eISSN 2500-0632
https://mst.misis.ru/

GEOLOGY OF MINERAL DEPOSITS

Research paper

https://doi.org/10.17073/2500-0632-2023-10-165
UDC 556.3

Analysis and evaluation of prospects for high-quality quartz resources in the North Caucasus

I.I. Bosikov[1], **R.V. Klyuev**[2] ✉, **V.Ch. Revazov**[1], **N.V. Martyushev**[3]

[1] *North Caucasian Mining and Metallurgical Institute (State Technological University), Vladikavkaz, Russian Federation*

[2] *Moscow Polytechnic University, Moscow, Russian Federation*

[3] *Kh. Ibragimov Complex Institute of the Russian Academy of Sciences, Grozny, Russian Federation*

✉ *kluev-roman@rambler.ru*

Abstract

Quartz resources play a crucial role in the development of key economic sectors, particularly in the production of chemically pure silicon. The extraction and processing of these resources necessitate high-tech methods to obtain the desired silicon output. Presently, the demand for silicon stands at 5–6 Ktpa, while the supply remains at 2300 t. An analysis of the chemical properties of various rocks (quartzites, quartz sands, vein quartz) in the Republic of North Ossetia–Alania reveals that their parametric characteristics align with the requirements for silicon production. The researchers in North Ossetia have successfully grown single-crystal silicon and produced photovoltaic converters. Russian scientists have also achieved the first melting of metallurgical silicon into polycrystalline silicon using vacuum furnaces and electron-beam remelting, yielding promising results. The goal of this research is to analyze and assess the potential of high-quality quartz resources in the North Caucasus. The main objectives include identifying sites with optimal quartz deposits suitable for silicon production, conducting localization, estimating forecast resources, and designating areas for further investigation. The selected sites are expected to possess advantageous geographical and economic features, along with favorable mining conditions conducive to open-pit mining. The study focuses on the Fiagdon site in the Alagir District, RNO-Alania. Various methods, including laboratory work, sampling, examination of constructed sections, and a comprehensive review of mine workings and borehole documentation, were employed. Conclusions from mineralogical and petrographic analyses, alongside laboratory studies and process tests, contributed to the research methodology. The results of the research encompassed the analysis of statistical, economic, geological, and process-related information necessary for addressing primary geological objectives. Subsequent steps involved the selection of prospects for further exploration, specification of geological maps at a 1:10000 scale with accompanying legends and sections, determination of the conditions, morphology, and parameters of productive deposits, and preliminary studies on the quality and process characteristics of quartz resources. Furthermore, the P_2 forecast resources of high-quality quartz raw materials for silicon production were localized, estimated at 500 Kt, and rigorously tested. The study's discoveries have led to the formulation of recommendations for future exploration endeavors.

Keywords

quartz resources, silicon, prospects, mineralogical and petrographic analysis, process tests, productive deposits, quality and process characteristics of quartz resources

For citation

Bosikov I.I., Klyuev R.V., Revazov V.Ch., Martyushev N.V. Analysis and evaluation of prospects for high-quality quartz resources in the North Caucasus. *Mining Science and Technology* (*Russia*). 2023;8(4):278–289. https://doi.org/10.17073/2500-0632-2023-10-165

ГЕОЛОГИЯ МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Научная статья

Анализ и оценка перспективных участков высококачественного кварцевого сырья на территории Северного Кавказа

И. И. Босиков[1], **Р. В. Клюев**[2] ✉, **В. Ч. Ревазов**[1],
Н. В. Мартюшев[3]

[1] *Северо-Кавказский горно-металлургический институт (государственный технологический университет)», г. Владикавказ, Российская Федерация*

[2] *Московский политехнический университет», г. Москва, Российская Федерация*

[3] *Комплексный научно-исследовательский институт им. Х.И. Ибрагимова Российской академии наук, г. Грозный, Российская Федерация*

✉ *kluev-roman@rambler.ru*

Аннотация

Кварцевое сырье является стратегическим ресурсом, так как обеспечивает развитие важнейших отраслей экономики. При этом необходимо учитывать, что при его добыче и переработке следует применять высокотехнологичные методы, позволяющие получить в результате обогащения этого сырья химически чистый кремний. На сегодняшний день потребность в кремнии составляет 5–6 тыс. т в год при предложении 2300 т. Анализ особенностей химизма ряда горных пород (кварцитов, кварцевых песков, жильного кварца) Республики Северная Осетия – Алания показал, что они по своим параметрическим характеристикам могут отвечать требованиям, предъявляемым к кварцевому сырью для получения кремниевой продукции. К настоящему времени учёные Северной Осетии также имеют успешный опыт выращивания монокристаллического кремния и изготовления фотоэлектрических преобразователей. Российские учёные провели первые плавки металлургического кремния в поликристаллический в вакуумных печах способом электронно-лучевого переплава. Во всех случаях результаты обнадёживающие.

Цель, задачи: провести анализ и оценку перспективных участков высококачественного кварцевого сырья на территории Северного Кавказа. Основной задачей исследований является выявление объектов высококачественного кварцевого сырья для производства кремниевой продукции, локализация, оценка их прогнозных ресурсов и выделение участков для дальнейшего изучения. Выявленные объекты должны иметь благоприятные географо-экономические положение и горнотехнические условия, способствующие возможности их открытой (карьерной) отработки.

Объекты: Фиагдонский участок Алагирского района, РСО-Алания.

Методы: Проведение лабораторных работ, опробования, исследование построенных разрезов, изучение документации горных выработок и скважин, заключений минералого-петрографических, лабораторных исследований и технологических испытаний.

Результаты. После выполнения намеченного комплекса исследовательских работ проведен анализ статистической, экономической, геологической, технологической и другой информации, необходимой для решения основных геологических задач; выделены перспективные участки для дальнейших работ; уточнены геологические карты перспективных участков масштаба 1 : 10000 с легендами и разрезами к ним; определены условия залегания, морфология и параметры продуктивных залежей; предварительно изучены качество и технологические характеристики кварцевого сырья; локализованы, оценены и апробированы прогнозные ресурсы высококачественного кварцевого сырья для производства кремниевой продукции по категории P_2 – 500 тыс. т; разработаны рекомендации для проведения геологоразведочных работ.

