ISSN 1028-334X, Doklady Earth Sciences, 2012, Vol. 442, Part 1, pp. 120–125. © Pleiades Publishing, Ltd., 2012.
Original Russian Text © A.M. Fedorov, V.A. Makrygina, A.E. Budyak, A.I. Nepomnyashchikh, 2012, published in Doklady Akademii Nauk, 2012, Vol. 442, No. 2, pp. 244–249.

GEOCHEMISTRY

New Data on the Geochemistry and Mechanism of Formation of Quartzites of the Bural-Sar'dag Deposit (Eastern Sayan Mountains)

A. M. Fedorov, V. A. Makrygina, A. E. Budyak, and A. I. Nepomnyashchikh

Presented by Academician M.I. Kuz'min July 5, 2011

Received August 8, 2011

DOI: 10.1134/S1028334X12010126

Deposits of high-purity quartz necessary for production of high-purity quartz grains and development of new solar energetics in most cases are represented by vein varieties of various genesis and, as a rule, have small resources. Because of this, of special importance are deposits of quartzites and quartz sandstones, although they are characterized by a low quality on huge scales. The Bural-Sar'dag deposit is one of the quite rare exceptions by the low concentration of admixtures and, accordingly, the highest perspectives. The established resources are 66 000 tons for "superquartzites" for metallurgy of silicon and production of quartz grains (by the C_1 category), 497 000 tons, for microquartzites for metallurgy of silicon (by the C_1 category), and 484 000 tons (by the C_2 category) [10].

The first data on the geology, geochemistry, and genesis of quartzites of Eastern Sayan were presented in the papers of E.I. Vorob'ev et al. [3] and N.G. Bydtaeva et al. [2]. In these studies the authors suggested original models of the formation of ultra-pure quartzites in the apical parts of anticlinal folds as a result of thermal-fluid (carbon dioxide–hydrous) influence of granitoids of the Sumsunurskii Complex [3] and in shift–thrust zones in dislocated siliceous rocks during carbon dioxide metasomatism [2]. In the opinion of authors, the mentioned hypotheses are not confirmed completely; for this reason, to solve this problem, detailed petrographic and geochemical study of two areas of the quartzite-bearing belt of the Irkutnaya Suite (Bural-Sar'dag Mountain and Urunge-Nur Lake) in places of its crossing with granitoids of the Sumsunurskii and Munkusardykskii Complexes is required.

Geology. The Bural-Sar'dag deposit is located within the cover of the Garganskii Block (Fig. 1) in the eastern part of the Tyva–Mongolia massif. It is a part of the quartzite-bearing belt of the Irkutnaya Suite composed of schist–carbonate–quartzite rocks (879 Ma, K–Ar) [1]. Deposits of the Irkutnaya Suite are widely abundant in the northern and northwestern framework of the block core occupying the lower stratigraphic level of its cover and overlain by significant schist rocks of the Urtagol'skaya Suite. The metamorphism of schists and quartzites of the Irkutnaya Suite does not exceed the lower part of the greenschist facies (300–350°C).

The basement of the Garganskii Block of the Archean–Lower Proterozoic age is represented by gneisses, granite gneisses, amphibolites, and migmatites (2.3–2.4 Ga) with the degree of metamorphism reaching the granulite facies. The Garganskii Block is entirely surrounded by rocks of Upper Riphean ophiolites of the front-arc basin of the Dunzhugurskaya island arc represented by fragments of serpentinized and eroded allochthone thrust over the block. To the southwest of the Bural-Sar'dag deposit, rocks of the Irkutnaya Suite are intruded by plagiogranites of the Garganskii Pluton (790 Ma) [5] related to the Sumsunurskii Complex of the tonalite–trondhjemite–dacite type.

Granitoids of the Munkusardykskii Complex (Early Paleozoic) in the association of high-niobium basic rocks (adakites) are widely abundant to the south of the Garganskii Block [4]. The geotectonic position and geological structure of the Garganskii Block on the regional scale and location of the Bural-Sar'dag deposit in it are described in publications of some authors (see, for example, [2, 3]).

