

Genesis and Composition of Lazurite in Magnesian Skarns

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Abstract—The genesis and composition of lazurite was considered in the metasomatic rocks and deposits of the Baikal area, Pamirs, Hindu Kush, and other regions. It was shown that formation of lazurite is related to the prograde bimetasomatic or contact–metasomatic magnesian skarn processes developing in dolomites. The skarnized sedimentary or metamorphic rocks should be salt-bearing, contain sulfur-bearing minerals, and be affected by Cl-bearing hydrothermal solutions. Both abyssal and hypabyssal skarn bodies show distinct zoning. Depending on the *PT* parameters, their metasomatic columns can vary, with the preservation of the Mg/Ca ratio from the carbonate precursor. The formation of contact–metasomatic lazurite mineralization is promoted by high-alkali magmatic solutions, which cause the replacement of dolomites by skarn. Lazurite can also be formed during the postmagmatic stage, owing to a change in the mineral composition of the adjacent aluminosilicate and magnesian–skarn rocks at abyssal and hypabyssal deposits around the world. The occurrence of authigenic lazurite emphasizes its polygenetic formation.

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INTRODUCTION

Magnesian skarn ore deposits are rich in many mineral resources, including iron, borate, tin, tungsten, beryllium, lithium, gold–copper, and base-metal ores. Moreover, they can host economic deposits of gems and cut or ornamental stones, as well as minerals used for the production of high-Mg, chemical, abrasive, and ceramic materials and cement. All of these mineral resources are genetically related to the metasomatic and/or bimetasomatic alterations of sedimentary dolomites and magnesites in contact with compositionally diverse magmatic intrusions or other aluminosilicate rocks.

The lazurite deposits considered in this publication are situated in the Baikal area, Badakhshan, Hindu Kush, and other Precambrian provinces around the world, where they are localized in the metasomatized aluminosilicate rocks adjacent to abyssal magnesian skarns developing after dolomites, as was shown by Korzhinskii [1, 2]. Literature on lazurite deposits around the world and newly obtained data suggest that they can be formed in hypabyssal conditions and by local decompression at Precambrian deposits [3].

Lazurite $(\text{Na,Ca})_{7-8}(\text{Si,Al})_{12}(\text{O,S})_{24}[(\text{SO}_4)\text{Cl}_2(\text{OH})_2]$ is formed as the common feldspathoid of magnesian skarns during the postmagmatic bimetasomatic alteration of dolomites at contacts with enclaves of feldspathic rocks or high-alkali intrusions. The mineral belongs to the sodalite group and contains both sulfate and sulfide sulfur. The presence of the latter defines the blue color of variable intensity of this mineral [4, 5].

The mineral typically occurs as optically isotropic cubic crystals, with rarer orthorhombic, monoclinic,

and triclinic varieties [6–8]. The latter are optically anisotropic. Lazurite-bearing skarns and calciphyres often contain feldspathoids: sodalite $\text{Na}_8[\text{Al}_6\text{Si}_6\text{O}_{24}]\text{Cl}_2$, hauyne $\text{Na}_{4.5}\text{Ca}_2\text{K}[\text{Al}_6\text{Si}_6\text{O}_{24}](\text{SO}_4)_{1.5}(\text{OH})_{0.5}$, as well as afghanite $(\text{Na,Ca,K})_8[(\text{Al,Si})_{12}\text{O}_{24}](\text{SO}_4,\text{Cl},\text{CO}_3)_3 \cdot \text{H}_2\text{O}$, bystrite, and tounkite of the cancrinite group, as well as nepheline, apatite, relics of magnesian-skarn assemblages, carbonates, and zeolites.

Lazurite is now believed to be a typical product of the abyssal-facies metasomatism of dolomites, often forming economic concentrations [7]. In the Baikal area, these are the Malaya Bystritsa, Slyudyanka, Tultui, Talinsk, and Pokhabinsk deposits, as well as the occurrences of Mount Ermoskhin–Sardag and the Arshing Range in the Eastern Sayan. Its deposits and occurrences are also known in the Southwestern Pamirs (Lyadzhvardara and others), Ukraine (Delavetskii quarry in the Rakhov Massif, Carpathians), in Afghanistan (Sar-e-Sang, Badakhshan province), Canada (the Main and North occurrences, Lake Harbour, Baffin Island [9]), and Chile (Karen et al. [10]). At the same time, lazurite forms hypabyssal occurrences: Chernushka in the Baikal area, Italian Mountain in Colorado [11], San Bernardino county [12], and the Big Horn Mine in California [6, 13], Zardalek massif in the Altai Range, Kyrgyzstan [14], and the Albani Hills and Vesuvius in Italy [6, 15]. All of these occurrences have a contact–metasomatic genesis.

We studied lazurite-bearing rocks and nearby calciphyres from the Baikal Area and Pamir deposits and compared them with literature data.

