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Resources of quartz raw materials, Gargan block, East Sayan quartzite-bearing area

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Abstract. The evaluation (according to structural and geochemical rock properties) of the quartzites from the East Sayan quartzite-bearing area as a potential source of quartz raw material for crystalline silicon and optical glass manufacturing can significantly expand the forecast resources of this type of raw materials. The geological structure of the Irkut Formation, productive of high-purity quartzites is specified within the Oka-Urik, Urengenur and Urdagargan quartz-bearing areas; geological, mineralogical-petrographic and geochemical characteristics of the main quartzite types are given, the main morphological features of productive high-purity quartzite bodies are specified to predict their occurrence at depth. The major factors in the formation of high-purity quartzite bodies include: 1) quartzites are accumulated in the siliceous-carbonate sequence of the Middle Riphean Irkut Formation within a broad but isolated basin; 2) high-purity quartzite bodies are produced as a result of dynamic recrystallization due to the deformation of primary microquartzites resulting from the collision of the Dunzhugar island arc with the Gargan microcontinent margin. Within the western part of the East-Sayan quartz-bearing area, quartzite reserves as a potential source for silicon metallurgy and production of optical glass were estimated as 134 mln tons.

Keywords: quartzites, superquartzites, geochemistry, recrystallization, quartz raw materials reserves, Eastern Sayan

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Introduction

The consumption of chemically pure natural silicon-bearing raw materials as the main source of high-quality quartz concentrates for manufacturing optical silica glass and quartz ceramics is intensively growing. However, the shortage of high-purity natural silicon-bearing raw materials requires Russia and other developed countries to treat quartz as a key strategic raw material (Götze, Möckel, 2012; Muller et al., 2007). The major types of natural raw materials for such industries include vein quartz varieties, quartz cores of pegmatites, quartz of alaskite granites (USA) and quartzites. High-purity varieties of vein quartz, including granular quartz, and quartz cores of pegmatites contain scarce impurities, but their reserves are limited. Quartz deposits within granites have not been discovered in Russia so far. However, this type of quartz raw materials can be distinguished by high quality, though it requires a complex extraction and purification procedure. Quartzites display average quality indicators, but mineral impurities can be easily removed. The major problems for all varieties are structural and fluid impurities.

Although quartzites are fairly widespread in Earth's lithosphere amongst sedimentary-metamorphic rocks, the highly-pure varieties (impurity content less than 0.1%) are quite rare (Vorob'ev et al., 2003; Götze, Möckel, 2012). In Russia, in addition to the Cheremshanka deposit developed for the production of crystalline silicon (Tsarev et al., 2007), there are deposits and occurrences of quartzites and microquartzites in the Western Baikal region (Petrova et al., 1996; Makrygina, Fedorov, 2013) and in the south of the Western Siberia (quartzites of Antonovka Formation) (Anan'eva, Korovkin, 2003).

The leaders in the production of high purity quartz materials such as Germany and Norway traditionally consider quartzites as raw materials for manufacturing refractory materials, silicon and silicon alloys such as ferrosilicon FeSi (Götze, Möckel, 2012). However,

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the European experts do not exclude application of quartzites from Norway, Sweden, if the enrichment technology for obtaining high purity concentrates even from kyanite quartzites with SiO_2 content of less than 80 % is well developed (Muller et al., 2007).

Scientists of IGC SB RAS jointly with the enterprises of the Irkut Region have been conducting long-term studies of quartzites aimed at increasing in Russia the mineral-resource base of quartz raw materials, including high purity varieties. Quite perspective could be quartzites occurring in the south-east of the Eastern Sayan Mountains, including the explored Bural-Sardyk deposit (Vorob'ev et al., 2003).

The article focuses on the analysis aimed at possible significant increasing of reserves of quartzites from the East Sayan quartz-bearing area as a source of quartz raw materials for production of crystalline silicon or optical silica glass. The analysis is based on geochemical data obtained from studies of quartzites occurring at the Bural-Sardyk deposit and several quartzite occurrences using the proposed geochemical and structural criteria of rocks.

Geologic structure of East Sayan quartz-bearing area

The East Sayan quartz-bearing area comprises the northwest and northeast slopes of outcrops of the Gargan Block. The studied quartzites mostly occur in the west within the siliceous-carbonate sequence of the Irkut Formation of the Riphean age (1.25 Ga (Kuznetsov et al., 2010). The Irkut Formation lies monoclinally and discordantly on the Archean rocks (2.7 Ga (Anisimova et al., 2009) of the Gargan Block granite-gneiss basement dipping 25–55^o toward NW 290–320^o (Fig.1). The outcrops of the Irkut Formation stretch as narrow (from 12 km in the southern to 0.5 km in the northern part) band from the Lake Urunge-Nur to the Urik River. They are overlapped by a thick sequence of siliceous shales of the Urtagol Formation. Both Formations make up the Gargan Block cover.

In the interfluve of the Urda-Gargan and Khoito-Gargan rivers, the Irkut Formation is crosscut by the granitoids of the Sumsunur compex aged 790 Ma (Kuzmichev, 2004), which divide the Formation into the northeast and southwest zones. The northeast zone comprises the Oka-Urik area with the Bural-Sardyk deposit and several occurrences of high purity quartzites. In the southwest zone, there is the Urdaragan area and the Urungenur area, which lies on the left bank of the Oka River. In the south, they are framed by the granitoids and gabbroids of the Munku-Sardyk Ridge.

The rocks of the Irkut Formation were produced in a vast but isolated basin during at least two significant lithocycles. The basement of the Formation represents the transgression of the rhythm and is composed of conglomerates consisting of small pebbles. Upward in the cross-section, conglomerates are replaced by gravelly sandstones and siltstones and further up by light-colored fine-grained dolomites with siliceous lenses. The sequence composing the second rhythm starts with quartz sandstones, containing pebbles of quartz, dark gray quartzites and dolomites. They are overlapped by massive grey limestones and siliceous-carbonate rocks with a thin strata of black coaly shales. Upward in the cross-section, they are replaced by abnormally pure chemogenic silicites-quartzites, which serve as a protolith for the formation of high purity quartzite varieties (compact and sugar-like, fine-grained dark gray and discolored, as well as unique superquartzites). At different sites of the area, the thickness of the quartzite sequence is varying and at the Oka-Urik site, in the vicinity to the Bural-Sardyk ridge, the total thickness reaches 350–400 m.