Ключевые слова

кварцевое сырье, кремний, перспективные участки, минералого-петрографический анализ, технологические испытания, продуктивные залежи, качество и технологические характеристики кварцевого сырья

Для цитирования

Bosikov I.I., Klyuev R.V., Revazov V.Ch., Martyushev N.V. Analysis and evaluation of prospects for high-quality quartz resources in the North Caucasus. *Mining Science and Technology* (*Russia*). 2023;8(4):278–289. https://doi.org/10.17073/2500-0632-2023-10-165

Introduction

Quartz resources play a pivotal role as strategic assets, crucial for the development of key economic sectors. The imperative development of effective technologies for processing these resources is vital to yield high-quality silicon [1, 2].

As of now, the demand for silicon stands at 5–6 Ktpa, with a supply of 2300 t. Encouragingly, Russian scientists have achieved a breakthrough by melting metallurgical silicon into polycrystalline silicon using vacuum furnaces and electron-beam remelting [3, 4].

In the pursuit of securing advantageous positions in the mining, production, and marketing of products derived from exceptionally pure quartz resources in Russia (e.g., Eastern Siberia's "Solar Silicon" project, the Urals' "Silicon–Ural," and "Polar Quartz" projects), enterprises specializing in the deep processing of quartz resources are being established based on known deposits [5, 6]. Most quartz deposits are traditionally located in the Urals or Siberia [7, 8].

Chemical analysis of rocks (quartzites, quartz sands, vein quartz) from the North Caucasus [9, 10] has shown that their parametric characteristics can meet the requirements for quartz resources to produce silicon products.

Notably, in the Republic of North Ossetia–Alania, scientists have demonstrated successful experiences in cultivating single-crystal silicon and producing photovoltaic converters [11, 12].

The structure of quartz contains various impurity elements (IEs), such as Al, Fe, Ti, H, Li, Na, K, Cr, B, P, Ca, Mg, and Co, which directly impact resource quality.

A study of five vein quartz samples collected in 2019 from the Vodorazdelnoye occurrence by NIP SKGMI LLC (GTU) "Stroykomplekt-Innovations," and conducted in the Rostec laboratory using atomic absorption methods (in flame and emission) in plasma, reveals that the impurities in the samples can be readily removed. Moreover, the quartz resources adhere to GOST 41-07-014–86 standards (Table 1).

In order to evaluate the suitability of quartz rocks within the territory of North Ossetia and identify research sites with significant resource potential, a preliminary analysis of available materials was conducted. The selection of these sites adhered to specific criteria:

– the examined rocks should exhibit homogeneity and be situated in favorable geographic and economic conditions, minimizing material costs for infrastructure preparation and road network development [13, 14];

– potential projects should possess necessary reserves and offer mining and technical conditions conducive to mechanized open-pit mining [15, 16].

Based on these criteria, four areas emerged as the most promising: Naro-Mamison, Fiagdon, Dzhimara, and Fiagdon-Kambileyevka. The research focus spans the central, predominantly eastern part of Mountainous Ossetia, specifically within the interfluve of the Ardon–Kambileyevka Rivers situated in the Alagir District of North Ossetia.

The study area is delineated to the west by the Ardon River valley and to the east by the basin of the Kambileyevka River. The northern border aligns with parallel 43°00', and the southern border corresponds to the latitude of the Zakkadon River source. The selection of the work area in the Central Caucasus region is influenced by its highly dissected topography. Major watercourses include the Terek, Ardon, Fiagdon, Gizeldon, and Kambileyevka Rivers, along with numerous tributaries. The hydrological regime across all watercourses in the area exhibits a distinct seasonal nature.

Within this district, four areas have been designated for prospecting activities: Naro-Mamison, Fiagdon, Dzhimara, and Fiagdon-Kambileyevka. The geographical and economic positioning of these areas varies, reflecting the diverse characteristics of each.

The **Naro-Mamison area** situated in the upper reaches of the Ardon River and its tributaries (Zakkadon, Zrugdon, Vartsedon, and Mamisondon),

Table 1

Impurity element content in quartz from Vodorazdelnoye occurrence

Item No.	Sample No.	Element content, $n \cdot 10^{-4}$ %, ppm														
		B	P	Na	K	Li	Ca	Mg	Fe	Cu	Mn	Ni	Cr	Co	Al	Ti
1	KZh-1	–	–	23	40	10	5	2	5	0.3	10	1.5	0.5	1.5	15	1
2	KZh-2	–	–	23	20	10	7	3	10	0.7	10	2	0.5	2	20	2
3	KZh-3	–	–	35	40	15	10	10	30	1	10	3	1	3	30	6
4	No. 1	0.625	< 0.16	46.07	16.12	1.629	25.6	0.24	0.149	< 0.02	0.055	0.099	< 0.02	< 0.06	10.2	0.134
5	No. 2	0.295	0.2	22.62	5.656	0.68	169.1	2.547	0.521	< 0.02	0.214	0.049	< 0.02	< 0.06	13.24	0.124
Sum		0.92	0.28	149.69	121.78	37.31	216.7	17.79	45.67	2.02	30.27	6.65	2.02	6.56	88.44	9.26
Average		0.46	0.14	29.94	24.36	7.46	43.34	3.56	9.13	0.40	6.05	1.33	0.40	1.31	17.69	1.85

is categorized into three distinct zones: Vartse, Zrug, and Baikom, based on a comprehensive review of materials from geological archive. The Vartse site is positioned 0.4 km south of the Village of Vartse and 2.0 km southwest of the Village of Nar; the Zrug site is located 1.5 km south and southwest of the Village of Nar in the lower reaches of the Zrug gorge; while the Baikom site is confined to the left side of the valley of the Zakkadon River, situated 3 km northeast of the Village of Kesatikau.

Occupying a high-altitude expanse of the Main Caucasian Range, the Naro-Mamison area features a topography characterized by sharply dissected surfaces, slope angles reaching up to 30° in the northern part, and rocky serrated ridges with steep precipitous slopes exceeding 60° in the southern part. Elevations span from 1700 to 3200 m, with a relative difference in heights of 1500 m.

The river network well-branched, with major watercourses including the Mamisondon, Nardon, Zakkadon, and Zrugdon Rivers. Upon merging, the waters of the Mamisondon and Nardon rivers combine to form the Ardon River. The hydrological regime mirrors the area's climatic conditions, exhibiting a winter low-water period (1.5–3.0 m^3/s in the Mamisondon and Nardon Rivers) and summer floods (6.0–8.0 m^3/s), sourced primarily from glacial melt and rainwater in summer and ground and snow water in winter.

