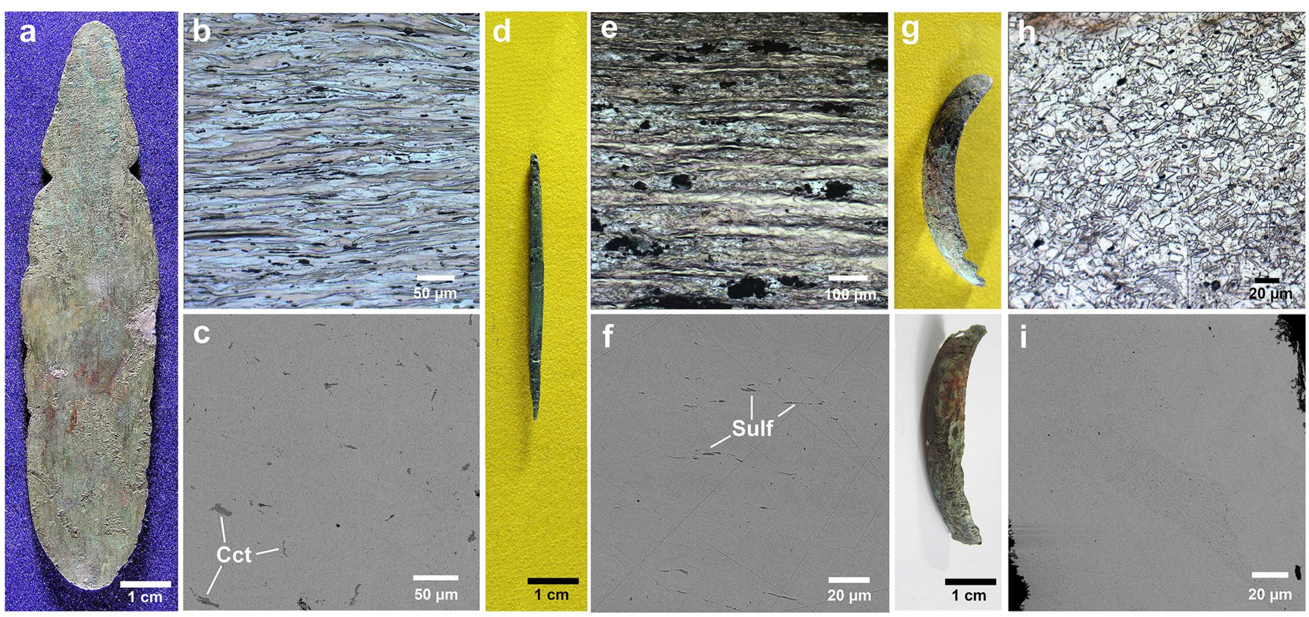


Fig. 12 Metal items from burial #3, mound #10 in the Krivoe Ozero burial ground. Knife: **a** – general view, **b** – post-etching metal microstructure, reflected light image, **c** – chalcocite inclusions in the metal, BSE image; awl: **d** – general view, **e** – post-etching metal microstructure, reflected light image, **f** – sulfide inclusions in the metal, BSE image; fragments of bracelets: **g** – general view, **h** – post-etching metal microstructure, reflected light image, **i** – pure metal, BSE image

bronze with a large number of impurities (SF III-3, Table 7) (Fig. 12g). The pronounced Fe-As-Ni-Se-(Co-Sb-Te-Au-Bi) association in the metal items is typical for the Sintashta tradition of metallurgy (Artemyev et al. 2024). It is assumed that this association is linked with adding arsenic-containing minerals to the copper ore charge to produce bronze at the stage of smelting metal from ore.

