Ore sources of raw materials of the ancient metallurgy in the steppe Cis-Urals region

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Abstract. The paper considers problems to define the primary source of raw material for metallurgical production in the Bronze Age in the IV-II centuries BC on the steppe Cis-Urals area. The data of field, experimental, and geochemical analytical researches for 2016-2020 are used. The summary indicating the relation between the initial ore protolith and sulfide and silicious-carbonate oxidized ores dated by the end of the Permian period is formulated. Radiocarbon dates of bearing monuments of mining archaeology are given.

1. Introduction

In the epoch of the early metal age, from the IV century to the II century BC, the steppe Cis-Urals region was the principal mining and metallurgical area of North Eurasia. During the mentioned period in the region, the sizeable metallurgical center functioned. It combined several cultural metallurgical sites. Not-ore metal sources, including the scrap, raw, and purified copper in ingots and prills from the other regions, and imported metal artifacts did not play a significant role. The principal source of raw material for miner-metallurgists of the stock-raising cultures in the epoch of the early metal in the steppe Cis-Urals region was deposits of oxidized copper ore from the Kazan and Tatar horizons dated by the end of the Permian period [1]. Oxidized ore in the Cis-Urals area was extremely heterogeneous in the chemical-mineralogical and petrographic aspects. The question of which ore protolith served as the principal source of copper raw material has not yet had a definite answer. In 2016-2020 archeologists of the Orenburg Federal Research Center UB RAS, geologists, and geochemists of the Institute of Mineralogy UB RAS in the course of the joint expeditions within the steppe Cis-Urals region, including the central part of Orenburgskaya oblast, the south-west of Bashkiria and the north-west of Aktyubinskaya oblast in Kazakhstan, detected and examined 270 geoarchaeological copper-ore objects in the four adjacent mining and metallurgical regions (MMR): Kargalinskaya (Sakmaro-Samarskiy), Sakmaro-Ushatyrskiy, Sakmaro-Uralskiy, Uralskiy Levoberezhny [2, p. 134, figure. 1, 3].

A discovery and studying of mining and processing complexes (MPC) of Mikhaylovskiy (N52°09'30,85" E54°57'00,55") and Belousovskeyi (N52°11'17,93" E54°48'18,07") mines of the Bronze Age in the south-west of the Kargalinskoe ore field and several similar monuments with pits for fire setting of ore concentrates, slug-heaps, etc. became a significant advance of 2017-2020. It promoted to form a notion about ore sources of the ancient metallurgy, the ways of enrichment and refinement of ore materials, and others [3, 4]. Ore concentrates of these monuments were used in archeological experiments during 2018-2020 [4, 5]. The project devoted to studying the ancient metallurgy was realized in 2016-2020. It was based on geoarchaeological and experimental methods. It continues and develops principal ways of the research conducted by the Kargalinskaya expedition of the
Laboratory of Natural-Scientific Methods of the Institute of Archeology RAS under the leadership of E.N. Chernykh [6-10].

The most widespread point of view about ore sources of the ancient metallurgy, perhaps, is a concept of the relationship between the ancient metallurgy of the IV-II centuries BC with carbonates of copper (azurite-malachite) in sandstone deposits dated by the end of the Permian period, so-called "copper sandstones" [11, 12]. The stated hypothesis is conditioned by a lack of empirical data on technological algorithms of mining and metallurgical production and an absence of fundamental research on sources of ore raw material of the Bronze epoch. In researchers' opinion, the high purity of ancient metal items is conditioned by an absence of sulfur and other pollutants in the initial protolith. Mass data of modern geochemical analysis do not confirm the hypothesis about exclusively carbonate source of ore protolith. Any sample of metallurgical slag and rough copper from most parts of monuments in South Ural in the epoch of early metal from the beginning of the Bronze Age to its end has traces of copper sulfide [13, 14]. Rough copper from archeological monuments in the steppe Cis-Urals region, the same as experimental samples, contains sulfur from 0.5 to 1.5% [4, 5, 15]. Thus, copper minerals of charge mixture for melting included 8-10% sulfur. In the course of multiple lines of successful experiments (24 melting for copper and over 80 tests of refinement of rough copper with the following casting and forging of tools) for 2019-2020, the author of the paper managed to ascertain that rough copper refinement smelted from sulfide ore materials from 0.2 to 1 kg on charcoal in a metallurgical furnace under the temperature from 1050°C to 1150°C is accompanied by a transfer of rough copper in the sponge cuprile phase and sulfur burn for 10-15 minutes to the total transfer in the fluid phase under the temperature 1180°C.