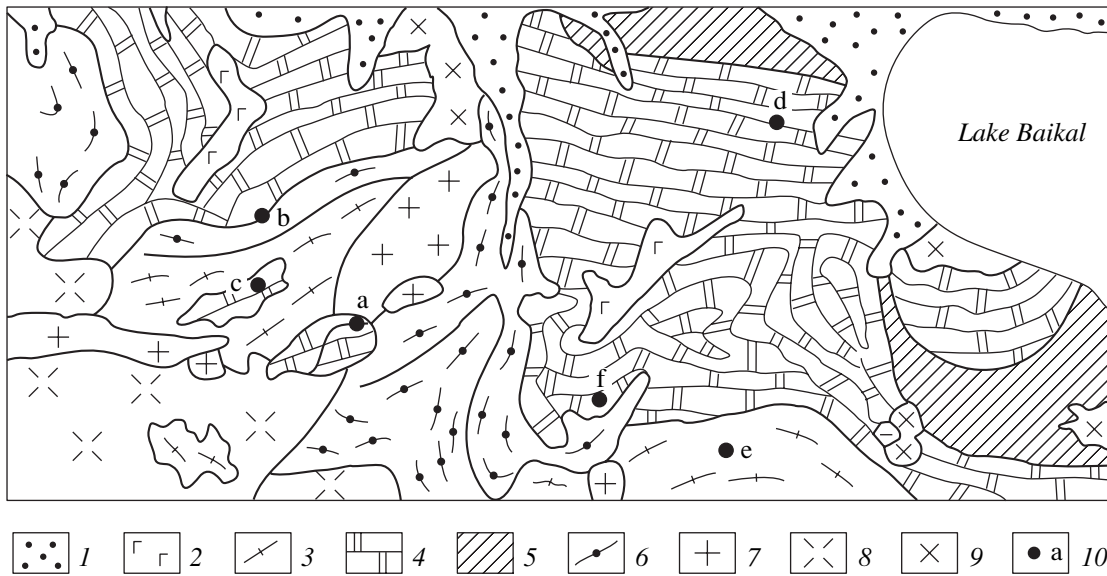


Fig. 1. Geological scheme of the lazurite-bearing region in the southwestern Baikal area (after Shalfeev [8]). (1) Quaternary deposits, (2) flood basalts, (3) rocks of the Khamardaban Group, (4) marbles of the Pereval'naya Group, (5) rocks of the Kultuk Formation, (6) rocks of the Kharagol Formation, (7) granites, granosyenites, and syenites of the Dzhida Complex, (8) biotite granites, (9) granite pegmatites, (10) lazurite deposit: (a) Malaya Bystritsa, (b) Tultui, (c) Chernushka, (d) Slyudyanka, (e) Talinskoe, (f) Pokhabinsk.

ABYSSAL LAZURITE DEPOSITS

The abyssal lazurite deposits in Russia occur in the Slyudyanka district, Irkutsk oblast, southwestern Baikal area, and were studied by Korzhinskii [1]. This author established that they were formed bimetasomatically, at contacts with aluminosilicate rocks and dolomites and belong to the magnesian-skarn association, and this was confirmed by the data of many geologists [7, 8, 10, 16–19]. The most famous lazurites occur in the Slyudyanka and Malaya Bystritsa skarn fields (Fig. 1). Lazurite-bearing rocks were also found along the Talaya River in the Slyudyanka River basin and along the Tultui and Pokhabikha rivers in the Malaya Bystritsa basin, and others. A poorly studied lazurite occurrence [10] was found at the Chernushka River, a tributary of the Srednyaya Tibel'ti River in the Irkut Basin. This occurrence shows unusual metasomatic zoning [3].

The Slyudyanka deposit is hosted in diopside skarns and spinel–forsterite calciphyres developing after dolomites in the upper reaches of the Slyudyanka River and in its left tributary (Sporny Creek) [8]. Lazurite rocks occur at their contacts with weakly boudined granitoids (Fig. 2).

Korzhinskii showed [1, 2] that the bodies of the Slyudyanka deposit reveal a clearly pronounced metasomatic zoning, which was associated with the prograde magnesian skarn stage and was overprinted by retrograde postmagmatic assemblages, which were formed together with lazurite-bearing rocks under the influence of alkaline S–Cl-bearing hydrothermal solutions. These solutions caused microclinization of blocks of leuco-

cratic granite with the formation of lazurite in the inner-skarn zones. Potassium solutions caused phlogopitization of the host rocks.