Within the study area, the structural-geological data reveal several rupture dislocations, being different in the character of transformations and expressed as foliation, mylonitization, talc alteration and brecciation of rocks. The dislocations in the apical part of the ridges directed northeast, while the dislocations mapped at the basement are thrust faults and overthrusts directed northwest and having relatively low angles of the fault plane dip (15–45^o) (Fig. 1). In addition, rare asymmetric folds are found in plastic carbonates, therefore the compression vector directed from the northwest to the southeast was reconstructed.

The collision of the Dunzhugur island arc (1Ga) and the continental margin of the Gargan microcontinent at about 800 Ma (Kuzmichev, 2004) led to the ophiolite obduction onto the continental crust. The rocks produced as a result of the obduction overlapped the sedimentary cover and through the action of movement they deformed it into folds and divided into separate slabs thrust over one another.

In the process of the Gargan Block rising due to its granitization and emplacement of the Sumsunur granitoids, the ophiolite cover was eroded. Its fragments are still preserved as remnants framing the Block (Fig. 1).

The geological structure of the area and geochemical and petrological features of the Bural- Sardyk deposit were previously given in a number of publications (Vorob'ev et al., 2003; Fedorov et al., 2011; Fedorov et al., 2012; Makrygina, Fedorov, 2013; Volkova et al., 2017; Nepomnyashchikh et al., 2018; Volkova et al., 2019; Fedorov et al., 2019; Mazukabzov et al., 2020; Ayurzhanaeva et al., 2020).

Methodology

The quartzite samples and the produced quartz concentrates were analyzed at the Vinogradov Institute of Geochemistry (SB RAS) by ICP-MS, flame photometry (FP) and atomic emission spectrometry (AES).

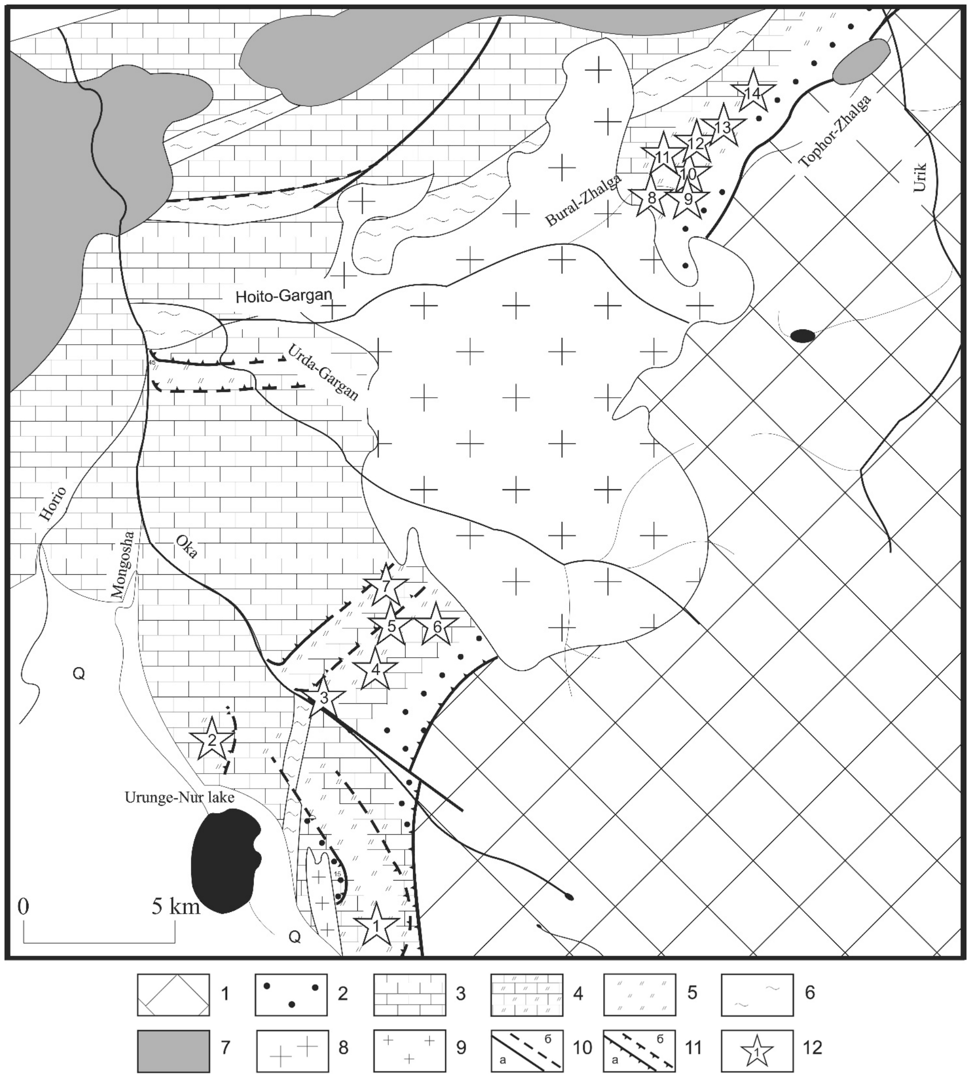

Fig.1. Western part of the Gargan Block : 1 – Gargan block basement, Neoarchean; 2–6 – Gargan block cover, Mesoproterozoic: 2 – terrigenous sequence, Irkut Formation (metasandstones, gravelites, quartzites, carbonaceous shales); 3 – carbonate sequence, Irkut Formation (calcite and ankerite-dolomite-calcite limestones); 4 – siliceous-carbonate rocks, Irkut Formation (calcite and ankerite-dolomite-calcite limestones with interlayers of quartzite-silicite); 5 – quartzite-silicite, Irkut Formation; 6 – shales, Urtagol Formation; 7 – undifferentiated ophiolite complex, Neoproterozoic; 8 – granitoids, Sumsunur complex, Neoproterozoic; 9 – granitoids, Munku-Sardyk complex, Lower Paleozoic ?; 10 – tectonic dislocations (a – true, b – assumed); 11 – thrusts (a – true, b – assumed); 12 – quartzite occurrences and their numbers: Urengenur: 1 – Urengenur, 2 – Mongosha; Urda-Gargan: 3 – Oka-1, 4 – Quartzite Otrog, 5 – Semiorka, 6 – Belaya Sopka, 7 – Oka-2; Oka-Urik: 8 – Southwest, 9 – South, 10 – Bural-Sardyk deposit (North), 11 – Northwest, 12 – Northeast-1, 13 – Northeast-2, 14 – Quartzite Hill