Metallurgical complex from 250 burnt pieces of slag with the total weight 4.5 kg of an unsuccessful melting dated by the middle of the II century BC from Gorny settlement belonging to the Srubnaya culture within the Kargalinsk mines confirms special features of raw material used under the composition of charge mixture [7, p. 47, figure 2.20; 8, p. 101, figure 3.1]. According to these samples, the base of charge forms chalcocite mixed with silicous-carbonate ore materials. A part of the pieces formed slag. Chalcocite was partly replaced by matte bornite. Needle-shaped crystals of delafossite were developed on the ferruginized parts of the charge sinter due to sulfur burn from sulfides. At the same time, the most desulphated part of the charge was replaced by cuprite. Ancient metallurgists made a mistake in the course of the melting. Air supply to the furnace was stopped for a few minutes. Meanwhile, the furnace was warmed to reducing temperatures (1200-1300°C) in the process of charge loading to the mouth of the stove. Resumption of air supply led to explosive ignition of a mixture of the gas and coal dust, and the furnace was damaged. 4.5 kg of the slag-charge combination called in Modern History "bear" and required to melt a pancake-shaped ingot with a weight of 1.5-2.5 kg, was thrown by ancient metallurgists into a slag-heap. Thus, copper sulfides formed a significant part of the charge mixture under pyrotechnical conversion of ore materials into rough copper in the Bronze epoch [16]. At the same time, there was no objective evidence of carbonate minerals prevailing in the ore protolith.

2. Methods and Materials

The common notion about special features of ore raw material in the Bronze Age was formed on the base of 1.5 thousand geochemical analysis of ore samples, products of metallurgical conversion, slag dated by the epoch of the Bronze Age in the steppe Cis-Urals region, and analogous experimental models of metal, slag, etc. analyzed for 2016-2020 by the South Ural Federal Scientific Center of Mineralogy and Geocology UB RAS (Mias) and Common Use Center of the Ural Branch of RAS "Geoanalitik" FSBO Zavaritsky Institute of Geology and Geochemistry UB RAS using the methods of inductively coupled plasma mass spectrometry (ICP-MS), X-ray fluorescence analysis (XRF), electron microscopy, X-ray phase analysis and others.

In the geological-stratigraphic aspect, any ore occurrence dated by the Late Permian period in the steppe Cis-Urals region is connected with one vast syncline cut on the south-east of the Jurassic depressions. Riverbeds of large rivers – Ural, Sakmara, and others were formed on these depressions. A
part of ore occurrences developed in the Bronze Age was revealed by small inflows of the Sakmara and Ural rivers. The piece was revealed by ancient miners digging a hole.