Thus, the sequence of mineral assemblages in hand-specimens from the southern quarry [1] is as follows (Fig. 3): (I) leucocratic microcline–perthite granite with oligoclase, (II) narrow phlogopite zone (5 mm) with microcline relics and diopside intergrowths, (III) diopside–lazurite zone with sporadic phlogopite (2 cm), (IV) rim of colorless phlogopite with hauyne and diop-

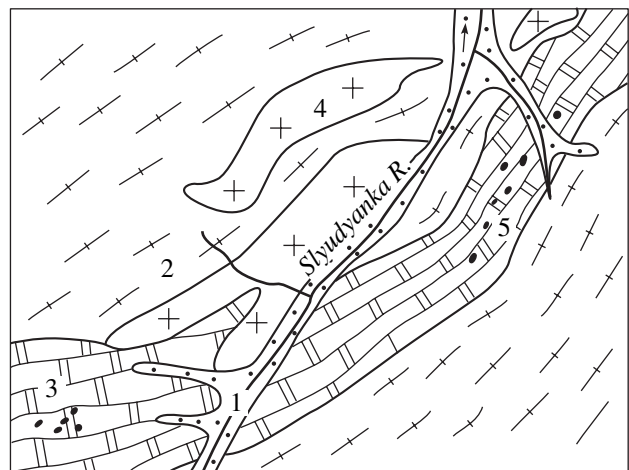


Fig. 2. Slyudyanka lazurite deposit [8]. (1) Alluvial deposits, (2) gneisses, (3) dolomite and calcareous marbles, (4) granites, (5) lazurite rocks.

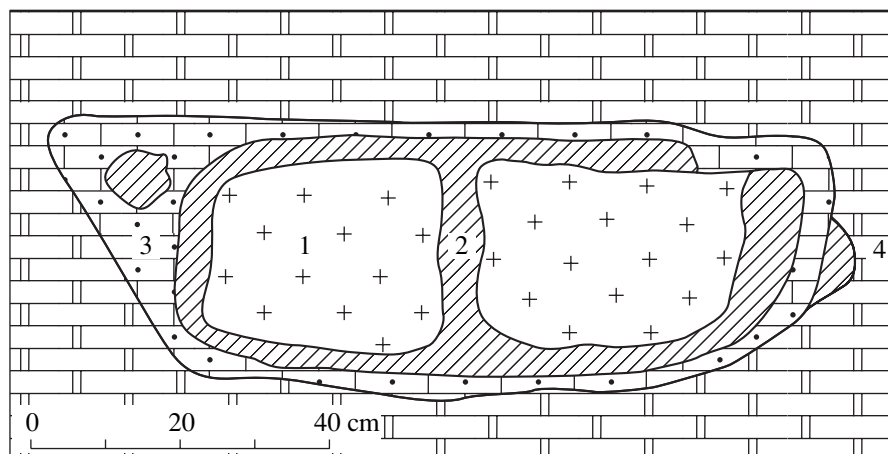


Fig. 3. Lazuritization of pegmatite and metasomatic zoning in skarns developing after dolomites, Slyudyanka deposit (1). (1) Pegmatite, (2) lazurite–diopside zone with a phlogopite rim, (3) calciphyre, (4) dolomite

side (up to 2 cm), (V) white calciphyre with diopside and phlogopite (1–2 cm), and (VI) dolomite with disseminated forsterite, spinel, and pyrite.

The lazurite–forsterite vein located in the middle quarry of the Slyudyanka diopside–lazurite metasomatic deposit [1, samples 383–386] contains calcite, pink spinel, and intergrowths of late phlogopite and is rimmed by calcite bearing large (>1 cm) crystals of dark blue lazurite with anomalous birefringence in the presence of colorless forsterite and spinel.

In addition to this deposit, two digging pits expose pockets and lenses of disseminated lazurite. They are confined to the sequence of skarnized dolomite in contact with granite pegmatites at the left bank of the Talaya River [20, 21] and are presently only of mineralogical significance.

The Malaya Bystritsa lazurite deposit (Fig. 4), the largest in the Baikal area, is located in the valley of Lazurnyi Creek, a left-hand tributary of the Malaya Bystraya River (in the Irkut River basin) [1, 8, 17–21]. The deposit is contained in dolomites with brecciated boudins of diopside-bearing microclinized granitoids, in which the quartz content decreases toward the diopside–lazurite rims (thickness ~3 cm) [1]. The rim is followed by an intermittent zone of lazurite-bearing calciphyres with diopside, phlogopite, and disseminated pyrite, grading into coarse-grained calcite marble. Korzhinskii [1] noted that lazurite and phlogopite develop after spinel.

The tectonic brecciation and boudinage of aluminosilicate rocks in dolomites predetermines the pocket type of the lazurite mineralization [8], which is expressed the most clearly in the Novyi prospect, which has high-quality lazurite. Near these pockets, dolomites were affected by pervasive calcitization with the formation of coarse-grained carbonate aggregates.

Lazurite at deposits in the Baikal area varies from bright to pale blue. Its almost colorless varieties occur

locally, mostly at the Slyudyanka deposit, while gray-blue lazurite was found at the Tultui deposit. Spinel–forsterite calciphyres at the Tultui deposit (Fig. 5) also contain dissemination of polychrome lazurites varying from dark blue (in rims) to blue (in central parts). Other occurrences are of mineralogical interest or their study is in progress.