The climate is extremely continental, marked by significant daily temperature fluctuations. Winters are cold, while summers are cool and humid. The climate of broadly N–S and W–E oriented valleys differs from each other. The climate in W–E valleys (Mamisondon, Zakkadon, Nardon) is milder due to minimal impact from strong cold winds of N–S orientation. The average annual temperature is +4.6 °C, with January averaging −5.7 °C, July at +14.7 °C, and annual precipitation totaling 650 mm. In broadly N–S valleys (Zrugdon), frequent strong cold mountain-valley winds contribute to a further decrease in air temperature. The average annual temperature is +3.8 °C, with January averaging −6.4 °C, July at +13.8 °C. The absolute temperature ranges from a maximum of +28 °C to a minimum of −30 °C, and annual precipitation reaches 900 mm.

Exposure is uneven: on the northern slopes it is 40–45%, and on the southern slopes it is 50–65%.

The vegetation comprises flora from alpine and subalpine meadows, providing essential grazing pastures for cattle. Occasional low-growing forests and shrubs dot the northern slopes, while the absence of valuable wood species is notable.

The area boasts diverse wildlife, including auroch, chamois, lynx, wolf, bear, fox, and hare. No protected or conservation areas are present at the work sites.

Economically, the Naro-Mamison area is well-developed, intersected by major highways (Ossetian Military Road and Transcaucasian Highway). Residential villages are accessible by asphalted roads, with work sites linked by dirt roads, bridle paths, and foot trails. The region has been explored for mercury in the past.

The nearest settlement, the Village of Nar, is 1.5–2.0 km from the Vartse and Zrug sites, while the Baikom site is more distant at 17 km. Vladikavkaz and Alagir, with railway stations, are 92 and 52 km away. Power lines do not cross the work sites, but a 110 kW power line passes through the Village of Nar to the Republic of South Ossetia.

Water supply resources are abundant, with numerous outlets of fresh and mineral water. The area has an ample supply of skilled workers in mining professions. Seismicity is recorded at 9 points according to SNiP-II–81.

The Fiagdon area encompasses the headwaters and upper reaches of the Fiagdon River (Fig. 1). Three distinct sites have been identified through preliminary material generalization: Arsikom, Bugulta, and Vodorazdelny. The first two are located on the right and left sides of the Bugultadon River valley, respectively, while the Vodorazdelny site is confined to the left side of the Dzamarashdon River valley. These river valleys are closely situated, with a spatial separation of no more than 3 km.

Situated in the high-altitude region of the Bokovoy Ridge, the Fiagdon area features a typical high-altitude topography, with elevations ranging from 2000 to 2750 m.

The primary river network consists of the Dzamarashdon and Bugultadon Rivers, which converge to form the Fiagdon River. The elevations of these rivers vary between 1900 and 2500 m, with the watershed elevations ranging from 2500 to 4000 m.

The flow patterns of the rivers and their numerous tributaries are influenced by both topographical features and climatic conditions, including winter low-water and summer floods.

The climate is continental and high-altitude, characterized by cold winters and cool, humid summers. In the valleys, the average annual temperature is +4 °C, with January averaging −7 °C and July reaching +14.5 °C. The absolute minimum temperature is −26 °C, the maximum is +28 °C, and the annual precipitation ranges from 600 to 900 mm.

Distinct vertical climatic zonality is evident, and the vegetation is primarily alpine-meadow. Up to elevations of 2100–2200 m, shrubs and small woods are present on the western and northern slopes.

The area hosts a diverse range of wildlife. In the alpine highlands, auroch, chamois, and lynx can be found. Below an elevation of 2500 m, the region is inhabited by bear, wolf, hare, badger, and roe deer. The western boundary of the area coincides with the eastern border of the conservation area of the North Ossetian State Reserve.

In economic terms, the Fiagdon area exhibits a lesser degree of development compared to the Naro-Mamison area. The closest settlement is the village of Kharisdzhin, connected to the area by a 12 km long dirt road. The village of Verkhny Fiagdon is situated 4 km north of Kharisdzhin. The distance from the Village of Kharisdzhin to Vladikavkaz and Alagir, where railway stations are located, is 65 km each way, accessible via asphalted roads. A high-voltage power line (110 kW) traverses the area, but it is currently de-energized.

There are no limitations on technical and household water supply resources, and there is an ample number of skilled workers in mining professions in the area.

The seismicity of the area is 9 points.

The **Dzhimara area** encompasses the upper reaches of the Midagrabyndon River. A preliminary review of geological archive materials has led to the identification of two distinct areas: Midagrabyn and Shtyrdon (Fig. 2). Positioned on the left and right sides of the Midagrabyndon River valley, respectively, these sites are spatially close, with a mere 1.4 km distance between them.

Similar to the Fiagdon area, the Dzhimara area occupies a high-altitude expanse of the Bokovoy Ridge, featuring sharply dissected topography characteristic of its northern slope. Deep gorges, sharp ridges, steep cliffs (40–60°), significant elevations (2000–3000 m), and relative differences in height (1000–1300 m) pose challenges for geological studies from the surface. The highest elevations in this region include Shaukhokh (4636 m), Donchenta (4318 m), and Khaikalankhokh (4242 m). These peaks are the focal points for three glaciers: Lartsi-tsiti, Midagrabyn, and Khrustalny.

The main river network in the Dzhimara area is defined by the Midagrabyndon River, a left tributary of the Gizeldon River. Characterized as a typical mountain river, the Midagrabyndon exhibits glacial feeding, an unstable water level, and flow rate, with frequent summer floods, rapids, and steep runoff. The water flow experiences abrupt fluctuations, ranging from winter low water (4–5 L/s) to summer floods and high water (20–25 L/s). During the summer, increased turbidity, carrying a significant amount of suspended matter, is observed due to snow and ice melting and heavy rains.

Fig. 1. Satellite image of the Eastern flank of the Fiagdon area:
1 – Lyadon quartz zone; *2* – Dargshuadon quartz occurrence; *3* – Dzagalym quartz occurrence

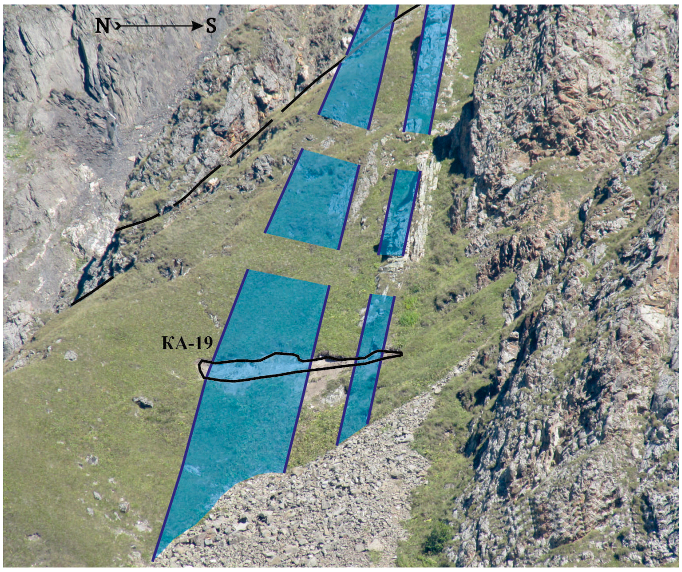


Fig. 2. Midagrabyn site – silicification zones (KA-19 – ditch)

The climate in the region is distinctly high-altitude, featuring a relatively low average annual temperature (+3.5 °C), high precipitation levels (1000–1100 mm), a not excessively cold winter

(–6.5 °C), prolonged cold spring (+2.4 °C), cool summer (+13.5 °C), and sunny autumn (+4.0 °C). Frosts begin in late September and conclude in mid-May.