According to the main petrographic signs, all oxidized ores from the end of the Permian period studied by us in the steppe Sic-Urals region are divided into three groups. The first group includes ore occurrences in grey arkosic sandstones saturated with copper carbonates (usually 1.5-5% Cu, an average – 2.5% Cu). In lenses and patches in thalwegs of the fossil Permian streams, the copper content is usually higher (from 5% to 15-20% Cu) due to the second enrichment under cementation of ore materials. Mineralization is more variable due to silicious-carbonate minerals, sulfides, sulfates, and copper oxides. In Modern History, in the XVIII-XIX centuries, these ores were called "sandstone." A "sandstone plate" with a thickness of over 2.5-3 cm was produced. Slim layers of sandstone ore were not developed. The second group includes ore occurrences in dark-grey (with ashy, cream-colored, brown, brownish-black tints) or almost black silt-shale deposits. Mineralization in them was connected with sulfide-oxide minerals. These ores called in the Modern History "vapa" [17], "clay slates," "slate," and copper content could reach 14-18% Cu. Pebbled conglomerates on calcite cement or grey marl saturated with copper oxides represented the third group. As a rule, these ores were developed neither in the Bronze Age nor in Modern History. There is only one exception – the Velyanskiy I mine located to the east from Orenburg and to the south of Chuloshnikov homestead, where extracted calcite conglomerates were annealed on a concentrating ground, and then they were crushed. Chalcocite pebble was selected from the mass of dead rock (rounded buildings from 0.4 to 3.5 cm). Later, it was annealed in special holes for partial desulfurization (to 8-10% S) and concentration.

According to the mineralogical content, all oxidized ores in the steppe Cis-Urals region are divided into three types. The first type is represented by sulfide-oxide mineralization. It includes chalcosine, and at the smaller degree – covellite, bornite, other sulfides, brochantite, antlerite, and other copper sulfates, copper carbonates – malachite, azurite, and cuprite and barrel-copper. Sulfide-oxide ores representing the comparatively little segment of oxidized ore occurrences in the steppe Cis-Urals region (5-7%) played the leading role in metallurgy in the early metal epoch. The second type of mineralization is connected with the silicious-carbonate mineralization of ore bodies. They consist of chrysocolla, called "glassy ore" in the Modern Age, associated with carbonates, copper oxides, and sulfides and sulfates. Despite its small number (5%-8%), this ore had great significance for ancient metalworking. The third type is represented by the most wide-spread carbonate-oxide variant of mineralization (87%-90%) with a prevalence of malachite in associations with rarer azurite, cuprite, and tenorite (black copper). In the Bronze Age, the wealthiest part of these ores (15%-20% Cu), less than 1.5%-2% of the total bulk, was produced in galleries, mines, and quarries on thalwegs riverbeds of the Late Permian streams.

Although the broad territorial isolation of ore occurrences within four mining regions of the Cis-Urals mining and metallurgical center (MMC), copper ores' chemical composition does not have a large variation. Based on XRF and ICP-MS data, we managed to detect four geochemical groups of oxidized ores used in ancient times in the Cis-Urals region [18, p. 118-123]: the first group – "pure copper"; the second group – with a higher content of silver; the third group – with a stable impurity of lead; the fourth group – with the combination of zinc and nickel, and chromium and nickel. No one group prevails absolutely. All four groups have mosaic distribution within the area of the steppe Cis-Urals region. Silver exceeding in ore materials, as a rule, can be explained by amalgams. The high content of lead, zinc, nickel, and chromium gives different variants of sulfides.

Residual combination of viscous impurities of lead, silver, chromium, and zinc with a variety of nickel in the ancient metal is an evident sign of belonging to the Cis-Urals group [11; 19; 20]. Fe, Mn, Ti, and Ba are in oxidized ores in thousand g/t. About 30 elements registered by XRF and ICP-MS are markers of an ancient metal belonging to the Cis-Urals oxidized ores. They are Cr, Zn, Pb, As, Ni, Ag, Sr, and V; they represented in several hundred g/t; Sn, Sb, Cd, Co, Bi, U, and others are in ten g/t. In the group of "pure copper,” all principal elements (Ag, Pb, Cr, Zn, and others) are less than 100 g/t. Less arsenic is in all ores of the Cis-Ural MMC with Ag, Pb, and S. Sulfide and silicious-carbonate ores contain 1% As. Ancient miners-metallurgists used any available type of chemically heterogene-
ous ore raw material with a copper content from 15\% to 20\% Cu that confirms enough high levels of technologies. The relative purity of Cis-Urals metal is conditioned by a connection with specific exceptionally "pure" sources of the raw material, peculiarities of technologies of ore preparing to the melting, segregative method of pyrotechnical copper revivification in small furnaces by reflecting types [16], the following refinement of blister copper, and special features of blacksmith's work made under premelting temperatures.