The lazurite rocks of the region (Table 1) are made up of early diopside, forsterite, spinel, phlogopite, cancrinite [16], nepheline, and other feldspathoids.

The study of the modes of occurrence and isotopic composition of sulfur in the Baikal area deposits [22] showed that the carbonate, possible saliferous rocks, typically contain sedimentary gypsum and anhydrite. During metamorphism and bimetasomatism at contacts of dolomites with aluminosilicate rocks, sulfur was incorporated into feldspathoids, including lazurite, in which it is contained in sulfate and reduced forms. During later stages, sulfur was incorporated into pyrite and pyrrhotite that developed after pyrite, as is detected in the lazurite-bearing forsterite calciphyres from the Tultui occurrence. Sulfur also occurs in the native form as a biogenic product [22]. The authors argue that the presence of both sulfur and chlorides is required in skarnized dolomites to form lazurite in the distribution area of phlogopite deposits.

The ubiquitous presence of monomineralic forsterite zones is a characteristic feature of prograde bimetasomatic zoning in magnesium skarns. This zoning is formed if the outer-contact skarns were not affected by magmatic replacement [3] and can be ascribed to the primitive type.

The contact aureoles are subdivided into zones of diopside skarn, forsterite calciphyre, and dolomite marble. The Chernushka occurrence also contains a zone of periclase marbles after dolomites [3]. The periclase–calcite rocks rimming forsterite skarns are more typical of hypabyssal skarns. They were presumably formed by