Vegetation predominantly consists of alpine-meadow formations within the alpine and subalpine belts, featuring forbs, Alchemilla caucasica, Alchemilla sericea, Carum caucasicum, and rhododendron. Woody vegetation is limited to single low-growing birch shrubs.

The animal population is diverse, including auroch, chamois, and lynx in the alpine highlands, and bear, wolf, fox, badger, roe deer, and hare in the subalpine belt. There are no designated conservation zones in the Dzhimara area.

Economically, the Dzhimara area is less developed than other regions. The nearest settlement, the Village of Dzhimara, is located 6.5 km away and is connected by a dirt road, bridle paths, and foot trails. The distance from the Village of Dzhimara to the City of Vladikavkaz is 48 km, 45 km of which are asphalted roads. A 6 kW power line services the Village of Dzhimara.

There are no restrictions on technical and household water supply resources in the district, and there is an available workforce of mining professionals in Dzhimara, Fazikau, Dargavs, and other villages.

Seismic activity in the area is recorded at 9 points.

The **Fiagdon-Kambileyevka area** is situated between the valleys of the Fiagdon River to the west and the Kambileyevka River to the east, encompassing their middle course. A review of archive materials has led to the identification of six distinct sites: Fiagdon (Fig. 3), Mygvare-Barzond, and Kodakhdzhin in the western part of the area, within the Fiagdon River valley, and Tatarsky II, Medvezhegaysky, and Kambileyevka in the eastern part, within the Kambileyevka River valley. Spatially, the western three sites are located 25–30 km away from the eastern ones.

This area is situated in the low-altitude zone of Mountainous Ossetia, on the southern slope of the Lesisty Ridge.

The topography is characterized by typically low-altitude features, with gentle slopes (up to 30°), smooth peaks, and a landscape dissected by transverse river valleys. Elevations in this region range from 1000 to 1300 m, and the surface of all sites is covered with forests.

The river network is defined by the Fiagdon and Kambileyevka Rivers along with their tributaries. The river flow regime is influenced by climatic conditions, resulting in winter low-water levels and summer floods.

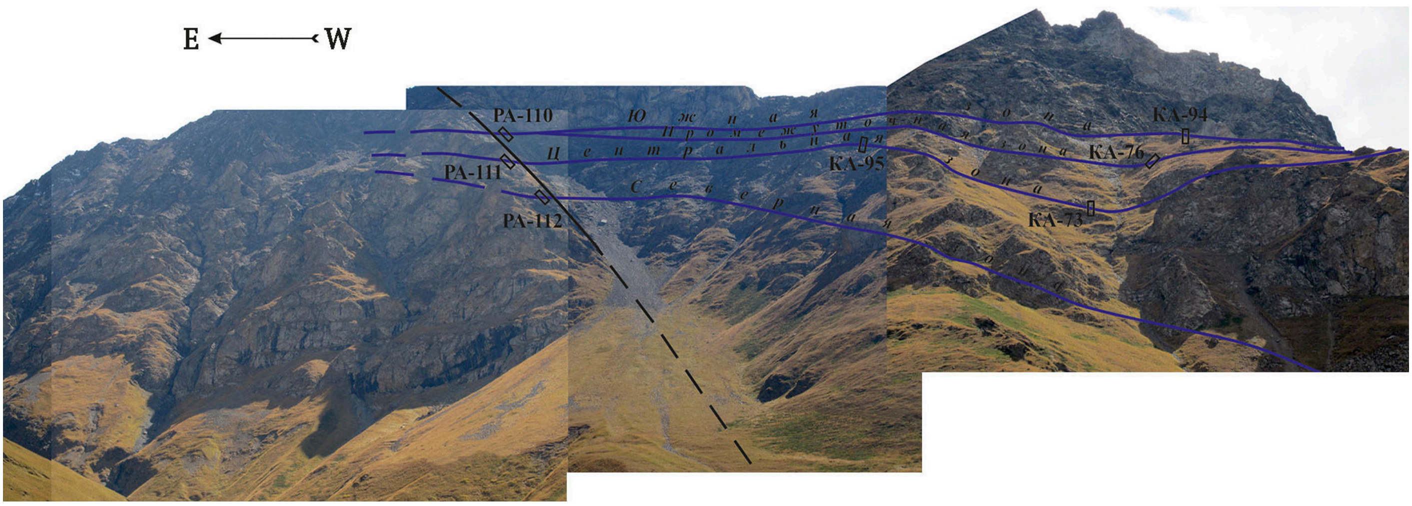


Fig. 3. Fiagdon site – Southern Zone, Intermediate Zone, Central Zone, Northern Zone

The snow cover in this area is unstable, lasting from December to February. Winds are periodic, originating from the north and northeast in winter and from the south and southwest in summer. The geographical conditions do not favor the formation of avalanches, mudflows, and landslides.

Vegetation is characterized by broad-leaved formations, including beech, hornbeam, maple, ash, linden, and oak. The soils are mountainous, brown forest, and relatively thin (up to 20 cm), with no agricultural value. Various plants such as wild pear, apple-tree, alycha, raspberry, dogwood, hazel, and blackberry are found throughout the area.

The animal population is diverse, featuring brown bear, forest cat, lynx, dormouse, marten, red deer, bison, among others. Birds such as siskin, bullfinch, woodpecker, etc., contribute to the rich biodiversity.

In economic terms, the area is reasonably well-developed. The distance from the western sites to the Villages of Mayramadag, Kodakhdzhin, Dzuarikau ranges from 3 to 5 km, while from the eastern sites to the Village of Tarskoye, it is between 1.0 and 3.2 km. The nearest railroad station (Vladikavkaz) is located 20 and 16 km away, respectively. Although there is no power line at the work sites, the nearby villages receive sufficient electricity.