3. Geochemical and archeological specialization of the reference object
The study of the mining and processing complexes of the Bronze Age connected with the Mikhaylovskiy and Belousovskiy mines in the south-west area of the Kargalinsloe ore field had been conducted for 2018-2020. It showed that sulfide-oxide ores were processed there; carbonate and silieeous-carbonate ores were extracted at a smaller degree. Each MPC could process ores from several mines: in the Belousovskiy I MPC – the ore from the Belousovskiy and Pyatisotenny mines, in the Mikhaylovskiy MPC – ores from the Mikhaylovskiy, partly from Belousovskiy and Karpovskiy mines, the Ordynskiy ravine and others. A study of copper isotopy in samples refined by fire setting of enriched ore concentrates from the Mikhaylovskiy MPC showed their adequacy to ores from the Mikhaylovskiy and Belousovskiy mines [21]. About 16 kg refined ore concentrates were gathered on the surface of sludge discharge of the Mikhaylovskiy and Belousovskiy MPC. They were used for experimental melting in 2018-2019 [4, 5]. About 17 kg sulfide ore materials used later in experimental melting was found in the shaft of №2 in the Belousovskiy mine. It contained ceramics and bones dated by the Bronze epoch.

By 2019, within the territory of four mining and metallurgical region in the steppe Cis-Urals region, it was ascertained about 40 the most ancient mining ore objects with enriched and refined ore concentrates dated by the Bronze Age. Similar refined ore materials were detected in the geochemical analysis of copper ores from the ancient Yamny cultural layer of the Turganikskaya site dated by the first half of the IV thousand BC [22] within the west steppe area of the Kargalinskoe ore field. Also, the walls of a clay vessel belonging to the Srubnaya culture of the middle part of the II thousand BC found in №3 and №4 of the Pershinskiy burial mound in the central Kargalov were analyzed [23, p. 61, figure 2.21]. It was ascertained that in ancient times, due to the burning of the vessel containing abundant impurities of crushed refined ore concentrates of matte type in its wall, a part of copper revived itself as tiny granules and bars inside of sulfide-magnetite capsules. Some amount of it formed cuprites. Enriched and refined ore concentrates were noticed in the Gorny settlement's cultural layer – the reference mining and metallurgical object of the Kargalinskoe ore field, and in sludge discharges located to the north-west from the settlement under ore stockpiles bedding of the Modern Age.

In the Mikhaylovskiy and Belousovskiy mines, ancient miners-metallurgists produced sulfide-oxide ores deposited in lenses in association with oxide-carbonate, silicious-carbonate, and other minerals in silt-shale deposits of sebkha facies – inner lagoons and limans of sea coast of deserts separated from bays of the Late Permian sea Tetis by sand-clay spits. These deposits are connected with the highest Tatar horizon of mineralization. They are overlaid by sandstone-malmstone slabs, sand, and pebbles having the power of 3-5 m. As was mentioned above, in Modern History, such type of mineralization was called "vapa" (sulfide-oxide ores on clay slates). Such mixtures of rich Late Permian ores from the highest horizon of mineralization containing an average of 30\%-45\% Cu were a basis of mass metal production in the steppe Cis-Urals region during the Bronze Age from the IV thousand BC to the end of the II century BC. Sometimes, sulfide and other variants of ores from the lower Kazan horizon were used due to relative inaccessibility.