Poorly metamorphosed microquartzites with a total true thickness of ~600 m are the most abundant within the outcrop of rocks of the Irkutnaya Suite [8]. These rocks are one of the earliest forms of lithified siliceous–carbonate sediment and occur in productive series of the Bural-Sar'dag deposit, as well as in siliceous dolomites outside the deposit including the area

Vinogradov Institute of Geochemistry, Siberian Branch, Russian Academy of Sciences, Irkutsk, Russia
e-mail: sashaf@igc.irk.ru

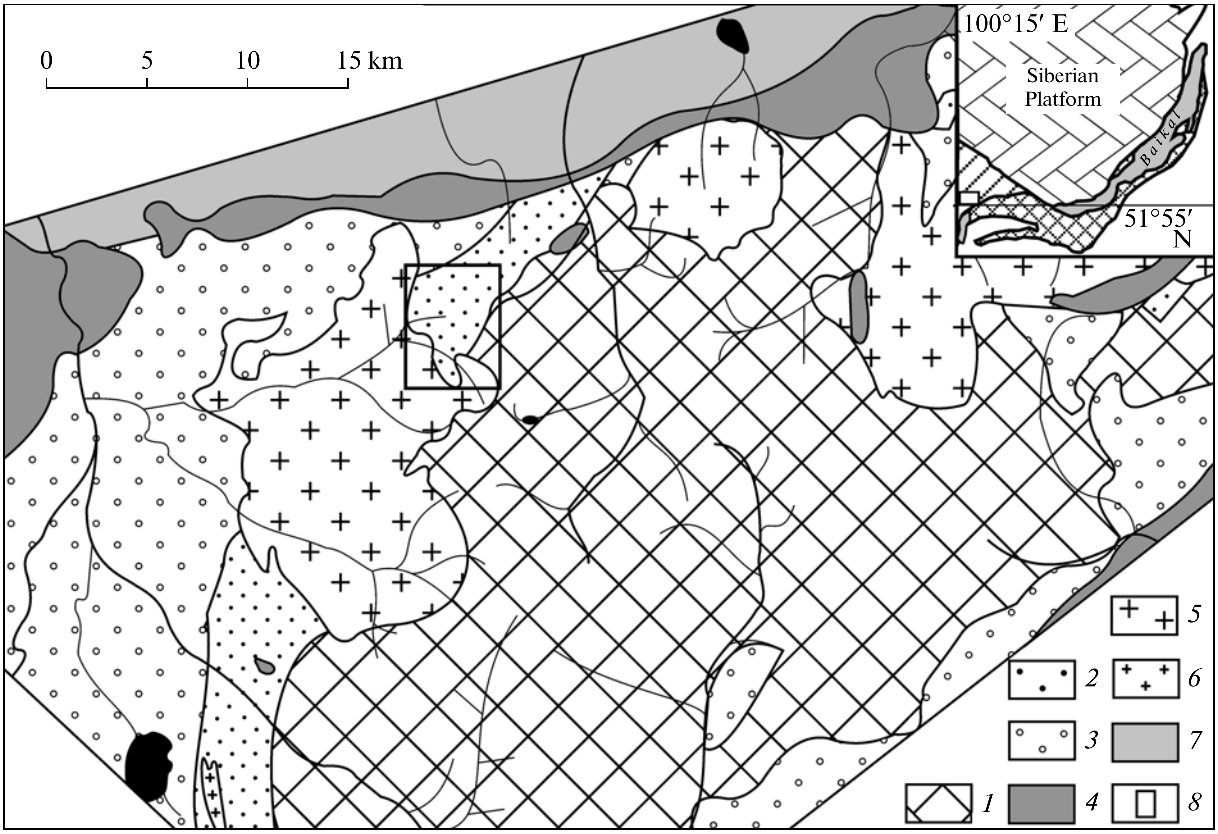

Fig. 1. Scheme of the geological structure of the northern part of the Tyva–Mongolia massif (after [5] with additions). (*1*) Garganskii Block basement ($AR–PR_1$); (*2, 3*) Garganskii Block cover: (*2*) lightened quartzites of the Irkutnaya Suite, (*3*) Irkutnaya and Urtagol'skaya Suites ($R_{2–3}$); (*4*) ophiolite complex (R_3); (*5*) granitoids of the Sumsunurskii Complex (R_3); (*6*) granitoids of the Munkusardykskii Complex (PZ); (*7*) cover of the Tyva–Mongolia massif (PZ); (*8*) area of the Bural–Sar'dag deposit. The inset demonstrates the location of the studied region.

of the Urunge-Nur Lake, which provides evidence for their belonging to the same stratigraphic level. The authors consider microquartzite as a primary rock, after which other quartzite varieties of the Bural-Sar'dag deposit and other manifestations in the studied region (Urdagarganskii, Okinskii, and others) are formed; in this paper these rocks are called "silicites" [8]. The main mineral admixture in silicites is represented by thin layers of limestones and dolomites, which are registered in quartzites of the Bural-Sar'dag deposit as well.