The seismicity of the area is recorded at 8 points.

Statement of the problem

The primary objectives of the research are to identify sites with high-quality quartz resources suitable for silicon production, localize these sites, estimate forecast resources, and designate areas for further in-depth study. The chosen sites should possess favorable geographical and economic conditions, conducive to open-pit mining [17].

To achieve these goals, the research will involve addressing the following tasks:

– prospective areas for research to uncover high-quality quartz resources;

– conduct comprehensive research activities, including geological traverses, examination of previously drilled boreholes, and laboratory and laboratory-technological sampling;

– investigate morphostructural features and the internal structure of productive deposits;

– localize, evaluate, and test the forecast resources of high-quality quartz raw materials [18, 19];

– develop recommendations for exploration and licensing of identified prospects [20, 21].

In the initial stage of the research, materials from quartz rock development sites will be collected and synthesized, along with information on silicon production methods and the regulatory requirements for raw materials.

Subsequently, the comprehensive study of the most promising sites will progress, incorporating studies that provide reliable, objective information on the mineralogical, chemical-spectral, and petrochemical composition of quartz rocks in these areas. Laboratory-analytical and mineralogical data will inform the calculation of process parameters for different types of quartz resources. Technological samples will be extracted from the quartz rock sites meeting theoretical regulatory requirements, forming the basis for classifying these rocks as suitable raw materials for silicon production. Simultaneously, the selection of sites with the most favorable mining and geographical-economic conditions will be made. Prospects will be used to calculate forecast resources and develop recommendations for further research and site preparation for licensing for subsoil use.

The complex set of methods employed to address these tasks includes prospecting traverses at a scale of 1:10,000, geological traverses for compiling reference lithological-structural sections at a scale of 1:500, sampling and sample processing, mineralogical and petrographic studies, laboratory-analytical assessments, process tests, and field data analysis.

Materials and methods

The laboratory and process studies of quartz sands involved several key parameters, including determining the particle-size distribution of the product fraction (−0.25 + 0.1 mm), assessing the light transmission coefficient (K_{lt}) of grains, analyzing the chemical composition (SiO_2 and impurity element content), and conducting mineralogical and petrographic analysis of the non-magnetic fraction.

The silicon dioxide content in the natural sand was found to be relatively low and did not fully comply with the requirements of GOST 2169–69 for quartz resources intended for the production of metallurgical (crystalline) silicon.

To gain insights into the material constitution and morphological features of impurity minerals, along with their quantitative interrelations influencing the process properties of the considered vein quartz, a semi-quantitative optical and mineralogical analysis was conducted. This analysis included the examination of electromagnetic, magnetic, heavy (2.67 g/cm^3), and light (2.63 g/cm^3) monofractions.

Data preparation and preliminary processing, such as regression plots in a two-dimensional configuration, were performed using MSExcel. Subsequent processing of experimental data involved the application of the simple b-spline method, similar

eISSN 2500-0632
https://mst.misis.ru/

to previous studies [1*, 5*], implemented as scripts in the ViIMproved software (version 9.0) in the Python language. The construction of final three-dimensional plots was carried out using the gnuplot software.

Research results

Throughout the research, sites containing quartz rock suitable as raw materials for the production of solar-grade silicon products were identified. These selected sites fulfill essential criteria: they are situated in regions with favorable geographical and economic conditions, allowing for open-pit mining.

The investigation successfully identified high-tech raw materials conducive to a cost-effective approach for large-scale production of solar-grade (SG) silicon. The comprehensive set of studies resulted in the localization and estimation of forecast resources, accompanied by the formulation of recommendations for further exploration and development of these prospects.

Given the novelty of the problem and the absence of widely accepted requirements and methodological approaches, this type of work involves dealing with numerous specific factors.

The study areas were previously subjected to works primarily focused on identifying ore projects, with some attention given to construction materials, raw materials for basalt fiber production, alkaline bentonite clays for drilling fluids, among others.

However, these previous studies proved to be of limited information in addressing the objectives of the current research. Early reports on the aforementioned works, which had different primary goals, often lacked substantial information on quartz rocks and quartz raw materials. The Fiagdon-Kambileyevka area stands out as an exception, with in-depth studies conducted on sands intended for applications in silicate bricks, the glass industry, glass wool, and molding mixtures.

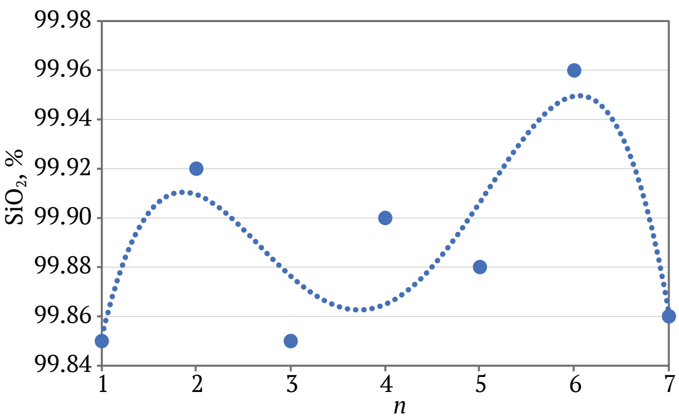


Fig. 4. Graphical representation of silica content variation based on occurrence type

During the conducted works, areas featuring quartz veining and silicification zones containing ore mineralization were documented. The primary focus was on studying the material constitution and interrelations of ore minerals and associated elements. This involved examining the internal structure, crystallization stages, the extent of alteration due to superimposed processes, volumetric characteristics related to the presence of rocks with different compositions, and the composition and parameters of quartz rocks (mineral resources)

Results and discussion

The relationship between the change in silica content (SiO_2) and the type of occurrence has been determined through the established polynomial equation ($R^2 = 0.72$, Fig. 4):

$$SiO_2 = -0.0034n^4 + 0.0529n^3 - 0.2775n^2 + \\ + 0.5712n + 99.509, \quad (1)$$

where SiO_2 is the silica content, %, and n is the occurrence number (1 – Arsikom; 2 – Lyadon I; 3 – Dzagalykom; 4 – Dargsuadon; 5 – Vartse; 6 – Baikom; 7 – Lyadon).