The most wide-spread versions of oxidized carbonate ores of copper sandstones with malachite and azurite containing an average of 2.5\% Cu were not considered as metallurgical raw material and thrown out in a heap of rocks in the Bronze Age. We clearly can notice the initial raw material of copper in the ancient metallurgy under the examination of the reference monument ores – the Belousovskiy mine. Perhaps, so-called "secondary" sulfides, mainly chalcocite (Cu$_2$S) having a rhombic shape of mineralization, and, to a less degree, covellite (CuS) and bornite (Cu$_3$FeS$_4$) forming to
three-quarter of the bulk of raw material were sorted to the further processing. Relict chalcopyrite (CuFeS₂) can be seen as tiny granules; microscopic dendrites of native copper can be noticed. Copper sulfates are represented by antlerite (Cu₃(SO₄)(OH)₄) and brochantite (Cu₄(SO₄)(OH)₆). In separate ore buildings, they can prevail under sulfides. Vanadate is represented by mottramite (PbCu(VO₄)(OH)). Copper hydrochloride atacamite (Cu₅(Cl(OH)₃)) is noticed practically in every second sample, sometimes calcium arsenate and copper conichalcite (CaCu(AsO₄)(OH)) can be seen. Copper silicate – chrysocolla ((CuAl)₂H₂S₄O₄(OH)₄) in the association with sulfides and carbonates can be noticed on the contact with petrified wood. Oxidized minerals are represented by tenorite (CuO) and cuprite(Cu₂O), carbonate minerals – azurite (Cu₃(CO₃)₂(OH)₂), and malachite (Cu₅(CO₃)(OH)₂). The complexity of mineralization of sulfide-oxidized versions of the Late Permian ore occurrences in the steppe Cis-Urals region was conditioned upon their formation and development under hypergenesis. Initially, chalcocite mineralization was developed in associations with covellite, and other sulfides and sulfates in the separated silty deposition of the Late Permian limans and inner lagoons (sebkha facies) dried up twice a year – in the summer and the winter, in hydrogen-sulfurous barriers based on fallen grains of chalcopyrite and sulfate of the chalcantite type as the reaction of the principal sulfide with sulfate. The other copper minerals are secondary; they were formed in the course of oxidation of the former. Chemism of sulfide buildings formation in the late vapa (silty) accumulation of inner limans (sebkha facies) of the seaside deserts can be introduced in the following way:

\[ \text{CuFeS}_2 + \text{CuSO}_4 + 2\text{H}_2\text{S} + \text{O}_2 = \text{Cu}_2\text{S} + \text{FeS}_2 + 3\text{H}_2\text{O} + \text{SO}_2 \] (syngen.);
\[ \text{CuSO}_4 + \text{H}_2\text{S} = \text{CuS} + \text{H}_2\text{SO}_4 \] (syngen.);
\[ \text{Cu}_2\text{S} + 2\text{O}_2 + \text{H}_2\text{O} = \text{Cu}_2\text{O} + \text{H}_2\text{SO}_4 \] (epigen). and others.

About 2-3% chalcocite mineralization is connected with fragments of roots and branches of trees washed off in silt, and they provided copper to be deposited from brines. Large woody stems were not in sebkha. Wood formed channel obstructions washed off by sandy-argillaceous materials higher of streams’ flow at the end of the Permian period. Flora and fauna of "vapa" in the Belousovskiy mine are poor and monotonous; it is represented by shells of Bivalvia (Dreissena Polymorpha) that deposited in the course of piled-up sea waves and backwaters. Also, steam imprints of reed are noticed in alerie surrounding sulfide buildings. Entire shells of the Zebra mussels (Dreissena Polymorpha) were found inside several chalcocite nodules. Copper sulfates and copper carbonate entirely replaced them. A predominant slabby-nodules shape of sulfide buildings in "vapa" reproduces structural singularity of silty fossil formations on the bottom dried up inner limans and lagoons.