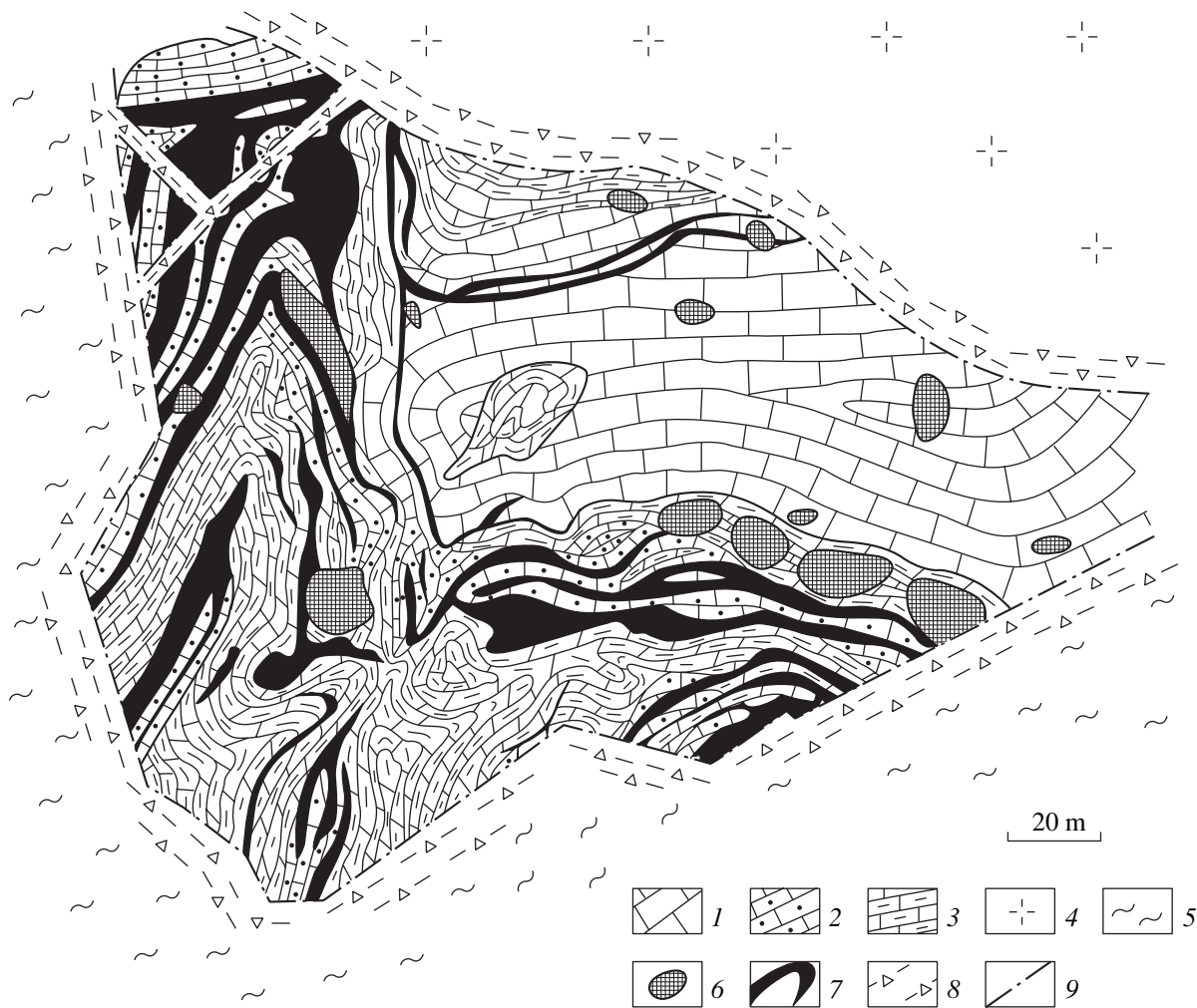


Fig. 4. Geological map of the Malaya Bystritsa lazurite deposit [21]. (1) Calcite coarse-grained marbles, (2) white calcite-dolomite marbles, (3) banded gray calcite-dolomite marbles, (4) syenites, (5) diopside gneisses and marbles of the Kharagol Formation, (6) boudined, partially skarnized bodies of granitoids, (7) lazuritization zone, (8) brecciated zone, (9) tectonic contacts.

the thermal decomposition of dolomites at skarn temperature during deformation-related local decompression.

Lazurite was recently found in the marbles abounding in granite bodies on the southern slope of Mount Ermoskhin-Sar'dag in the Eastern Sayan [23]. Lens-shaped metasomatic bodies were found there at the Arashing occurrence. They show concentric zoning (from core to rim), with plagioclases in the central part subsequently rimmed by phlogopite-bearing diopside-scapolite rock, lazurite-amphibole zone, and dedolomitized marbles. The lazurite-bearing rock has a cornflower blue color and variable thickness, from 0.5 to 6 cm. The amphibole is pargasite (edenite). Lazurite belongs to the cubic system ($a = 9.07(1) \text{ \AA}$) and shows an intense blue color with a violet tint (Table 2). The Arashing lazurite occurrence of Eastern Sayan expands the prospects of this Siberian region for the discovery of new lazurite deposits.

A lazurite occurrence was reported [24] to be found in the Delovetskii marble quarry in the Rakhov area, Carpathians. The bright cornflower blue isotropic lazurite ($N = 1.500$) composes pockets in calciphyres, together with calcite, Fe-free diopside, relict olivine in iddingsite, and rare disseminated pyrite. The authors noted its high quality and supposedly contact-metasomatic genesis.

Another economically important region of lazurite rocks is Badakhshan, which contains several skarn deposits on the territory of Tajikistan and Afghanistan. These are Lyadzhvardara and others deposits [8, 10, 25–28], including Ishkashim [27] in the Nagornyi Badakhshan, southwestern Pamirs, and Sar-a-Sang and other deposits in the Hindu Kush, Afghanistan [10, 29–35].

The Lyadzhvardara deposit, the largest in Tajikistan, is localized in calcite-dolomite marbles contained in the sequence of biotite gneisses and migmatites [26].

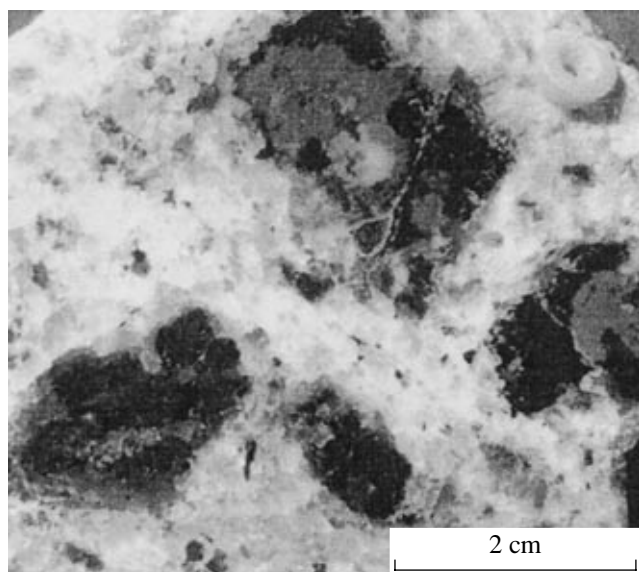


Fig. 5. Zoned variably colored lazurite in forsterite calciphyres. Tultui deposit. Sample BT-5-10.

The high-quality lazurite rocks compose 100–150 pockets and lenses restricted to boudined aplites.

Diopside skarns developed at the contact with desilicified microcline aplites and are rimmed by forsterite calciphyres grading into dolomites (Fig. 6). The microcline rocks were replaced during the retrograde stage by diopside and lazurite with relics of anorthoclase and

albite or became fringed by concentric zones of diopside–lazurite, calcite–diopside, and phlogopite rocks and forsterite calciphyres grading into dolomites. The presence of S and Cl in the host carbonate rocks facilitated lazurite formation (Table 2) by bimetasomatic reactions with the participation of high-alkali hydrothermal solutions [32].

Blue to almost colorless lazurite was found in the same region of Tajikistan in 1983 by Levitskii [27] at contact between leucocratic biotite granites and dolomitic marbles (Table 2). The lazurite occurs as pockets, dashed dissemination or veinlets in altered granites and amphibole or phlogopite-bearing diopside skarns.