The productive bodies of snow-white "superquartzites" and light-gray microquartzites of the Bural-Sar'dag deposit are localized on the ridge top as gently pitching layers (7°–10° WNW), whereas siliceous–carbonate rocks of the Irkutnaya Suite are characterized by steep dipping. There is a continuous series of gradually alternating varieties from "superquartzites" of the upper level to dark-gray and black fine- and micro-granular quartzites in the lower parts of the Bural-Sar'dag deposit.

Dark-gray and black carbon-bearing microquartzites (from 0.008×0.008 to 0.15×0.04 mm) with poor primary banding resulting from uneven distribution of carbonaceous matter particles occur as layered and lenslike bodies among dolomite and limestone series at the section base of the Bural-Sar'dag deposit. Quartz grains compose 97–99% of the rock; interstitials between them are formed by carbonaceous matter particles (0.5–2%). Sericite and other more rare admixtures (muscovite, epidote, and hematite) compose up to 0.01–1%. Among dark-gray microquartzites of the layered bodies are relics of black and dark-gray ultra-microgranular, almost massive quartz rocks ("silicites") colored by finely dispersed carbonaceous material.

Several varieties are distinguished among lighter quartzites: gray fine-granular massive quartzites, sometimes with dark-gray layers and banded texture; light-gray with fine-granular texture (a grain size of 0.5×0.2 mm); fine-granular with spotty–banded (from light-gray to white) color; white sugarlike fine-granular quartzites with massive structure (grain size up to 1 mm, granoblastic, mosaic texture) and white quartzites with a bluish hue containing a small portion of carbonaceous material.

The thickness of the "superquartzite" layer occupying the upper part of the section directly within the

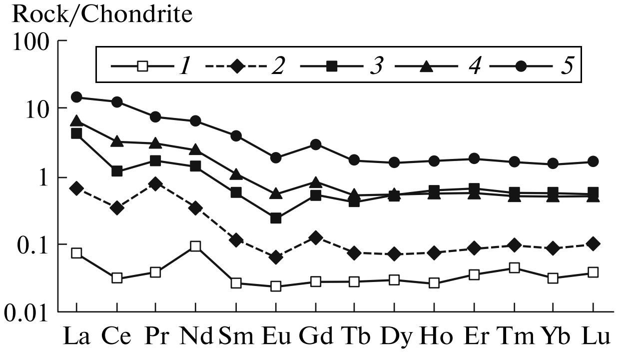

Fig. 2. Relative concentrations of REE in siliceous series of the Irkutnaya Suite. (*1*) Primary "silicate" (4); (*2*) "superquartzite" (8); (*3*) near-contact "silicate" (5); (*4*) light-gray quartzite (2); (*5*) near-contact dark-gray quartzite (3). Analyses were performed in the laboratory of the Institute of Geochemistry, Siberian Branch, Russian Academy of Sciences, by the ICP-MS method, analyst Yu.V. Sokol'nikova. Thenumber of analyses is given in parentheses.

Bural-Sar'dag deposit is estimated as ~8.4 m. "Superquartzites" are characterized by an almost monomineral quartz composition and coarse irregular-granular texture. Larger grains with sizes from 1.6×0.5 to 4×2 mm and even 9 mm occupy from 5 to 50% of the total groundmass. They are characterized by an elongated shape with subparallel orientation by the long axis, winding, serrate boundaries, and wavy extinction. Large grains are distinguished against the background of the more fine-granular quartz aggregate with the same grain orientation along the long axis. The subparallel orientation of porphyraceous segregations in "superquartzites" provides evidence for their formation (recrystallization) under the conditions of long unilateral stress.

Geochemistry. The low totals of minor elements in primary rocks ("silicites"), as well as "superquartzites," are the main geochemical characteristics of quartzites of the Irkutnaya Suite. Petrogenic elements are admixtures in them composing 99% of the total admixtures (Table 1). The concentrations of many minor elements are so low that their analysis was possible only using highly sensitive methods (ICP-MS and AESA). Only these methods allowed us to compare the patterns of element distribution by quartzite varieties in sections correctly.