In the part of slabs and nodules (less than 1%) from the ore stockpile of the Belousovskiy mine, copper mineralization was developed only in the crust. Small chalcosine contractions were noticed under the crusts. Clay materials were the central part of nodules or slabs with the inclusion of chalco-pyrite. Slabby, racemose, and amorphous limonite concretions with chalcocite pseudomorphs were noticed among samples taken from the ore stockpiles of the Belousovskiy mine. Jarosite and siderite concretions do not form considerable accumulation. Magnetite formations with microscopic contractions of telluric iron were developed inside limonite concretions. In the Belousovskiy mine's ore stockpile, one of the limonite concretions in the diameter of about 3 m contained a nugget of telluric iron in weight about 30 g. The metal is so clean and does not have evident impurities except for nickel. The reaction of iron reconstruction from magnetite and chalcopyrite on the sebkha's hydrogen-sulfurous barrier can be the following:

\[ \text{CuFeS}_2 + \text{Fe}_2\text{O}_3 + \text{H}_2\text{S} = \text{Fe}_3\text{O}_4 + \text{FeS}_2 + \text{CuS} + \text{H}_2\text{O} \] . Origin of iron items, episodically noticed in the Srubnaya culture's monuments of the Late Bronze Age, perhaps can be connected with similar sources.

Sulfide buildings extracted in the Belousovskiy and Mikhaylovskiy mines after sorting on the ore stockpiles were transported by ancient miner-metallurgists several hundred meters from the mines. They were annealed in holes to obtain enriched and refined ore concentrate – pyrolite [16], consisting of a mixed crystal of chalcocite of hexagonal syngony, tenorite, cuprite, and unstable sulfates of the dolerophanite type. Traces of similar technological actions were seen among other ore occurrences worked out in the Bronze Age. A link of the ore base of the Bronze Age's cultures, mainly with sulfide protolith, does not cast certain doubts. Pilot data on lead isotope of the part of blister copper ingots of
the Bronze Age in the steppe Cis-Urals region showed a connection of metal and ore materials from the Belousovskiy mine and other objects in the south-west area of the Kargalinskoe field [24]. To the west from the steppe Cis-Urals region, in the Donetskoe MMC within the Bakhmutskaya and Kalmius-Toretskaya depressions, ancient miner-metallurgists extracted slabby-nodules chalcosine buildings similar to ore occurrences of the Lowest Permian period, according to morphology and chemism [25, p. 193]. Sulfide-silicious-carbonate ores were removed from the second concentration of principle deposits to the west – in Trans-Ural, Mugodzhary, and Central Kazakhstan. [26].

Two radiocarbon dates were received according to AMS-technology in the Center of Applied Isotopic Researches conducted by the University of Georgia (USA) for a cultural-chronological complex of the Belousovskiy mine in 2020. Sample preparation was carried out in the Center Common Use, "the Laboratory of Radiocarbon Dating and Electronic Microscopy" of the Institute of Geography RAS. A sample of cattle bone from a fire setting hole №1 (a fragment of animal's tooth) in the Belousovskiy 1 MPC (shaft №1, the depth 1.6 m) № 8130 gives a date 3430±20 14C, BP (1σ). The second bone sample of cattle № 8132 from filling of excavation in the Belousovskiy mine (shaft № 1) from the depth 1.5 m, where a bone together with ceramics of the Srubnaya culture dated by the Late Bronze Age and small constructions of chalcosine placed under obstruction of sandstone slabs, showed the date 3370±20 14C, BP (1σ). Metering intervals of both dates (figure 1, 2) correspond to a principal chronological interval of the Srubnaya culture of the Late Bronze Age [27, p. 189, table 2].

![Image](image_url)

**Figure 1.** Probabilistic interval of a radiocarbon date of a bone sample from the fire setting hole №1 of the Belousovskiy mining and processing complex №1 in the Belousovskiy mine of the Late Bronze epoch.

The mentioned dates reflect the time of the "metal boom" in the steppe regions of North Eurasia connected with the miner-metallurgists activity of the Srubnaya and Alakulskaya cultures of the Late Bronze Age exhausted of reserves sulfide and silicious-carbonate ores in the most of available deposits. Metallurgy of the final phase of the Bronze Age represented by materials of the classical Pine-Masa hoard on the Lower Volga [28], was based on the usage of principally new ore protolith – copper pyrite (chalcopyrite) [16]. Thus, monuments of mining archeology in the south-west area within
the Kargalinsloe ore field – the Belousovsyk, Mikhailovskiy mines and connected with them associations of fire sitting holes and sludge discharge, represented themselves the reference objects in studying of the metallurgical raw material of the early metal epoch.