The largest reserves of high-quality lazurite were found in nine productive zones of the Sar-e-Sang deposit. Other nearby occurrences of this mineral are also at Chelemek, Derevo Balo, Duk, Sahi, and others [10, 29, 31, 33, 34]. All of them are localized at the contact of leucocratic and biotite granites with dolomites, which are transformed into diopside skarns and occasionally contain feldspar, or are hosted in diopside- and forsterite-bearing calciphyres, often containing tremolite. The lazurite occurs both around granite and pegmatite bodies and in the diopside metasomatites and calciphyres (Fig. 7) [31].

Intrusive bodies are typically rimmed by plagioclase–diopside rims, which grade into lazurite-bearing rock with disseminated sodalite, hauyne, afghanite, and pyrite. With an increase in the lazurite content, the rock acquires a bright or dark blue color, whereas the pres-

Table 1. Composition (wt %) of lazurite from deposits in the Baikal area

Component	1	2	3*	4	5	6	7	8	9	10*	11*
SiO ₂	31.17	31.83	35.10	32.10	32.30	32.98	33.70	31.84	31.96	33.91	34.24
TiO ₂	–	–	0.00	–	–	tr.	0.03	–	–	0.00	0.00
Fe ₂ O ₃	0.04	0.02	0.00	0.05	–	–	–	0.05	0.05	0.01	0.02
Al ₂ O ₃	26.98	28.06	25.44	27.29	27.38	28.20	27.40	27.41	26.99	25.36	24.74
MgO	0.26	0.04	0.01	0.19	0.11	0.00	0.40	0.14	0.23	0.00	0.02
CaO	9.24	9.14	7.29	6.65	8.21	7.99	7.43	6.01	5.88	6.68	6.36
Na ₂ O	17.18	16.85	17.64	17.07	18.03	14.80	16.14	18.40	18.32	17.53	17.75
K ₂ O	0.00	0.32	0.32	0.20	0.35	0.90	0.95	0.51	0.31	0.23	0.68
CO ₂	1.03	–	–	1.11	–	1.10	1.29	1.50	1.49	–	–
H ₂ O	1.56	–	–	3.02	–	1.72	1.09	2.14	2.92	–	–
SO ₃	13.08	13.04	14.92	10.97	12.62	11.40	10.05	11.41	10.30	16.18	16.59
Cl	0.20	0.18	0.36	0.41	0.31	0.22	0.24	0.20	0.28	0.14	0.11
F	0.10	–	–	–	–	0.03	0.05	–	–	–	–
S	–	0.06	–	1.48	0.44	1.24	2.60	1.70	1.77	–	–
Σ	100.77	99.56	101.07	99.71	99.75	100.12	100.14	100.49	99.56	100.03	100.49

Note: Slyudyanka deposit: (1) cubic, SrO = 0.03% [8], (2) triclinic, SrO = 0.01% [7], (3*) cubic, Sample BC-04; Tultui deposit: (4) cubic [8]; Malaya Bystritsa deposit: (5–7) cubic (SrO = 0.19 in (6), SrO = 0.13 and BaO = 0.01% in (7) [8]), (8) triclinic, blue, and (9) triclinic, light green (in (8) SrO = 0.08% [8]), (10*) and (11*) cubic: sample MB-024 and MB-027.

*Minerals were analyzed by V. G. Senin in the Central Analytical Laboratory at the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences.

Table 2. Composition (wt %) of lazurite from deposits in Russia and Tajikistan

Component	1*	2*	3*	4*	5	6*	7*	8	9	10	11
SiO ₂	35.61	35.03	36.60	35.84	32.10	33.73	32.58	33.70	33.36	32.6	33.12
TiO ₂	–	–	–	–	–	0.06	0.18	–	–	–	–
Fe ₂ O ₃	0.01	0.02	0.03	0.00	–	0.00	0.01	–	–	–	–
Al ₂ O ₃	27.77	29.96	26.70	26.79	27.39	26.11	25.10	28.31	26.89	24.9	28.52
MgO	0.00	0.00	0.00	0.00	0.00	0.05	0.04	–	–	0.00	–
CaO	7.15	6.09	12.13	12.13	6.45	7.83	7.39	6.78	6.55	7.3	6.47
Na ₂ O	15.92	16.69	13.28	13.20	18.44	15.88	17.39	18.42	18.10	17.6	18.60
K ₂ O	1.04	0.16	0.56	0.56	0.02	0.32	0.15	0.38	0.33	0.47	0.37
SO ₃	10.42	10.76	10.47	10.87	17.97	6.97	7.82	13.12	13.16	12.9	12.60
Cl	0.36	0.37	0.33	0.30	0.48	0.25	0.19	0.30	0.30	0.21	0.34
F	0.07	0.00	0.02	0.00	–	–	–	–	–	–	–
Σ	98.35	96.08	100.12	99.68	100.85	91.20	90.84	101.01	98.69	95.98	100.02

Note: Slyudyanka deposits: (1*) sample BC-38-6, (2*) sample BC-32-12, Tultui deposit: (3*) Sample BT-011, (4*) Sample BT-015, (5) Ermoskhin–Sar'dag deposit, Eastern Sayan [23], Lyadzhvardara deposit, Tajikistan, (6*) sample PL-07, (7*) sample PL-012 with fassaite, (8) isotropic lazurite [27], (9) anisotropic [27], (10) [33], (11) Ishkashim Mt., Tajikistan [28].