The preliminary sample preparation procedure of non-enriched samples of high purity quartz materials is unified and includes: (a) flushing the specimen in distilled water; (b) preliminary mechanical crushing; (c) chemical purification of quartz pieces of – 5–20 mm fraction from sorbed components on the surface in 10% solution of super clean hydrochloric acid (HCl) chemical purification of quartz pieces of – 5 – + 20 mm fraction from sorbed components on the surface in 10 % solution of superclean hydrochloric acid (HCl); (d) thermal crushing via heating to T = 900 ^{o}C and cooling by deionized water; (e) grinding to 0.1– +0.5 mm in a mortar with a pestle made of superquartzite recovered from the Bural-Sardyk deposit.

To determine impurities, a high-resolution double focusing ICP-MS ELEMENT-2 (Finnigan MAT, Germany) was used. Rhodium in a concentration of 3 ng/mL was added as an internal standard. The multielement standard solutions CLMS-2 and CLMS-4 (Spex, United States), ICP solution X Certipur (Merck, Germany), and IQC-026 (Ultrascientific, United States) were applied in the analysis.

For determination of main elements with AES, multichannel spectra recording was fulfilled by spectral installation, including a diffraction spectrograph DFS-458 C (PO KOMZ, Kazan) and multichannel analyzer of emission spectra MAES based on a microassembly of eight photodiodes. The generator ‘‘Vesuvius’’ (VMK-Optoelektronika, Novosibirsk) was used as the spectra excitation source.

To decipher the structure of ore zones, tectonic studies were performed on macro and micro scales.

Macro-level studies were performed using traditional methods of geological mapping with a detailed scale, which included the investigation of the composition of rocks and conditions of their occurrence, folded and rupture dislocations. For deciphering the formation of structures and the mechanism of rock transformation during deformation, the methods recommended for microstructural analysis were applied. These studies also included sampling of oriented pieces of ores for petrostructural analysis. The thin-sections were studied with a polarized microscope and the universal stage (Fedorov stage). The microstructural analysis revealed the predominant orientation of linear quartz aggregates, deformation mechanism and stress orientation.

The forecast reserves of the East Sayan quartzite-bearing area were calculated using the geometric method by multiplying the outcrop area of the counting quartzite blocks by their estimated thickness. The thickness of quartzites was estimated from their outcrops. The density of quartzite is assumed to correspond to the density of quartz, without taking into account the decompression in sites weakened by tectonic processes. The calculations were accomplished from field studies of three areas (Urdagargan, Urengenur and Oka-Urik), excluding reserves identified for the Bural-Sardyk deposit (Northern site). Moreover, the blocks of substandard quartzite were not taken into account.

Quartzite occurrences, East Sayan quartzite – bearing area

At present, 18 quartzite occurrences have been identified in the East Sayan quartz-bearing area. They are grouped into four zones: Gargan, Kharanur, Onot and Ilchir. Most of the quartzite occurrences are located in the Gargan Block (Table 1). The zones are different both in the composition of intrusive rocks and productive bodies, and in structural and tectonic settings. As opposed to the eastern (Ilchir and Onot) zone, the western (Gargan) and northern (Kharanur) zones of the Irkut Formation have thinner sequences of siliceous rocks and gently-inclined layers. The azimuths of the layer dipping are also different: the Gargan and Kharanur zones demonstrate layer dipping directed to the northwest, while the Ilchir zone exhibit dipping directed to the southeast. The Onot zone has a complex structure within a large anticline fold (Prospecting of quartz..., 2006).

Quartz-bearing areas	Quartzite occurrences (sites) and deposits
Oka-Urik	North (Bural-Sardyk deposit), Northeast, Northwest, Southwest, South, Quartzite Hill
Urda-Gargan	Semiorka, Quartzite Otrog, Belaya Sopka, Oka-1, Oka-2
Urengenur	Urengenur, Mongosha ?

Table 1. Grouping of quartzites occurrences within Gargan zone, East Sayan quartzite-bearing area

Quartzites, Oka-Urik area

A significant part of the Oka-Urik area is occupied by Irkut Formation, which comprises the lower carbonate and upper quartzite parts (Fig. 2). The quartzite sequence is composed of sand-silt-sized quartzites and microquartzites. Its total thickness appears to be about 300 m. The carbonate sequence consists of dark gray calcite limestones intercalated with laminae of banded dolomites and laminae of stromatolites. The carbonate outcrops occur in the central part of the area and likely composes an anticline, whose hinge dips towards the north-east. The rocks of the formation are broken by dikes of Vendian (?) gabbro and Riphean granitoids of the Sumsunur complex. Disjunctive tectonics of the site includes zones of increased fracturing and detachment fault fragment (breakdown zone). Close to intrusive bodies, carbonates are intensively metasomatized.

The Bural-Sardyk deposit lies at 2600 m a.s.l. in the axial part of the asymmetric ridge separating the streams of the Urik and Gargan rivers. It is located close to the north-western contact between the Irkut Formation and the Archean granite gneisses of the Gargan Block.