The evaluation of the qualitative characteristics of quartz rocks and their concentrates as raw materials for silicon product production has revealed the following findings:

1) quartz rocks of different genetic affiliations exhibit heterogeneity in chemical composition, particularly in SiO_2 content, dividing into two groups:

– those with low SiO_2 content (≤ 98.2%) including quartz sands, quartzite-like sandstones, and quartz gravelstone);

– those with high SiO_2 content (> 98.2%) encompass vein milky-white coarse-grained quartz;

2) sedimentary (quartz sands) and sedimentary-metamorphic (quartzite-like sandstones and quartz gravelstone) rocks and concentrates derived from them are deemed non-processable and unsuitable as raw materials for producing high-purity quartz concentrates required for the production of "solar grade" silicon products;

3) vein milky-white coarse-grained quartz from the majority of occurrences in the Fiagdon and Naro-Mamison areas, in its natural form, meets the chemical composition requirements of GOST 2169–69 for quartz resources suitable for the production of metallurgical (crystalline) silicon.

Subsequently, the relationship between the change in light transmission and the type of occurrence was established with the following polynomial equation ($R^2 = 0.73$; Fig. 5):

$$K_{lt} = 0.1993n^4 - 3.5249n^3 + \\ + 21.666n^2 - 53.562n + 49.121, \quad (2)$$

where K_{lt} is the light transmission value, %, and n is the occurrence number.

The identified extremely low value of light transmission (K_{lt} – 31.1%) in vein quartz concentrates completely rules out their use as fusion raw material for manufacturing quartz crucibles.

In the final phase of the study, chemical composition parameters of impurities were obtained, summarized in Table 2.

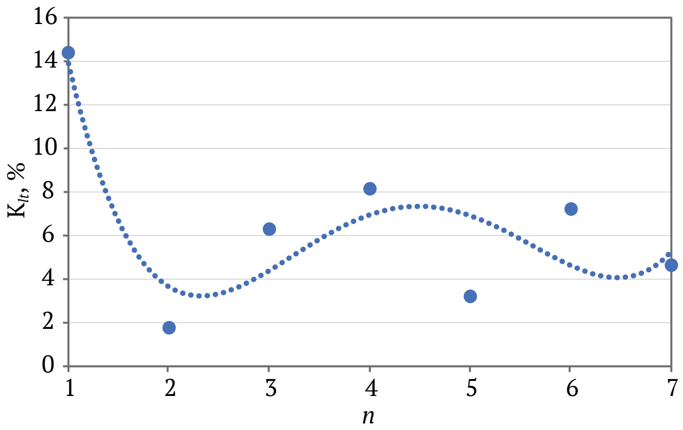


Fig. 5. Graphical representation of light transmission variation based on occurrence type

Elevated concentrations of Ti (45–65 ppm) and other elements such as Al, Ca, Mg, Na, K, Cu, Mn, and Fe in the concentrates indicate their unsuitability for the production of refined products intended for fusing on quartz glasses for various applications.

The mineralogical and petrographic analysis of the non-magnetic fraction revealed that quartz in sands consists of different generations, including water-transparent grains with a clean smooth surface and full transparency in reflected light. The bulk of the sand comprises 25.4–69.4% water-transparent grains.

"Quartzites" (quartzite-like sandstones) and quartz gravelstone from the Nazitkom, Lartsikom I and II, Skalny, Vodopadny, and Shtyrdon sites share the characteristic of containing significant amounts of feldspars (2.0–35.0%, occasionally up to 57%). They exhibit low quartz content (32.0–92.0%), a light transmission coefficient (Klt) of 5.9–8.0%, and high values of impurity elements (IEs) such as Al, Ca, Mg, Na, K, Fe, and Ti.

The vein milky-white coarse-grained quartz within the Fiagdon and Naro-Mamison areas underwent the same sequential analysis as quartzite-like sandstones and gravelstone. After sample preparation, parameters such as chemical composition (SiO_2 and IE

Table 2

Summarized weighted average content of impurity elements in vein quartz concentrates from the Fiagdon and Naro-Mamison areas, ppm

Name of elements	n	Arsikom	Lyadon I	Dzagalykom	Dargshuadon	Vartse	Baikom	Lyadon
		1	2	3	4	5	6	7
High concentration								
IE	1	71.69	69.88	68.53	60.64	60.31	44.53	40.02
Al	2	47.7	46.3	33.93	25.47	38	34.29	21.36
Na	3	15.6	19.8	25.67	20.49	17	11.4	14.53
K	4	2.17	0.72	2.03	5.87	1	1.8	0.97
Ca	5	2.74	1.3	3.63	4.92	1.8	1.26	1.53
Low concentration								
Li	6	2.23	0.65	1	0.82	0.51	0.83	0.64
Fe	7	0.4	0.6	0.7	0.7	0.8	0.6	0.4
B	8	0.36	0.25	0.28	0.45	0.42	0.24	0.33
Ti	9	0.38	0.36	0.4	0.39	0.35	0.2	0.31
Mg	10	0.21	0.28	0.39	0.21	0.24	0.71	0.84
Mn	11	0.09	0.06	0.04	0.13	0.07	0.05	0.2
Cr	12	0.02	0.06	0.15	0.1	0.08	0.09	0.02
P	13	0.02	0.04	0.23	0.02	0.02	0.02	0.02
Cu	14	0.03	0.01	0.01	0.01	0.01	0.01	0.03
Ni	15	0.01	0.01	0.01	0.01	0.03	0.01	0.01
Co	16	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Zr	17	0.01	0.01	0.01	0.01	0.01	0.005	0.01

oxide content), mineral composition, quantities of IEs in natural quartz, and processing middlings were determined, and mineralogical and petrographic analyses were conducted.

The analysis of Fig. 6 reveals the following: a) most vein quartz samples are most effectively processed for elements such as Ti, Ca, Mn, Cu, Mg, K, and Fe; less effectively for Al, Na, Li, B, and P; b) above-limit contents of Al, Na, K, and, less frequently, Ca and Fe relative to the KGO-3 grade in vein quartz concentrates exclude their application for producing quartz crucibles using the traditional “Siemens-process” for growing monocrystalline silicon; c) quartz concentrates from vein quartz of the Lyadon Zone, Arsikom, Dargshuadon, Dzagalykom, Vartse, Lyadon I, and Baikom occurrences, with the total content of impurity elements (IE) ≤ 100 ppm and low Ti, B, and P contents, are potentially suitable for the production of "solar grade" silicon products. Minor deviations in their chemical compositions relative to regulated IEs (Ti, B, and P) may require slight process modifications.