The key life events of the metalworker from birth to death

The above data are sufficient for making detailed inferences about the metalworker buried at the Krivoe Ozero cemetery. The first thing to note is the obvious predominance of Sintashta cultural stereotypes. This applies to almost all the main aspects of the archaeological complex. The individual was buried in a single space with other bearers of the Sintashta tradition, without serious deviations from the canons in the arrangement of the structure, methods of handling the body, and the composition and location of parts of sacrificial animals. The Sintashta attribution is confirmed by the appearance of the grave goods and, indirectly, by the technology of manufacturing metal artifacts. Individual burials of adults are present following Sintashta funeral practices, although insignificantly. For example, there is a well-known grave with a chariot from the same burial ground (Anthony and Vinogradov 1995). The studied case is distinguished by the non-standard appearance of the individual who lived to an old age, which is rarely found in Sintashta populations, and a complex of reliable metallurgy attributes illustrating the entire production cycle: ore – slag – scrap metal for remelting – finished products. The last category, of course, is widely represented in other burials and is included in the chain conditionally, based on the context. Only nozzles are missing to give a complete picture; single items of them are found in five graves of other Sintashta necropolises, including a single combination with slag and copper drops (Epimakhov and Berseneva 2016). Foundry molds and stone tools most likely belong to the metalworking phase.

The anthropological data of the studied individual distinguish him from others buried in the Krivoe Ozero necropolis (Kitov et al. 2018). First of all, this is about the features of the facial skeleton. The development of the girdle of superior extremity and skeletal pathologies indicate intense physical activity. We can assume that it involved not only ore crushing and grinding or metal forging, but also the regular actions of blowing air into a metallurgical furnace using bellows.

The main object of our interest – his lifetime mobility – can be inferred by studying the composition of Sr isotopes. As demonstrated above, the individual differs in Sr signal from the main group, and this can be also highlighted by the comparison with local background values.

The fragment of malachite copper ore with the inclusions of tourmaline and W-V-rutile should be considered most carefully out of all metallurgy attributes. The nearest porphyry copper deposits with tourmaline mineralization, which have signs of ancient exploitation, are Elenovka and Ushkatta (Zaykov et al. 2005). They are located in the northern Mugodzhar Range, i.e. at a distance of 300–350 km south from the Krivoe Ozero burial ground (Fig. 1). Tourmaline and rutile were also found in the ore samples from the ancient Elenovka mine and nearby Baytu settlement (Frotzscher 2021). The composition of tourmaline is similar to the mineral from the Krivoe Ozero burial (SF III-3, Tables 8 and 9; Fig. 1).

The discovery of copper ore in the Mugodzhar Range may reflect contacts between the population of the northern part of the Sintashta area with southern territories. The beginning of such contacts apparently dates back to the early spread of the Sintashta populations and is associated with the exploitation of copper ore resources in the Mugodzhar Range region. In addition to Elenovka and Ushkatta, there is at least one more mining site here – Ishkinino, which contains evidence of exploitation in the Sintashta period. According to radiocarbon dating, its exploitation began in the 21st–20th centuries BCE (Ankusheva et al. 2022). In this case, dates earlier than the grave are consistent with the general vector of the Sintashta population spread. Moving to the north of the southern Trans-Urals, the bearers of this tradition probably maintained channels to exchange ore with the Mugodzhar Range mining and metallurgical centers. This is indicated by samples of similar (probably Elenovka and Ushkatta) copper-tourmaline ores discovered during the excavations of the Sintashta settlements of Arkaim and Kamennyi Ambar located between the mine zone and the Krivoe Ozero burial ground (Bushmakin and Zaykov 1997; Ankushev et al. 2015). Studies of tourmaline using the LA-ICP-MS method showed two ore sources (SF Table 9). The copper-tourmaline ore of Krivoe Ozero corresponds to the Elenovka ancient mine (SF Fig. 1). The characteristics of the metallurgical slag from the grave, which has numerous direct analogies in other Sintashta sites, are consistent with these conclusions.

Discussion

Metal production and practices of mobility in the southern Trans-Urals during the LBA

As noted above, some degree of population mobility existed in the Ural steppes throughout the Bronze Age, but its extent changed over time due to the transition from mobile to settled pastoralism. In addition, at the beginning of the Sintashta period, episodic long-distance movement could have been a result of the migration from a distant area. This notion is supported by the apparent non-local origin of the cultural tradition (Anthony 2007; p. 389–410, Narasimhan et al. 2019) and the poor adaptation of at least some of the population to climatic conditions, as evidenced by markers of diseases such as mastoiditis, brain infections, and dento-facial diseases traced among buried individuals from Krivoe Ozero (Rykushina 2003; p. 360).