The quartzite sequences are distinguished by the bodies of totally white superquartzites and light-grey fine-grained quartzites, which sit at the top of the ridge and occur as layers or lenses dipping gently towards the northwest. Superquartzites represent monomineral quartz rocks, whose fine-grained groundmass contains large and transparent quartz grains (Vorob'ev et al., 2003). The superquartzites and light-grey fine-grained quartzites are overlapped by grey quartzites which down the cross-section transit into dark-grey and black fine-grained varieties. In the western segment of the site, the discolored quartzite variety is distinguished by a new type of primary pure quartzites, the so-called compact quarzites (Nepomnyashchikh et al., 2018). The compact quartzites represent quartz rocks of massive structure bearing no visible mineral impurities, except for rare thin sericite scales observed at grain margins (Volkova et al., 2019). The rock color results from the content of the carbonaceous substance occurring as graphite. In the Bural-Sardyk quartzites, the organic carbon content (analyzed by E.A. Razvozhaeva, IGC SB RAS), varies from 0.63 mass % (and more) in dark-grey varieties to 0.36 % in grey quartzites and less than 0.2 % in superquartzites. It should be noted that the insoluble C_{org} contents both in the samples of the Bural-Sardyk deposit and occurrences of the Urdagargan site are slightly overestimated as the carbon-bearing impurities were not separated from the gas-liquid component of rocks. The thickness of superquartzites reaches 6 m, the total thickness of light-grey fine-grained quartzites

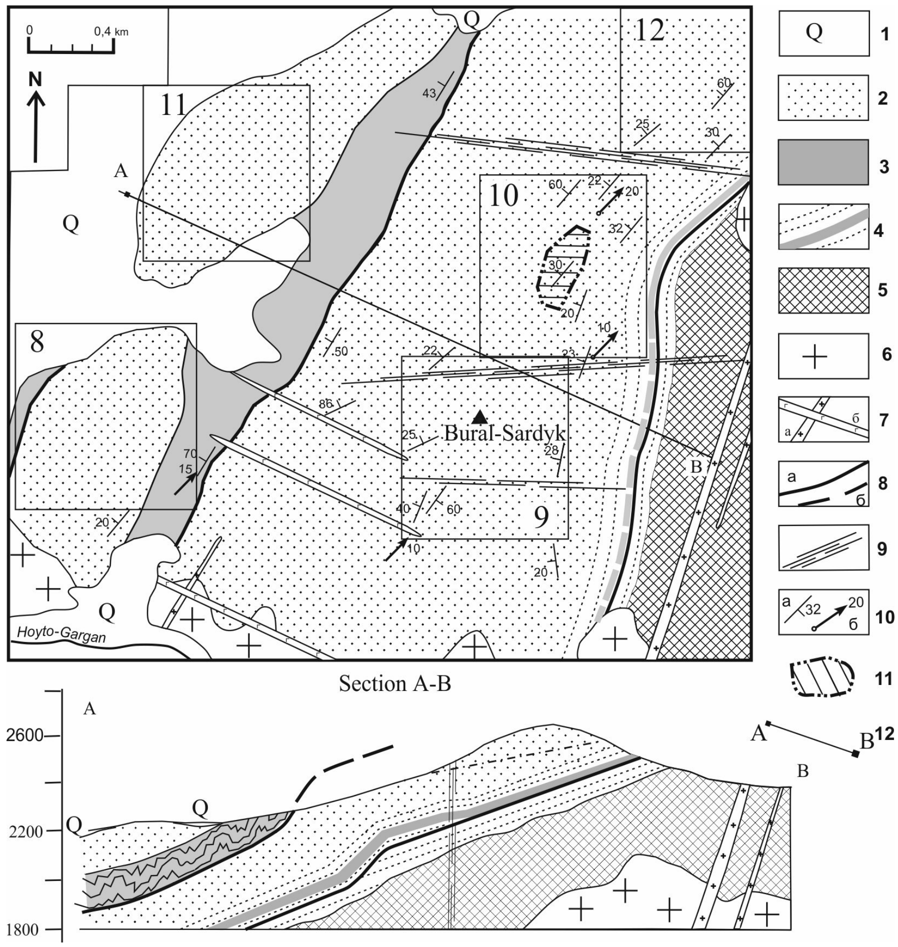

Fig. 2. Geologic map, Oka-Urik block with Bural-Sardyk deposit. 1 – Quaternary sediments; 2 – 4 Irkut Formation (Mesoproterozoic): 2 – quartzites, 3 – carbonate rocks, 4 –quartz-bearing sandstones with different grain size, gravelites; 5 – Neoarchean tonalites and granitic gneisses (Gargan block); 6 – granitic rocks, Sumsunur complex (Neoproterozoic); 7 – gabbro dikes (Early Paleozoic ?); 8 – breakdown zone (detachment), a – true, б – supposed; 9 – areas of increased intensity of fracturing; 10 – elements of occurrence: a – layering, б – dipping of hinges; 11 – outlines of the explored area; 12 – cross-section line. Note: In cross-section, the quartzite varieties are divided by a dashed line: light-colored quartzites are given above the line of demarcation, while dark-grey to black varieties are given below

is estimated as 30 m, and that of compact quartzites is tens of meters. At the Bural-Sardyk ridge site, the thickness of dark-grey and black fine-grained quartzites can reach 300 m.

Structural and geological studies of the Oka-Urik area have provided more information about the geologic structure of the area under study. In this area, there are numerous large isoclinal folds, and as proposed by E.I. Vorob'ev (Vorob'ev, 2003) superquartzites were produced in their anticlinal parts. The quartzite cross-section is dominated by weakly fractured (weakly plastic) formations (quartzites and silicate-carbonate rocks) which determine the deformation properties of the sequence. It gives rise to thick detachment zones occurring concordantly to layering and asymmetric folds of longitudinal curvature with axial planes dipping northwestwards. At the same time, bended and detachment folds appear to have formed in the limestone layer, occurring amongst quartzites. This layer is a zone of viscous interlayer thrust sliding in the southeast direction. Such a structural paragenesis can be explained by the northwest-southeast oriented compression and by the influence of the Gargan Block basement rocks, occurring at shallow depths (Mazukabzov et al., 2020).