![Figure 2. Probabilistic interval of a radiocarbon date of a bone sample from filling of a shaft №1 in the Belousovsyk mine in the Late Bronze epoch.](image)

**Figure 2.** Probabilistic interval of a radiocarbon date of a bone sample from filling of a shaft №1 in the Belousovsyk mine in the Late Bronze epoch.

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**References**

[1] Zelenetsky A A, Zyablitksy I I and Malyutin V L 1948 *Mineral resources of the Chkalov* (Chkalov: Chkalovskoe Publ) p 213

[2] Bogdanov S V 2017 *Systematics of the Ancient Yamnaya Culture’s Complexes of the Eastern Ponto–Caspian Steppes in the Frame of Transfer of Ore Mining and Metallurgy Traditions into Northern Eurasia* *Stratum plus* Issue 2 Archaeology and Cultural Anthropology (Saint Petersburg, Kishinev, Odessa, Bucharest) pp 133-157

[3] Bogdanov S V, Tkachev V V, Yuminov A M and Avramenko S V 2018 The geoarcheological system of historical copper mines in the Cis-Urals (Kargalinsloe) steppe mining and metallurgical centre *Geoarkheologiya i arkeologicheskaya mineralogiya* 2018 (Miass: Institute of Mineralogy UB RAS) pp 121-133

[4] Bogdanov S V 2019 Technologies of mining and metallurgical production in the early metal epoch in the context of experimental archeology *Phenomena of the Early Bronze Age’s cultures in the steppe and forest-steppe zone of Eurasia: ways of cultural interaction in the V-III thousand centuries BC* (Orenburg: Publ. OGPU) pp 161-174

[5] Bogdanov S V 2019 The Triad by V.A. Gorodtsov in the aspect of succession of traditions of mining and metallurgical production in Eastern Europe *Antiquity of Eastern Europe, Central
Asia and South Siberia in the context of connections and interactions in the Eurasian cultural space (modern views and concepts): Materials of international conference, 18–22 November 2019, Saint-Petersburg. Vol. II. Connections, contacts and interactions of ancient cultures of North Eurasia and the East civilization in the epoch of paleometal (IV-I centuries BC). To the 80th –birthday of the famous archeologists V.S. Bochkarev (SPb.: IIMK RAN, Nevskaya Tipografiya) pp 143-145

[6] Kargaly I Geological-geographical descriptions. History of discovering, exploitation and researches. Archeological monuments 2002 E N Chernykh (eds) (Moscow: Languages of the Slavic cultures) p 112

[7] Kargaly II Gornyi – the settlement of the Late Bronze Age. Topography, lithology, stratigraphy. Industrial-domestic and sacrac constructions. Relative and absolute chronology 2003 E N Chernykh (eds), (Moscow: Languages of the Slavic cultures) p 184

[8] Kargaly III Settlement Gornyi: Archeological materials. Technologies of mining and metallurgical production. Archeobiological studies 2004 E N Chernykh (eds) (Moscow: Languages of the Slavic cultures) p 321

[9] Kargaly IV Necropolis in Kargaly. Population: paleontological researches 2005 E N Chernykh (eds) (Moscow: Languages of the Slavic cultures) p 240

[10] Kargaly V. Kargaly: the phenomenon and paradoxes of development; Kargaly in the system of metallurgical provinces: Sacral life of archaistic miners and metallurgists 2007 E N Chernykh (eds) (Moscow: Languages of the Slavic cultures) p 200

[11] Chernykh E N 1966 a History of the ancient metallurgy in Eastern Europe (MHA) 132 p 144

[12] Degtyareva A D 2010 History of metal production in South Trans-Ural in the Bronze epoch. (Novosibirsk: Nauka) p 162

[13] Ankushev M N, Petrov F N and Blinov I A 2018 Metallurgical slag and copper ores of Levoberezhnoe settlement (South Ural) in the Bronze Age Geoarcheology and archeological mineralogy 2018 (Miass: Institute of Mineralogy UB RAS) pp 155-161