Investigations of vein quartz from these areas have shown that most unprocessed samples meet the requirements of GOST 2169–69 (SiO_2 ≥ 98.2%, Fe_2O_3 ≤ 0.25%, CaO ≤ 0.25%, Al_2O_3 ≤ 0.6%) and are suitable for obtaining metallurgical (crystalline) silicon. Samples with increased calcite content (10.0–24.0%) taken at the Vodorazdelny Shtok and Bugultinsky sites are an exception.

The elevated calcite content in the veins of these sites is believed to be associated with the chemical composition of hosting rocks (diabase, diabase porphyrites), influencing the composition of hydrothermal solutions that formed the vein bodies.

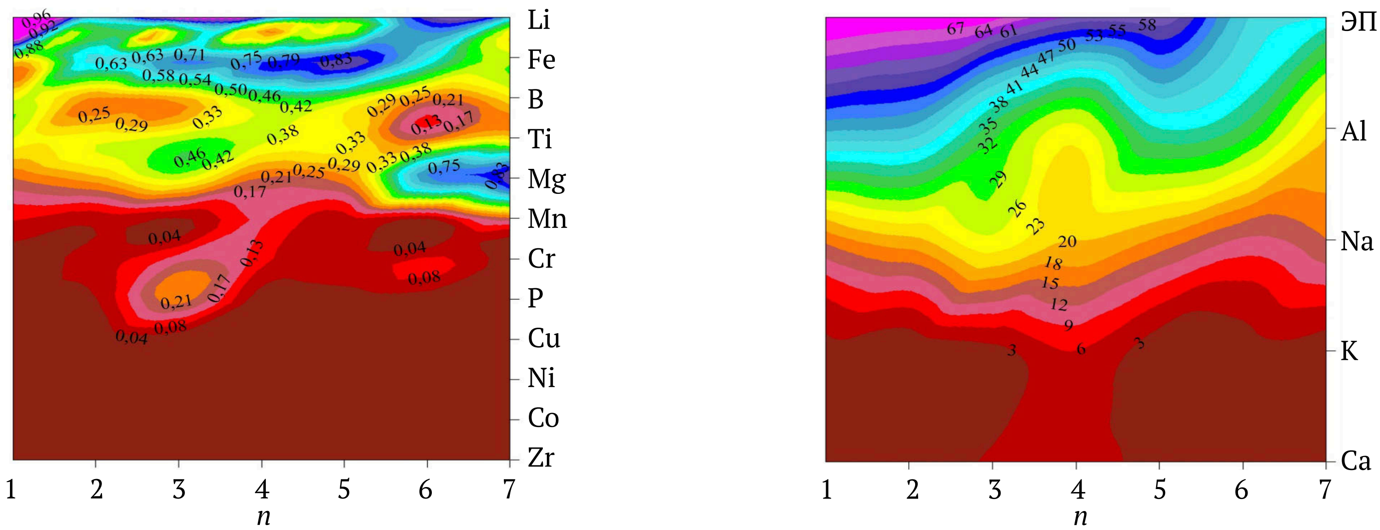
The data obtained indicate that vein quartz samples sometimes contain calcite, feldspars, sericite, and chlorite. Ore minerals such as pyrite and arsenopyrite are rarely present, and epidote, amphibole, and sillimanite group minerals are found in single samples.

Quartz in the samples is represented by transparent and milky-white grains, mostly isometric, occasionally elongated, with rare inclusions of hematite, magnetite, and muscovite.

Quartz grains may exhibit different structures, with some having smooth transparent flat faces, and others showing a wavy-ribbed structure and a greenish-gray color. Electron microscopy of the surface revealed the presence of Al (2.8%), K (1.48%), and Fe (0.42%) in addition to silicon and oxygen.

In summary, the studied vein quartz and concentrates are generally unsuitable for growing single-crystal silicon using the “Siemens-process” according to traditional technology. The above-limit content of alkali metals in the concentrates negatively impacts the thermal stability of crucibles, as alkalis act as flux, reducing the melting temperature of quartz glass products.

These quartz concentrates are considered promising for the production of silicon products, particularly for direct production of “solar grade” silicon products, without the process and environmental complications associated with the traditionally used “Siemens process”.



a *b*

Fig. 6. Distribution of chemical elements concentration in impurities for occurrences of the Fiagdon and Naro-Mamison areas:
a – for elements of the “high concentration” group; *b* – for elements of the “low concentration” group

Conclusion

Following the completion of the planned research tasks and objectives, the following results have been achieved for the studied object:

– an analysis of materials, along with the generalization of statistical, economic, geological, and process information, necessary for addressing the primary research tasks, has been conducted;

– prospects for further research have been identified;

– geological maps of prospects, at a scale of 1:10,000, with legends and corresponding sections, have been specified;

– the conditions of occurrence, morphology, and parameters of productive deposits at the prospects have been determined;

– preliminary studies on the quality and process characteristics of quartz resources have been conducted;

– the forecast resources of high-quality quartz raw materials for the production of silicon products, falling under category P_2 (500 Kt), have been localized, estimated, and tested;

– recommendations for geological exploration and licensing have been developed;

– objects for licensing for subsoil use have been prepared.

These results have been obtained through a comprehensive approach involving laboratory work, sampling, the study of constructed sections, examination of mine workings and borehole documentation, as well as mineralogical and petrographic analyses, along with laboratory studies and process tests.

References

1. Fedorov A.M., Makrygina V.A., Nepomnyashchikh A.I., Eliseev I.A. Quartz resource potential of Eastern Siberia for high-purity quartz production. *Geografia i Prirodnye Resursy*. 2016;(6):55–59. (In Russ.) https://doi.org/10.21782/GIPR0206-1619-2016-6(55-59)

2. Galiakhmetova L.Kh., Bydtaeva N.G., Nepryakhin A.E. Prospects of the Malo-Chipiketsky quartz-bearing zone for quartz raw materials of high quality. *Georesursy*. 2019;21(3):99–106. https://doi.org/10.18599/grs.2019.3.99-106

3. Nikolaev A.A., Kirpichyov D.E., Nikolaev A.V. Influence of material charging into plasma-arc furnace bath on energy parameters of reduction melting of quartz-leucoxene concentrate. *Fizika i Khimiya Obrabotki Materialov*. 2020;(1):36–41. (In Russ.) https://doi.org/10.30791/0015-3214-2020-1-36-41

4. Kaibichev A.V., Kaibichev I.A. Refining of technical silicon melts in the electrical field in helium. *Rasplavy*. 2019;(4):390–395. (In Russ.) https://doi.org/10.1134/S0235010619040066