The petrostructural analysis of quartzites (Fedorov et al., 2012; Fedorov et al., 2019; Ayurzhanaeva et al., 2020) suggests that the leading mechanism of their purification is the mechanochemical process during rock deformation. A scarce amount of water-saline impurities in quartz can likely result from the migration of impurities inside the crystal and towards the boundaries between grains. The driving forces of migration are temperature and pressure gradients under residual deformation energy effect (Ayurzhanaeva et al., 2020; Cherednichenko, 1986). A new viewpoint regarding the occurrence of recrystallized quartzites in a flat-lying strata of siliceous rocks can expand prospecting of economically attractive superquartzite sites.

Geochemical features of quartzites from the Oka-Urik area are exemplified by well-studied quartzites of the Bural-Sardyk deposit , Northern site and Northeastern-1 site. Superquartzites are characterized by particularly low contents of impurity elements and almost entire removal of pigmenting carbonaceous substance. These are not only the chemically purest quartzites at Bural-Sardyk, but are also outstanding in purity within the entire quartzite family worldwide (Vorob'ev et al., 2003, Götze, Möckel, 2012).

Regarding contents of major oxides, rare and rare-earth elements (Fedorov et al., 2012, Fedorov et al., 2019), the quartzites of the Bural-Sardyk deposit can divided into two groups:

- Productive sequence (or productive bedded bodies) is composed of quartzites with low contents of impurities (about 400 ppm in black and dark-grey siliceous varieties, 250 ppm in light-grey and grey, and about 100 ppm in superquartzites (Fedorov et al., 2012; Fedorov et al., 2019) and compact quartzites. The discolored high-purity quartzite varieties make up approximately 1 % of the whole quartzite sequence within the Irkut Formation (Table 2);

- Near-contact quartzites, occurring near the contact with granitic rocks of the Sumsunur complex. In comparison with productive bodies, the near-contact quartzites show elevated contents of major oxides and rare elements: concentrations of Mn, Fe, Ca, Na, K, B and Zr are 10–20 times higher; those of Ti, Li, Sc, Sr and Ba are 20–30 times higher, while contents of Al, V, Rb, Cs are two orders of magnitude higher. As an average, the sum of major oxide contents is over 30 times higher in near-contact varieties as compared with quartzites from bedded productive bodies (from 0.5 to 2.4 wt/%, 1.3 % as an average) (Fedorov et al., 2012; Fedorov et al., 2019).

Therefore, with regard to the amount of impurities, almost the entire quartzite sequence of the Irkut Formation, except for the near-contact varieties can be used as a source of quartz raw material for manufacturing of crystalline silicon. To give a precise calculation of quartzite blocks suitable as raw material in the production of crystalline silicon, excluding zones of near-contact metasomatic alteration, detailed prospecting works and technological experiments at silicon-producing enterprises are required.

In addition to the Northern site containing the Bural-Sardyk deposit, the site Northeastern-1 was sampled in 2017 (Table 3).

At the site Northeastern-1, the amounts of impurity elements gradually increase from porphyry-like varieties to fine-grained quartzites bearing porphyry-like inclusions and to fine grained grey and dark-grey varieties. The contents of visible mineral impurities (mostly sericite and iron hydroxides) are insignificant, which effect slightly the overall composition of rocks. A significant correlation between the content of carbonaceous matter and abundances of impurities suggests that most of the mineral impurities occur in the intergranular space. The contents of lithium, boron, phosphorus and copper in different quartzite varieties differ insignificantly , thus indicating their probable structural location and removal during the rock recrystallization. The correlation of aluminum and potassium contents suggests that both of them are contained in sericite

The experiments to purify quartzites at the IGC SB RAS (Vorob'ev et al., 2003; Nepomnyashchikh et al., 2018; Nepomnyashchikh et al., 2019) revealed that quartzites with porphyroblastic texture (superquartzites and their analogues) can be used for production of optical quartz glass (Technical Specifications "Quartz...", 1997). Therefore, porphyry-like quartzites and fine-grained quartzites with porphyry-like inclusions without visible mineral impurities were chosen for sampling in Table 3. With regard to the content of amorphous carbon, fine-grained quartzites can be divided into light- and dark-grey varieties, regardless of the content of visible mineral impurities. Since intrusive bodies have not been found on the surface within the area under study, it is not correct to distinguish near-contact quatzites by analogy with the Bural-Sardyk deposit.

Quartzites, Urdagargan area

Within the Urdagargan area, the most abundant are quartzites of the Irkut Formation, followed by carbonates including skarn-like ones. The quartzites are composed of spotted-banded and massive fine-grained varieties demonstrating a wide range of coloring (from dark-grey to white). In rare cases, there are high-purity varieties (superquartzites) occurring as thick lenses or bands as well as compact quartzites.

Almost all quartzite varieties demonstrate lower iron contents, thin interbeds of carbonate and quartz composition. In cases, they exhibit caverns filled with

Quartz type /site/number of samples	Fe	Al	Ti	Ca	Mg	Cu	Mn	Na	K	Li	Σ10
Superquartzite/ Bural-Sardyk deposit) / 59 samples	6	27	1.7	0.8	1	0.17	0.02	3.5	6.3	0.13	46.6
Fine-grained / Bural-Sardyk deposit / 11 samples	7.1	65.9	2.4	4.6	4.4	0.16	0.09	5.9	23.9	0.14	115
Compact /Southwestern site / 12 samples	4.9	10.4	0.3	7.3	0.9	0.2	0.1	19.3	6.2	0.3	50

Table 2. Mean contents of impurity elements in high-purity quartzites, Oka-Urik area, (ppm). Note: Analyses were performed by the ICP MS at the IGC SB RAS. Analysts Sokolnikova Yu.V., Pakhomova N.N. and Ponomareva V.Yu.