On the other hand, the analysis of $^{87}Sr/^{86}Sr$ ratios in tissues of domestic animals shows that most of them were grazed and consumed in their places of origin, suggesting a very limited degree of mobility (Epimakhov et al. 2023a). Possible exceptions are settlements near copper mining sites, as evidenced by the Vorovskaya Yama site, where the settlement was supplied with meat products from more distant regions (Ankusheva et al. 2024). Regarding people, the scenario is more diverse: a typical buried population usually breaks down into the main group with an isotopic signal similar to the locality and isotopic “outliers” interpreted as “non-local” individuals.

Similarly, Sintashta communities display genetic heterogeneity according to paleo-DNA data (Narasimkhan et al. 2019) and physical heterogeneity according to craniometric characteristics (Khokhlov and Kitov 2018; Kitov et al. 2018). Craniometric data helped distinguishing a small group of male individuals among the Sintashta population, including the metalworker, whose physical characteristics find parallels in the Botai and Yamnaya cultures of Western Kazakhstan, southwest from the Sintashta core area (Khokhlov and Kitov 2018; Kitov et al. 2018). Both lines of evidence suggest practices of exogamy, perhaps both patrilocal and matrilocal, or simply hosting non-local individuals by Sintashta communities, allowing for their cultural and social inclusion.

The buried population at the Krivoe Ozero cemetery demonstrates a similar tendency: the majority is associated with the location of the burial ground and the nearby settlement, as demonstrated by strontium values from tooth enamel. However, a small group most likely spent the early period of their lives somewhere else, presumably southwest of the Uy River valley, and, if the Sr signal derived from the metalworker’s tissues has not been distorted by diagenetic processes, we may assume that he spent the last years of his life in the vicinity of the cemetery or in a geomorphologically similar place. Despite his non-local origin and unusual physical appearance, the person practiced the same diet as other members of the community, as indicated by $\delta^{15}N$ and $\delta^{13}C$ isotope values. He was not ritually marginalized, as he was buried in accordance with the typical ritual. At the same time, he maintained some contact with the southern territories, as suggested by the presence in his grave of the southern ore.

The graves with attributes of metal production are found in several cemeteries of the Sintashta culture, usually one per cemetery. The only exception is the Bestamak cemetery on the southeastern periphery of the Sintashta ecumene, which contains three such graves (Kalieva and Logvin 2009). In those cases where the age and sex of deceased individuals are known, the correlation between attributes of metal production and adult males appears, but the strontium isotopic signature has been revealed only in the discussed case. For that reason, it is hard to assess whether individual mobility was an integral part of craft specialization in metal production during the LBA. However, the case of Krivoe Ozero demonstrates a conjunction of evidence with the contrasting Sr signal, metalworker’s belonging to the abovementioned group of individuals of plausible southern-western origin, and the presence of long-distance import. On that basis, it is possible to speculate that skills in metalworking were the reasons for hosting this foreign individual and even including him in the community, and that ore procurement expeditions or at least involvement into long-distance exchange could be a part of the specialized activities.

Conclusion

In this paper, we conducted a comprehensive analysis of the individual from the LBA cemetery of Krivoe Ozero in the southern Trans-Urals. Based on the ritual offerings and significant physical stress on the upper limbs, it is evident that this individual was a craft specialist specialized on metal production. His physical appearance was unusual in comparison to the rest of the buried people with widely spread cheek bones and acromegaly. The strontium isotope analysis revealed that the studied male individual had non-local origin, in a striking contrast with most deceased. The rest of the buried population from the Krivoe Ozero cemetery demonstrates the limited degreed of mobility and this observation is typical for other Sintashta cemeteries. In most cases, the same heterogeneity is observed: while the majority of buried individuals relate to the location of their burial, a minority originate outside of the place of burial (Epimakhov et al. 2023a).

The burial of the metalworker in the same sacred space as other members of the community indicates that neither his origin nor his craft specialization and unusual appearance caused his marginalization. This suggests that the same may be true for the whole group of metalworking specialists, as in other cases, their graves are distinguished exclusively by the presence of a specific set of artifacts but not ritual differences. In essence, the studied individual was born outside of the Krivoe Ozero microdistrict, but he was accepted to a new community, perhaps, due to his specific skills as the metalworker. His craft specialization undoubtedly required maintaining connections with distant sources of copper ore and may have necessitated traveling long distances.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Competing interests The authors declare no competing interests.

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