*Our data.

ence of hauyne imparts a greenish color. The lazurite-bearing rocks subsequently grade into phlogopite–diopside, phlogopite and forsterite calciphyre zones, which give way to dolomitic marbles.

The most productive rocks are high-quality lazurite rocks (lapis lazuli) with 25–40 vol % lazurite in diopside skarns, calciphyres, and marbles. Their lens-shaped lodes are hosted in orthoclase–microcline–perthite hornfels containing albite and quartz. The lazurite bodies at the Sar-e-Sang deposit are associated with diopside metasomatites bearing nepheline, pale blue hauyne, and blue lazurite

The lazurite rocks of the deposit contain up to 40–90 vol % lazurite. The rocks also contain diopside, hauyne, afghanite, and nepheline, as well as disseminated pyrite replaced by pyrrhotite. Pockets of lapis lazuli are up to 30–40 cm across, occasionally more than 1 m. They vary from pale blue to dark blue with a violet tint in monomineralic aggregates. Like the marbles, the diopside–forsterite calciphyres with a variable (up to 30%) amount of phlogopite, and subordinate sodalite and hauyne, contain no lazurite.

Another type of lazurite rocks in the Hindu Kush promising as a prospecting target for lazurite is calcite–diopside sheets in the calciphyre and marble sequences away from contacts of aluminosilicate rocks [31]. The zones prospected for lazurite consist of calcite, diopside, and lazurite and are located between calcite–diopside metasomatites containing albite and microcline and calciphyres with diopside, phlogopite, and forsterite (Fig. 7).

Such lazurite bodies at the Sar-e-Sang deposits are from 0.7–1 to 6 m thick and more and up to 70–450 m long [30]. The lazurite has a zoned color from blue or

violet-blue in the central part to blue-pale blue at the periphery. The nearby calciphyres are made up of 50–80 vol % carbonates, 5–20% diopside, up to 15% phlogopite, and up to 10% forsterite, as well as rare lazurite and sodalite. The color of the lazurite rocks becomes more intense around disseminated iron sulfides.

Occasional lazurite finds in diopside rocks among Precambrian marbles are known (Table 3) in Thabolin near Mogok, Burma [26], but this information is scarce. Poorly studied abyssal occurrences of lazurite rocks are known in Iran [10], India, Tibet, South Africa, and Angola [7, 10]. All of them are confined to bimetasomatically altered dolomites hosted in gneissic or other aluminosilicate rocks.

Abyssal lazurite deposits were also found in North America. They occur near Harbour Lake, Baffin Island in Canada (Table 3) [7, 9, 35, 36]. According to Hoggarth, the Main and Northern bodies of diopside–lazurite rocks of variable quality are localized in marbles among biotite gneisses. The Main (Southern) occurrence is as long as 170 m and 6 m thick.

At these deposits, sheets of high-quality lazurite rocks (up to 1 m thick) contain variable amounts of relict diopside and plagioclase, as well as newly formed hauyne, nepheline, or phlogopite. The quantitative proportions of these minerals define the color of the rocks, which becomes more intense with heating. The Northern occurrence (25 × 36 m in size) is less productive than the Main occurrence and consists of small (no more than 1 m) lenses with disseminated lazurite, which imparts a bluish green color to the polished surface of the rock. Chlorine and sulfur for lazurites, accessory pyrite, and pyrrhotite were presumably