Varieties	Porphyry-like quartzites without visible mineral impurities (24)		Fine-grained with porphyry-like inclusions without visible mineral impurities (38)		Fine-grained grey quartzites (119)		Fine-grained dark-grey quartzites (57)	
Elements	Mean		Mean		Mean		Mean	
	min.	max.	min.	max.	min.	max.	min.	max.
Al	**250**		**310**		**310**		**496**	
	57	486	67	1077	53	1260	76	4191
Ti	**12.68**		**17.04**		**16.84**		**26.95**	
	4.11	34.96	2.90	56.55	1.57	77.44	1.90	258.65
Fe	**37.12**		**29.06**		**47.95**		**86.77**	
	10.45	78.04	0.05	110.28	0.06	444.17	7.99	991.05
Mn	**0.12**		**0.32**		**2.71**		**0.34**	
	0.05	0.28	0.04	8.31	0.03	72.25	0.04	3.85
Mg	**22.60**		**38.63**		**33.48**		**66.81**	
	5.11	50.34	6.84	138.39	2.39	134.26	2.50	597.81
Ca	**9.46**		**8.33**		**9.67**		**10.22**	
	2.15	17.64	2.23	20.09	0.08	56.98	0.32	80.06
Na	**6.74**		**7.58**		**8.11**		**14.34**	
	4.50	23.09	4.07	12.32	2.12	131.02	3.10	213.87
K	**115**		**174**		**148**		**248**	
	44	247	36	579	14	691	21	2244
Li	**0.12**		**0.14**		**0.11**		**0.18**	
	0.04	0.52	0.04	0.41	0.01	0.56	0.03	1.37
B	**0.67**		**0.83**		**0.60**		**0.84**	
	0.35	1.16	0.18	3.15	0.04	5.66	0.21	4.40
P	**3.93**		**3.61**		**4.23**		**4.36**	
	0.65	10.50	0.70	7.93	0.06	20.20	0.97	19.23
Cu	**0.32**		**0.22**		**0.28**		**0.30**	
	0.17	0.81	0.10	0.42	0.08	3.23	0.12	1.50
Sum	**459**		**589**		**582**		**954**	
	190	876	163	1914	113	2263	141	7471

Table 3. Contents of impurity elements in quartzites, Northeastern site, Oka-Urik area (ppm). Note: Analyses were performed by the ICP MS at the IGC SB RAS. Analysts Sokolnikova Yu.V., Pakhomova N.N. and Ponomareva V.Yu.

iron oxides and fine-grained clay, ochreous mater. The grain size in different samples varies from invisible to the naked eye to large (first mm) quartz crystals. In some cases, the rocks that underwent deformation are split into schistose blocks or broken by a system of cracks partially filled with the ochreous substance.

The structure of productive bedded bodies of high-purity quartzite varieties from the Urdagargan area indicates that they have formed both in the top and middle parts of the dark-grey fine-grained quartzite sequence due to tectonic deformations. For larger bodies, the boundaries between dark-grey and discolored varieties, including porphyry-like quartzites, are mostly gradual, for smaller and thinner ones, they are sharp.

In terms of geochemistry, quartzites from the site Semerka within the Urdagaran area represent relatively pure varieties (Table 4). At the site Semerka, the chemically purest varieties include superquartzites and compact quartzites, changing in color from white to dark-grey. The minimum contents of the sum of the impurity elements in some compact quartzite samples amount to about 30 ppm; their mean values obtained for 8 samples are slightly over 100 ppm. The mean content of the sum of major oxides in dark- grey compact quartzites reaches about 800 ppm.

Near the contact with limestones, the superquartzites exhibit increased contents of calcium, magnesium, iron and manganese. The dark-grey varieties are characterized by a wider range in concentrations of impurity elements resulting from the amounts of carbonate impurity.

As the relationships between productive bodies and rocks of the hosting carbonate sequence and intrusive bodies of various compositions are complex, it is not possible to reveal the correlation between the element contents and color index of rocks. Some dark-color quartzite varieties have much less impurities than the discolored ones. Aluminum and potassium show stronger correlation owing to the sericite impurity, whereas Mn and Cu exhibit less correlation with other elements. When comparing this indicator at other quartzite sites, it may serve as a typomorphic characteristic of the entire siliceous sequence of the Irkut Formation.

Site	Semiorka				Belaya Sopka			
Varieties	White and light-grey quartzite (8)		Dark-grey and black quartzite (3)		White quartzite (8)		Dark-grey quartzite (3)	
Elements	Mean		Mean		Mean		Mean	
	min	max	min	max	min	max	min	max
Al	**55**		**370**		**511**		**758**	
	7	117	130	560	21	1529	73	2077
Ti	**1.58**		**24**		**28**		**63**	
	1.00	2.10	5.80	35	2.60	69.70	4.98	174
Fe	**4.13**		**20.73**		**125**		**593**	
	1.40	11.00	7.20	33	5.90	630	76.50	1559
Mn	**0.38**		**0.14**		**7.10**		**65.01**	
	0.10	1.00	0.08	0.2	0.15	41	2.20	175
Mg	**4.03**		**167**		**826**		**3673**	
	0.20	15.00	21	257	29	4957	9	10575
Ca	**8.10**		**12.80**		**1114**		**9397**	
	6.60	11.50	8.40	16	8.50	7208	18.70	27753
Na	**8.95**		**13.87**		**54.15**		**291**	
	4.80	11.70	9.30	17.5	8.80	205	11.70	845
K	**20.44**		**194**		**233**		**799**	
	1.40	60.00	41	343	4.90	739	26.70	2336
Li	**0.23**		**0.59**		**1.77**		**0.69**	
	0.10	0.89	0.16	1.1	0.65	2.71	0.20	1.00
B	**1.34**		**7.07**		**0.59**		**0.93**	
	0.70	2.20	2.40	16	0.15	1.76	0.60	1.20
P	n.d.		n.d.		5.19		20.04	
					0.20	50.90	3.35	51.00
Cu	**0.15**		**0.11**		**0.36**		**0.61**	
	0.07	0.21	0.09	0.13	0.22	0.59	0.56	0.65
Sum	**105**		**809**		**2907**		**15662**	
	30.26	182	249	1223	87.15	15415	228	45551

Table 4. Mean contents of impurity elements in quartzites, Urdagargan area (ppm). Note: Analyses were performed by the AES at IGC SB RAS by Vasilyeva I.E. Analyses of Na, K and Li were performed by the PF at IGC SB RAS by Sokolnikova Yu.V.