[14] Artemyev D A and Ankushev M N 2019 Trace elements of Cu-(Fe)-sulfide inclusions in Bronze age coper slags from South Urals and Kazakhstan: ore sources and alloying additions Minerals 9 p 746

[15] Pazukhin V A 1969 Copper ingots from the Orenburg museum Soviet archaeology 4 (Moscow) pp 239-245

[16] Bogdanov S V 2020 Technological algorithms of the pastoral model of metal production in the steppe regions of North Eurasia in the Bronze Age Ural Historical Journal 4 pp 6-14

[17] Bogachev V F 1889 A short essay of deposits of copper ores, brown coal, selenite and others in Turgayskaya oblast. Mining Journal Iss 3 pp 453-458

[18] Yuminov A M, Bogdanov S V, Tkachev VV, Avramenko SV and Manbetova G R 2017 Geochemical description of ores from historical copper mines in the steppe Cis-Urals region Geoarcheology and archeological mineralogy 2018 (Miass: Institute of Mineralogy UB RAS) pp 35-41

[19] Chernykh E N 1970 The ancient metallurgy of the Urals and Povolzhie areas (MHA) 72 185 p

[20] Degtyareva A D 2010 History of metal production in the South Trans-Ural in the Bronze epoch (Novosibirsk: Nauka) p 162

[21] Karpova S V, Kiseleva D V, Chervyakovskaya M V., Streletskaia M V, Shagalov E S, Bogdanov S V, Tkachev V V, Yuminov A M and Ankushev M N 2019 Copper isotope ratios in Cis-Urals copper sandstones and products of their processing as a tool for uncovering the Bronze Age smelting activities AIP Conference Proceedings. Proceedings of the VI International Young Researchers Conference Physics, Technologies and Innovation, PTI 2019 2174 020221 pp 1-4

[22] Morgunova N L, Vasil'eva I N, Kul'kova M A, Roslyakova N V, Salugina N P, Turetskii M A, Faiuzlin A A and Khokhlova O S 2017 Turganikskoe settlement in Orenburgskaya oblast. (Orenburg: Publ. OGAU) p 300
[23] Bogdanov S V 2005 The Pershinskiy necropolis: burial mounds №№ 3 and 4 Kargaly Vol IV Necropolis in Kargaly. Population: paleontological researches. E.N. Chernykh (eds.) (Moscow: Languages of the Slavic cultures) pp 49-69

[24] Kiseleva D V, Soloshenko N G, Streletskaia M V, Okuneva T G, Shagalov E S, Tkachev V V, Bogdanov S V, Ankushev M N, Koryakova L N and Vinogradov N B 2020 The isotopic analysis of lead in metal of the Bronze Age in the steppe Cis-Urals region and Trans-Ural XI All-Russian scientific conference: Minerals: structure, proprieties, methods of the study (Ekaterinburg: Institute of geology and geochemistry UB RAS) pp 122-125

[25] Tatarinov S I 1977 To the mining and metallurgical centre of the Bronze epoch in Donbass Soviet archaeology pp 192-207

[26] Zaikov V V, Melekestseva I Yu, Artem’ev D A, Yuminov A M, Simonov V A and Dunaev A Yu 2009 Geology and pyrites mineralization in the south side of the Great Uralfracture (Miass: Institute of Mineralogy UB RAS) p 375

[27] Kuptsova L V 2014 Funeral monuments of the Srubnaya culture in the west Orenburg region with the usage of stone: specifics, cultural connections, periodization and radiocarbon chronology Archeological monuments of the Orenburg region Iss 11 (Orenburg) pp 177-195

[28] Chernykh E N 1966 b To a chemical structure of metal from the Pine Maza’s hoard Short repots and field studies conducted by the Institute of Archeology Iss 108: Archeologuical monu-ments of Caucasus and Central Asia (Moscow: Nauka) pp 123 – 131