"Silicites" are most widely abundant near Urunge-Nur Lake. According to the geochemical signs, they are clearly distinguished into two separate groups. The first group includes primary "silicites" located at a distance from granites of the late phase of the Munkusardykskii Complex; the second group includes rocks located near their outcrops (near-contact).

Primary "silicites" are characterized by very low concentrations of admixtures, whereas in near-contact "silicitites," the concentrations of almost all rock-forming, rare, and rare-earth elements are high (Fig. 2). This is the most clearly observed for granitophylic elements, namely Al, Ti, K, REE, and Y, as well as Ba, Rb, B, and Cs with an increase up to 20 times in comparison with primary "silicites." The widest value range is typical for Ba and Sr with the concentrations in the Munkusardykskii granitoids from 758 to 1620 ppm and from 155 to 918 ppm, respectively [4].

The concentration of REE near the contact zone is ten times higher in comparison with "silicites" at a distance as well (Fig. 2). This is especially typical for LREEs, and the LREE/HREE ratio changes from 1.2 in primary "silicites" to 4.4 in near-contact rocks. The clear Ce minimum typical for sediments of marine basins is practically the same, but near the contact, REE spectra are characterized by a strong Eu minimum, which provides evidence for the influence of endogenic fluid related to granitoids of the Munkusardykskii Complex.

According to the concentration of petrogenic, rare-earth, and rare elements, quartzites of the Bural-Sar'dag deposit may be clearly subdivided into two groups.

The first group includes black and dark-gray flint-like quartzites with low concentrations of rock-forming and rare elements and comparable by these elements with primary "silicites," as well as lightened quartzites and even "superquartzites" of the Bural-Sar'dag deposit. Thus, black and dark-gray flintlike quartzites, lightened quartzites, and "superquartzites" have similar geochemical patterns and are united by the name "productive series" or "productive layered bodies."

The second group includes quartzites located at the contact with tonalities of the Garganskii massif, in which the concentration of petrogenic and rare elements is higher than that in black flintlike quartzites of layered bodies (by 10–20 times for Mn, Fe, Ca, Na, K, B, and Zr; by 20–30 times for Ti, Li, Sc, Sr, and Ba; by about two orders of magnitude for Al, V, Rb, and Cs. Thus, we may emphasize that intrusion of granitoids of both Riphean and Paleozoic ages had a negative influence (pollution) on the primarily pure quartzites of the Irkutnaya Suite.

The total concentration of minor components in light-gray microquartzites is higher by a factor of 5 than that in "superquartzites," but lower by a factor of 10 than that in near-contact quartzites. There is no clear correlation between the intensity of lightening and the content of the mineral admixture.

The most "impure" among quartzites of the Bural-Sar'dag deposit are dark-gray and black near-contact microquartzites, in which the concentration of minor elements reaches *n*% being higher than that in "superquartzites" by two orders of magnitude. More clear is the increase in REEs (LREE, by hundreds of times; HREE, by tens of times) in near-contact quartzites (Fig. 2). Such behavior of granitophylic elements may be explained by the intense influence of granitoids of

Average concentrations of minor elements in quartzites of various types from the Bural-Sar'dag deposit (ppm)