By geochemical characteristics, the quartzites from the site Semerka are divided into two types: dark-grey and black varieties and discolored fine-grained quartzites, including the analogues of "superquartzites" and compact quartzites of the Bural-Sardyk deposit. High-purity varieties underwent advanced enrichment by chemical and physical methods (Nepomnyashchikh et al., 2017, 2018, 2019), the results of compact quartzites enrichment (Table 5) are given as an example. The results reveal the prospects for the application of this type of raw materials (Nepomnyashchikh et al., 2019).

Resource assessment, Gargan Block, East Sayan quartz-bearing area

Beginning in the second half of the 20th century, comprehensive studied have been conducted in the quartz-bearing area of the East Sayan Mountains. The first resource assessment for quartzites as a source of chemically pure quartz raw material was given in 1976 by P.A. Roshchektaev. The site, lying between the Oka and Khoito-Gargan rivers was considered as the most economically attractive for prospecting (Roshchektaev, 1976). In 1982, the quartzite occurrence Dabanzhalga was discovered in the basin of the Daban-Zhalga river, the left tributary of the Onot River, in its upper reaches by S.A. Prokhor. It was thoroughly studied with the assessment of forecast resources, evaluated as P_{2-3} categories by All-Russian Research Institute for the Synthesis of Mineral Raw Materials (VNIISIMS) (Malyshev et al., 1988). The first attempt to assess quartzite resources as a promising feedstock for production of quartz glass was made by A.M. Rogachev during the geologic survey of the area at scale 1:50 000 (Rogachev et al., 1991). As a result of those geological surveys, the sites Bural-Sardyk, Kholba, Oka-1 and Oka-2 were distinguished. At the initial stage of studies, the East Sayan quartz-bearing area with the Gargan zone, framed by the outcrops of the Gargan Block in the west and north-west, was recognized. The quartzites of the Gargan Block are particularly attractive for exploration in terms of quartzite raw material quality.

Beginning from 1997, the quartzites of the area have

No.	Fe	Al	Ti	Ca	Mg	Cu	Mn	Na	K	Li	Σ
509	109	157	13.5	8.4	12.7	0.34	14.2	8.9	69.6	0.14	393.8
511	29.2	83.8	3.6	6.7	6.4	0.19	0.87	6.5	34.0	0.11	171.4
517	18.7	69.6	3.8	3.1	6.3	0.13	0.91	5.4	27.2	0.15	135.3
520	0.3	10.0	2.4	2.7	0.6	0.09	0.049	4.5	1.8	0.15	22.6
524	0.4	9.0	2.0	5.4	0.9	0.20	0.12	3.4	0.6	0.27	22.3

Table 5. Contents of impurity elements in quartz concentrates from compact quartz, ppm. Note: 509 – Compact quartzite after manual picking, 1,7 – 15 mm fraction; 511 – Compact quartzite after manual picking and chemical etching with a 10 % HCl, 1,7-15 mm fraction; 517 – Sample 511 after grinding to 100 0300 μm fraction; 520 – Compact quartzite after picking, chemical etching, 100-300 μm fraction, chemical beneficiation in a 20 % HCl–10 % HF mixture at a 3: 1 solid-to-liquid (S–L) ratio; 524 – Compact quartzite after picking, chemical etching, 100–300 μm fraction, chemical beneficiation in a 20% HCl, annealing in air – 400 ºC – 3 hours and 1450 ºC – 3 hours and chemical beneficiation in a 20 % HCl–10 % HF mixture at a 3:1. Technologist – O.N. Solomein, the analyses were performed by ICP MS, analyst V.Yu. Ponomareva.

been studying by the scientists of IGC SB RAS. As result of these studies, the characterization of major quartzite varieties including completely new – superquartzites and compact quartzites was obtained and the first geologic scheme of the Bural-Sardyk deposit was compiled. Along with this, the models of quartzite formation were proposed and quartzite reserves and forecast resources were assessed as 22.5 mln. tons (Geological and geochemical…, 2001; Vorob'ev et al., 2003)

In 2001–2003, LLC Oka-K was given a license to conduct prospecting and assessment of high-purity quartz at the Bural-Sardyk site. In collaboration with the Institute of Geochemistry SB RAS, the resource assessment was obtained for northern part of Bural-Sardyk ridge including prospecting and assessing superquartzites of the Bural-Sardyk deposit for the production of quartz grits and microquartzites for metallurgy.

In 2001–2005, exploration and surveys were conducted at 11 quartzite occurrences at scale 1:25 000 by JSC VZPK under the leadership of V.N. Yashin (Prospecting of quartz ..., 2006). As a result, the assessment of quartzite reserves as a feedstock of pure quartz raw material was obtained for 5 out of 11 quartzite occurrences. Based on the geochemical, mineralogical-petrographic and geological-structural features of quartzites occurring within the Gargan Block, a preliminary assessment of the explored occurrences was given taking into account distinguishing of certain types of raw materials. The obtained data suggest that the quartzites from the Oka-Urik area represent the main economic mineralization in terms of volume, quality of raw material and conditions of mining. The quartzites of Urdagargan area, which are next in importance and potential, are currently being actively studied both by the scientific organizations of Irkutsk and the Republic of Buryatia, as well as by industrial enterprises accomplishing their prospecting, evaluation and exploration. The potential of the Urengenur quartzites is still unclear due to the higher amounts of carbonate impurity, although test smelting from individual samples gives positive results. The assessment of resources of the Gargan quartzite- bearing Block is shown in Table 6.