5. Polenov Y.A., Ogorodnikov V.N., Kisin A.Y. History of prospecting and development of deposits of quartz raw materials in the Urals and the prospect of their further use. *News of the Ural State Mining University*. 2021;(2):48–59. (In Russ.) https://doi.org/10.21440/2307-2091-2021-2-48-59

6. Loginov V.G., Rudakov R.B., Koroteev N.D. Creating high-tech productions as a factor of raw material security ("Polar quartz" project). *News of the Ural State Mining University*. 2017;(1):84–87. (In Russ.) https://doi.org/10.21440/2307-2091-2017-1-84-87

7. Korekina M.A., Lyutoev V.P., Shanina S.N., Shtenberg M.V. Microelement composition of vein quartz of the Kuznechikhinskoe deposit (South Urals). *Obogashchenie Rud*. 2020;(5):23–29. (In Russ.) https://doi.org/10.17580/or.2020.05.04

8. Ogorodnikov V.N., Polenov Y.A., Savichev A.N. Extra pure quartz of the Ufaleysky quartziferous district (Southern Urals). *News of the Ural State Mining University*. 2018;(1):23–32. (In Russ.) https://doi.org/10.21440/2307-2091-2018-1-23-32

9. Klyuev R.V., Yegorova E.V., Bosikov I.I., Tsidaev B.S. Evaluation of use of effective technologies for increasing sustainable development of natural and technical system of oil and gas complex. *Sustainable Development of Mountain Territories*. 2018;10(3):392–403. https://doi.org/10.21177/1998-4502-2018-10-3-392-403

10. Bosikov I.I., Klyuev R.V. Assessment of Berezkinskoye ore field prospectivity using Micromine software. *Mining Science and Technology* (*Russia*). 2022;7(3):192–202. https://doi.org/10.17073/2500-0632-2022-3-192-202

11. Golik V., Komashchenko V., Morkun V., Burdzieva O. Metal deposits combined development experience *Metallurgical and Mining Industry*. 2015;7(6):591–594.

12. Bosikov I.I., Klyuev R.V., Khetagurov V.N., Silaev I.V. Comprehensive assessment of hydrodynamic processes in the Klinskoye Quarry with the use of their control methods in rock masses. *Sustainable Development of Mountain Territories*. 2023;15(2):284–297. (In Russ.) https://doi.org/10.21177/1998-4502-2023-15-2-284-297

13. Tyulenev M.A., Markov S.O., Gasanov M.A., Zhironkin S.A. numerical modeling in the structural study of technogenic rock array. *Geotechnical and Geological Engineering*. 2018;36(5):2789–2797. https://doi.org/10.1007/s10706-018-0501-3

14. Rybak Y., Khayrutdinov M.M., Kongar-Syuryun Ch.B., Tyulyayeva Y.S. Resource-saving technologies for development of mineral deposits.*Sustainable Development of Mountain Territories*. 2021;13(3):405–415. (In Russ.) https://doi.org/10.21177/1998-4502-2021-13-3-406-415

15. Golik V.I., Gashimova Z.A., Liskova M.Yu., Kongar-Syuryun Ch.B. To the problem of minimizing the volume of mobile dust in the development of pits. *Occupational Safety in Industry*. 2021;(11):28–33. (In Russ.) https://doi.org/10.24000/0409-2961-2021-11-28-33

16. Kulikova E.Yu., Balovtsev S.V., Skopintseva O.V. Complex estimation of geotechnical risks in mine and underground construction. *Sustainable Development of Mountain Territories*. 2023;15(1):7–16. (In Russ.) https://doi.org/10.21177/1998-4502-2023-15-1-7-16

17. Khalkechev K.V., Khalkechev R.K., Levkin Yu.M. Mathematical model of the stress field in the pillars with due account taken of the main crack in coal fields. *Ugol'*. 2023;(7):56–58. (In Russ.) https://doi.org/10.18796/0041-5790-2023-7-56-58

18. Knutsson H., Knutsson K., Molin F., Zetterlund P. From flint to quartz: Organization of lithic technology in relation to raw material availability during the pioneer process of Scandinavia. *Quaternary International*. 2016;424:32–57. https://doi.org/10.1016/j.quaint.2015.10.062

19. Guan Q., Dong D., Zhang H., et al. Types of biogenic quartz and its coupling storage mechanism in organic-rich shales: A case study of the Upper Ordovician Wufeng Formation to Lower Silurian Longmaxi Formation in the Sichuan Basin, SW China. *Petroleum Exploration and Development*. 2021;48:813–823. https://doi.org/10.1016/S1876-3804(21)60068-X

20. Brand N.W., Bottrell S.H., Miller M.F. Concentrations of reduced Sulphur in inclusion fluids associated with black shale hosted quartz vein gold deposits: implications for mechanisms of transport and deposition of gold and a possible exploration tool. *Applied Geochemistry*. 1989;4:813–823. https://doi.org/10.1016/0883-2927(89)90006-1

21. Sebutsoe T.C., Musingwini C. Characterizing a mining production system for decision-making purposes in a platinum mine. *The Journal of the Southern African Institute of Mining and Metallurgy*. 2017;117:199–206.

Information about the authors

Igor I. Bosikov – Cand. Sci. (Eng.), Assistant Professor, Head of the Department, North Caucasian Institute of Mining and Metallurgy (State Technological University), Vladikavkaz, Russian Federation; ORCID 0000-0001-8930-4112, Scopus ID 56919738300; e-mail igor.boss.777@mail.ru

Roman V. Klyuev – Dr. Sci. (Eng.), Assistant Professor, Professor of the Department of Engineering and Technology of Mining and Oil and Gas Production, Moscow Polytechnic University, Moscow, Russian Federation; ORCID 0000-0003-3777-7203, Scopus ID 57194206632; e-mail kluev-roman@rambler.ru

Vladimir Ch. Revazov – Cand. Sci. (Pedagogy), Assistant Professor the Department of Philosophy and Social and Humanitarian Technologies, North Caucasian Institute of Mining and Metallurgy (State Technological University), Vladikavkaz, Russian Federation; ORCID 0000-0003-1784-6531, Scopus ID 57201777428; e-mail revazov.v@yandex.ru

Nikita V. Martyushev – Cand. Sci. (Eng.), Senior Researcher, Kh. Ibragimov Complex Institute of the Russian Academy of Sciences, Grozny, Russian Federation; ORCID 0000-0003-0620-9561, Scopus ID 36671592800, ResearcherID AAO-2653-2020; e-mail martjushev@tpu.ru

Received 22.10.2023
Revised 30.10.2023
Accepted 01.11.2023