Element	Rock					
	"superquartzites" (ICP-MS, 8)	light-gray quartzites (AESA, 42)	black layered quartzites (AESA, 10*)	primary "silicate" (ICP-MS, 4)	near-contact "silicate" (ICP-MS, 4)	dark-gray near-contact quartzites (ICP-MS, 3)
Al	$\frac{9.1-59}{33.05}$	$\frac{9.3-475}{104}$	$\frac{20-257}{72}$	$\frac{19.64-68.25}{40.50}$	$\frac{216-1289}{649}$	$\frac{3488-8773}{5779}$
Ti	$\frac{0.39-23}{4.07}$	$\frac{0.1-252}{15.43}$	$\frac{1.3-113}{14.94}$	$\frac{0.87-1.48}{1.20}$	$\frac{9.5-30}{20.00}$	$\frac{104-612}{342}$
Fe	$\frac{4.8-23}{9.22}$	$\frac{5-887}{92.21}$	$\frac{17-500}{108}$	$\frac{9.89-47.95}{24.60}$	$\frac{15-94}{46.00}$	$\frac{302-876}{596}$
Mn	$\frac{0.02-0.11}{0.05}$	$\frac{0.1-21}{1.10}$	$\frac{0.05-1}{0.57}$	$\frac{0.83-2.72}{1.56}$	$\frac{0.07-4.6}{2.00}$	$\frac{0.72-4.5}{2.35}$
Mg	$\frac{0.5-2.7}{1.73}$	$\frac{3-740}{56.35}$	$\frac{3-170}{44.26}$	$\frac{45.4-505.5}{226.50}$	$\frac{83-1668}{722}$	$\frac{185-278}{239}$
Ca	$\frac{1.5-3.8}{2.47}$	$\frac{5-60}{14.84}$	$\frac{5-20}{8.50}$	$\frac{93.17-1049}{455.07}$	$\frac{3.7-3437}{1374}$	$\frac{24-217}{144}$
Na	$\frac{3.5-7.9}{4.95}$	$\frac{2.8-40}{9.73}$	$\frac{6-25.7}{12.60}$	$\frac{4.02-6.81}{5.02}$	$\frac{6.4-16}{11.00}$	$\frac{60-321}{227}$
K	$\frac{1.4-11}{6.12}$	$\frac{7.3-100}{81.37}$	$\frac{46.6-311}{163}$	$\frac{5.34-15.98}{10.56}$	$\frac{83-452}{243.00}$	$\frac{1228-3090}{2033}$
P	$\frac{0.5-0.9}{0.69}$	$\frac{2-6.7}{3.90}$	$\frac{1-8.6}{4.40}$	$\frac{0.52-0.76}{0.58}$	$\frac{2.4-7.4}{4.00}$	$\frac{17-110}{76.33}$
B	$\frac{0.12-0.26}{0.17}$	$\frac{0.5-7.1}{2.30}$	$\frac{0.5-4}{1.82}$	$\frac{0.04-0.29}{0.16}$	$\frac{0.42-1.7}{1.00}$	$\frac{14.5-28}{20.72}$
Total	62.51	381	430	765.75	3072	9459
Li	$\frac{0.4-0.6}{0.50}$	$\frac{0.07-2.3}{0.75}$	$\frac{0.2-1.1}{0.62}$	$\frac{0.25-1.08}{0.61}$	$\frac{0.1-0.9}{0.50}$	$\frac{0.3-2}{1.36}$
Rb	$\frac{0.009-0.056}{0.03}$	–	–	$\frac{0.02-0.1}{0.05}$	$\frac{0.35-1.7}{0.89}$	$\frac{4.8-9.5}{7.07}$
Ba	$\frac{0.22-0.86}{0.61}$	–	–	$\frac{0.43-1.16}{0.67}$	$\frac{5.2-17}{13.47}$	$\frac{29-82}{54}$
Sr	$\frac{0.07-0.33}{0.14}$	–	–	$\frac{0.24-0.87}{0.44}$	$\frac{0.17-5.3}{2.36}$	$\frac{2-6.6}{4.72}$
W	$\frac{0.07-2.1}{0.91}$	–	–	$\frac{0.08-0.3}{0.14}$	$\frac{0.013-0.3}{0.16}$	$\frac{0.26-0.51}{0.37}$
Ni	$\frac{0.1-0.3}{0.13}$	$\frac{0.2-1.2}{0.46}$	$\frac{0.2-0.7}{0.40}$	$\frac{0.05-0.21}{0.10}$	$\frac{0.05-0.17}{0.07}$	$\frac{0.9-1.2}{0.81}$
Cr	$\frac{0.01-0.13}{0.07}$	$\frac{0.5-18}{5.12}$	$\frac{0.5-16}{5.03}$	$\frac{0.12-0.53}{0.27}$	$\frac{0.27-1.4}{0.67}$	$\frac{4.3-15}{9.97}$
V	$\frac{0.011-0.22}{0.14}$	$\frac{0.5-3.2}{0.85}$	$\frac{0.5-4.6}{1.11}$	$\frac{0.09-0.34}{0.23}$	$\frac{0.6-2}{1.29}$	$\frac{25-71}{49}$

Note: Variation of the concentrations for rock types is given as the numerator; the average concentrations, as the denominator. The number of samples is given in parentheses. Analyses were performed in the laboratory of the Institute of Geochemistry, Siberian Branch, Russian Academy of Sciences, by the ICP-MS method, analyst Yu.V. Sokol'nikova, and the AESA method, analyst I.E. Vasil'eva.

* K and P concentrations are given for five samples.