Discussion of results

Within the Gargan quartz-bearing zone, the Bural-Sardyk deposit of the Oka-Urik area and occurrences Semiorka and Belaya Sopka of the Urdagargan area, which are comparable in terms of the type of high-purity quartz raw materials, are considered to be well-studied. Within these sites, there are common features indicating a common process for high-purity quartzite formation. It is primarily true for the geologic location, when discolored more pure varieties, including superquartzites occur as thick seams and lenses amongst dark micrograined quartzites. The bed thickness of discolored quartzites varies from few centimeters to few meters (rarely to tens of meters). At the Bural-Sardyk deposit, the well-studied superquartzite body is at least 6 m thick. Within the site South of the Oka-Urik area, the studies revealed several beds of discolored quartzites of up to 1 m thick occurring amongst dark-grey fine-grained quartzites. At the Urdagargan area, a similar body of up to 5 m thick was found amongst the quartzites of the Quartzite Otrog site. They demonstrate similar structural features: weakly altered quartzites display primary sedimentary features such as banded structures dipping within 25 to 70^o. The banded structures are cut by thick discolored layers dipping gently (10–20^o). The comparison of incidence angles of layering and banding in different bedrock outcrops and large blocks of eluvial-deluvial deposits indicates that in most cases, the primary layering has a steeper dip and is crosscut by younger banded structures dipping within 5–15^o that is related to fracturing. Such structures well agree with the model of superquartzite formation through recrystallization of primary micro-grained quartzites under conditions of thermobaric gradients and inhomogeneities resulting from the discrete-dynamic effect of tectonic nappe sliding southeastwards due to obduction (Fedorov et al., 2011) or northwestwards as a result of subsequent isostatic uplift of the Gargan Block or gravitational landslide of ophiolites along the Block's cover (Fedorov et al., 2012; Makrygina, Fedorov, 2013; Fedorov et al., 2019).

The geochemical data obtained for the quartzites

Area/Site (occurrence)	Variety	Length, m	Width, m	Thickness m	Volume thousand m^3	Density gr/cm^3	Mass, thousand tons
Oka-Urik							
Northeast -1	fine-grained	350	50	20	350	2.60	910
Northeast-2	fine-grained	400	50	50	1 000	2.60	2 600
Southwest	fine-grained	350	200	50	3 500	2.60	9 100
Southwest	*Compact*	*100*	*50*	*5*	25	2.60	65
Northwest	fine-grained	200	150	50	1 500	2.60	3 900
South	fine-grained	300	300	50	4 500	2.60	11 700
South	*Superquartzites*	*150*	*150*	*1*	22. 5	2.60	58.5
Total							**28 300**
Urengenur site	micro-grained with carbonate interlayers	1 000	200	50	10 000	2.60	**26 000**
Urdagargan							
Semiorka	fine-grained	500	200	50	5 000	2.60	13 000
Belaya Sopka	fine-grained	150	100	25	375	2.60	975
Quartzite Otrog	fine-grained	1 500	300	50	22 500	2.60	58 500
Quartzite Otrog	*superquartzites*	300	50	5	75	2.60	195
Oka-1	fine-grained	200	150	50	1 500	2.60	3 900
Oka- 2	fine-grained	300	200	20	1 200	2.60	3 120
Total							**80 000**
Total for quartz-bearing area							**134300**
High-purity varieties (superquartzites and compact quartzites):							**300**

Table 6. Forecast resources, east Sayan quartz-bearing area

of the Irkut Formation indicate their unique chemical purity. Decolorization and recrystallization of quartzites lead to a process of significant quartzite purification and formation of superquartzites that can be used in optic quartz glass production after their chemical enrichment. In the area under study, there are also occurrences of the compact quartzites, which are similar to superquartzites by their purity, therefore they can significantly increase the reserves of quartz raw materials. The contamination of near-contact quartzites by impurity elements allows to separate them from the productive sequence.

Conclusions

Comprehensive studies were accomplished to classify quartzites and define the structural position of the most promising types of quartz raw materials within the Irkut Formation (Eastern Sayan Mountains) as well as to reveal the petrographic features and purity of different quartzite varieties.

To increase the forecast resources and reserves of high-purity quartzites, systematic survey, sampling and analysis of the Irkut Formation sequence are required. They have to take into account the proposed evaluation criteria:

1. Subsurface mapping delineation of discolored quartzites to a depth;

2. Sampling of compact quartzites, which, taking account their purity, can significantly increase the forecast reserves of quartz raw material;

3. Geochemical sampling of all outcrops of Irkut Formation siliceous rocks.

Based on the studies of quartzite sequences occurring within the Oka-Urik and Urdagargan areas and weakly metamorphosed quartzites of the Urengenur area it can be concluded:

1. Depending on amounts of impurity elements in quartzites, the scope of quartzite application can be expanded: from quartz raw materials used for crystalline silicon production (all recognized productive quartzite varieties) to quartz concentrates used for manufacturing optical quartz glass (compact quartzites and superquartzites).

2. Factors, controlling spreading of productive high-purity quartzite bodies to a depth and recognition of potential quartzite blocks are:

- High-purity quartzites are produced within the Riphean siliceous-carbonate sequences of the Irkut Formation, underwent greenschist facies metamorphism;
- Dark-grey and grey micro-and fine-grained quartzites hosting rare thin carbonate interbeds and lenses are regarded as the initial substratum for high-purity quartzite bodies;
- Discolored quartzite bodies are produced through the recrystallization resulting from the deformation of more stable (as compared with plastic carbonates) primary quartzites. The recrystallization is related to the collision between the Dunzhugur island arc and Gargan microcontinents margin.

Near the contacts with intrusive bodies, all quartzite varieties are intensively contaminated by major oxides and rare elements, therefore their contents are up to 2 orders of magnitude higher as compared to unaltered ones. Discolored and recrystallized productive bodies with the thickness range of few dozen meters are flat-lying and can be produced both at the top and bottom of the dark-grey fine-grained quartzite sequence owing to the character of tectonic deformations. The thickness of quartzites varies from a few meters for maximally recrystallized quartzites to few dozens meters for discolored varieties. A preliminary resource estimate of quartzites from the western part of the East Sayan quartzite-bearing area to be used for silicon metallurgy and production of optical silica glass is about 134 million tons.

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