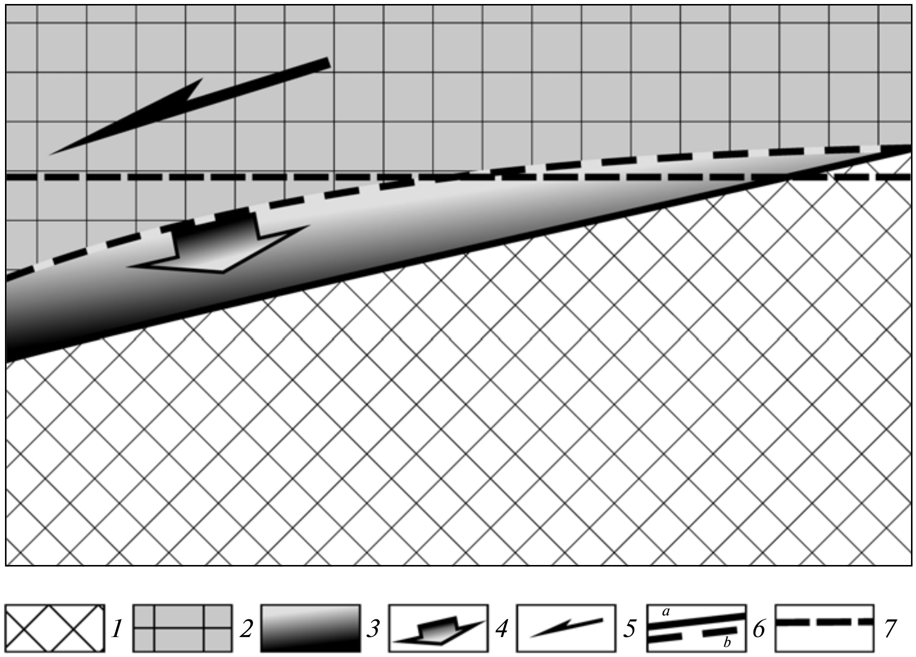

Fig. 3. Scheme of gravitational slipping of ophiolite nappe from the Garganskii Block. (*1*) Garganskii Block basement ($AR–PR_1$); (*2*) undissected ophiolite complex (R_3); (*3*) Garganskii Block cover (Irkutnaya Suite, $R_{2–3}$); (*4*) direction and degree of influence of the thermal field on the tectonic contact of ophiolites with rocks of the Garganskii Block cover; (*5*) direction of gravitational slipping of ophiolite complex from the Garganskii Block surface; (*6*) tectonic dislocations: (*a*) true and (*b*) assumed; (*7*) erosion surface.

the Sumsunurskii Complex on sedimentary series. On average, the concentration of the total petrogenic elements in black near-contact quartzites is 30 times higher than that in black and dark-gray layered quartzites of the Bural-Sar'dag deposit close to primary rocks.

On the basis of previous investigations [2, 3] and new geochemical data, we suggest a different concept of the formation of the deposit of ultrapure quartzites of Eastern Sayan. The essence of the model is that lightened quartzites and "superquartzites" were formed in the course of dynamo–thermal–metasomatic transformations of primary siliceous–carbonate rocks of the Irkutnaya Suite ("silicites") under the influence of rocks of the ophiolite nappe moving over them (Fig. 3).

A significant pressure gradient (stress metamorphism) at the bottom of the thrusting or slipping plate results in mobilization of the fluid component proper of primary siliceous rocks ("silicites") and in its migration along faults and dislocations to the area of the underlying layers, which did not undergo stress metamorphism. Judging from mineral parageneses, the temperature gradient was low within the greenschist facies.

As a result, in the upper part of the quartzite section, under maximal dynamo–thermal influence, most likely autolision of the primary quartz substrate and its recrystallization with increase of sizes and specific subparallel orientation of quartz grains reflecting the direction of nappe motion occurred. The areas of siliceous series at a distance from the tectonic contact underwent a smaller influence, and subsequently they not only underwent a lower degree of recrystallization, but could be an area of relaxation for minor elements from the overlying rocks.

The decrease in the degree of quartzite transformation at a distance from the plane of tectonic contact accompanied by growth of the content of only those elements that are typical for proper quartzites proves the influence of fluid components from rocks and the absence of introduction of endogenic fluids. Lightening of quartzites in this area occurred at the expense of complete or partial removal of only coloring carbonaceous matter. The concentrations of granitophylic elements not typical for primary rocks increase in quartzites only near the contact with granites.

In our opinion, metasomatic alterations of quartzites from the Bural-Sar'dag deposit occurred during collapse of the obduction regime as a result of uplift of the Garganskii Block and subsequent gravitational slipping of rocks of the ophiolite complex. This thesis is mainly supported by the fact that autolision and recrystallization of quartzites occurred after completion of the stage of granite formation, which most likely resulted in uplift of the Garganskii Block and gravitational slipping of sedimentary nappes and ophiolite plates from it. As was shown above, the influence of granitoids is limited by the pollution of primary "silicites" and all other quartzite varieties by granitophylic elements. Even upon subsequent recrystallization and purification from admixtures with the formation of "superquartzites," they are characterized by an Eu minimum and a high concentration of LREEs. Such behavior of REEs and other elements provides evidence for the fact that the history of transformation of quartzites of the Bural-Sar'dag deposit includes the stage of their "pollution" with admixtures related to intrusion of the Sumsunurskii intrusive complex and the second stage of slipping of the overlying series, when purification and recrystallization of quartzites took place. This is confirmed by the fact that purification and granulation of quartz as a result of similar geodynamic environments are not unique [6, 9]. Thus, tectonic slipping of metasedimentary rocks of the Olokitskii synclinorium is observed in the Northern Baikal area at the uplift of the Chuiskii Block. Milonitized gneisses of the Chuiskaya Series are outcropped in the autochthone; in its composition the quartz cores of pegmatites and veins underwent granulation and purification from admixtures, and at the bottom of the allochthone, quartzites of the Avkitskaya Suite are also granulated with the formation of the Tyiskoe deposit of ultrapure quartz [6].

In conclusion, we may emphasize that primary microquartzites of the Irkutnaya Suite ("silicites") are quite pure from admixtures; this may be the main reason for their subsequent transformation into "superquartzites." According to the geochemical signs, primary "silicites" may be considered as promising zones for an increase in resources of ultrapure quartz for production of multisilicon and they may be included in the productive series.

The influence of granitoids cannot result in the formation of ultrapure quartzites, since quartzites near the contacts of granitoids of the Riphean Sumsunurskii, as well as the Paleozoic Munkusardykskii Complexes, are polluted by granitophylic elements.

The formation of the most pure "superquartzites" of the productive series of the Irkutnaya Suite (Bural-Sar'dag deposit and others) occurs as a result of gravitational slipping of ophiolite nappes resulting in recrystallization and purification of the upper adjacent quartzite horizon with admixture removal to the underlying quartzite layers.

REFERENCES

1. N. A. Avdontsev, *Granitoids of the Garganskii Block* (Nauka, Leningrad, 1967) [in Russian].
2. N. G. Bydtaeva, R. A. Kiseleva, and V. N. Yashin, *Quartz. Silica. Mat. of the Intern. Seminar* (Geoprint, Syktyvkar, 2004), pp. 185–187 [in Russian].
3. E. I. Vorob'ev, A. M. Spiridonov, A. I. Nepomnyashchikh, and M. I. Kuz'min, Dokl. Earth Sci. **390**, 497 (2003).
4. S. V. Efremov, Geokhimiya **48**, 1112 (2010).
5. A. B. Kuz'michev, *Tectonic History of the Tyva–Mongolia Massif: Early Baikal, Late Baikal, and Early Caledonian Stages* (Probel-2000, Moscow, 2004) [in Russian].
6. V. A. Makrygina, *Geochemistry of the Regional Metamorphism and Ultrametamorphism of Moderate and Low Pressures* (Nauka, Novosibirsk, 1981) [in Russian].
7. Z. I. Petrova, A. A. Koneva, and V. A. Makrygina, Geokhimiya, No. 10, 1448 (1995).
8. I. N. Semeikin, Izv. Sib. Otd-niya Sektsii Nauk o Zemle RAEN. Geologiya, Poiski i Razvedka Rudnykh Mestorozhdenii, No. 2, 126 (2009).
9. E. V. Sklyarov, A. M. Mazukabzov, and A. I. Mel'nikov, *Complexes of Metamorphic Cores of the Cordillera Type* (Izd-vo SO RAN, NITs OIGGM, Novosibirsk, 1997) [in Russian].
10. http://geoconsult.ru/
11. N. M. Evensen, P. J. Hamilton, and R. K. O' Nions, Geochim. et Cosmochim. Acta **42**, 1199 (1978).