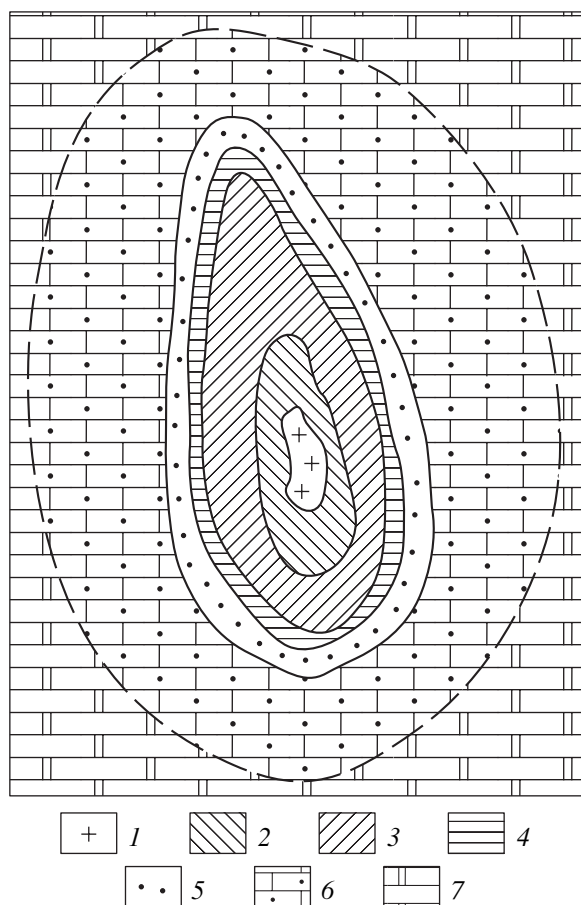


Fig. 6. Structure of the lazurite body at the Lyadzhvardara deposit (after Khoreva [25]). (1) Aplite, (2) desilicified aplite replaced by diopside, (3) diopside-lazurite zone, (4) calcite-diopside zone, (5) phlogopite rim, (6) zone of forsterite calciphyre, (7) dolomitic marble.

derived from metamorphosed Phanerozoic gypsum-, anhydrite-, and saliferous carbonate rocks [9].

Hogarth noted that lazurite rocks from Baffin Island are mainly grayish blue in color, with less common indigo blue rocks in the Main body and the occasional sky blue varieties in the Northern body. Lazurites from abyssal deposits in the Baikal area, Tajikistan, and Afghanistan are predominantly blue and dark blue [36].

Lazurite is also known from the Edwards mine, New York in the United States [37–39], where it composes the central parts of a zoned body in Grenvillian marbles containing small pegmatite bodies at talc and lead deposits. A lens of blue cubic lazurite (hauyne, $N = 1.153 \pm 0.002$) from 2 to 5 ft in size is subsequently fringed by actinolitized diopside with pyrite, phlogopite [37], and sphalerite. The lazurite has the following chemical composition (in wt %): 0.36 K_2O , 10.6 CaO , 1.8 Na_2O , 0.36 Cl , and 10.7 S . According to Hogarth [40], lazurite at the Edwards deposit is associated with diopside, oligoclase, and pargasite. Afghanite rimming forsterite is not associated with lazurite.

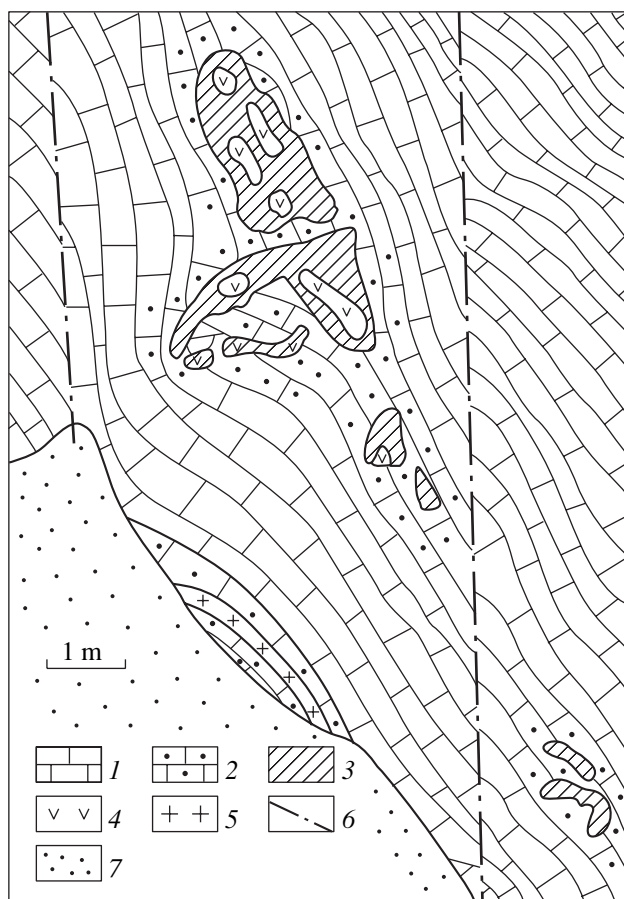


Fig. 7. Geological scheme of a lazurite body at the Sar-e-Sang deposit [31]. (1) Podiform pegmatite body, (2) diopside skarns, (3) diopside-phlogopite calciphyres with forsterite, (4) dolomitic marbles, (5) lazuritization zone, (6) tectonic dislocations, (7) diluvium.

The aforementioned lazurite deposits are ubiquitously confined to Precambrian granulites and amphibolites. They were subsequently formed by the prograde skarn process, ultrametamorphism, and retrograde alkaline, mainly Na bimetasomatic alteration of spatially associated but chemically unequilibrated carbonate and aluminosilicate rocks.

Magnesian-skarn aureoles in the abyssal lazurite deposits show a primitive structure, which is expressed in the inheritance of $Ca/Mg \sim 1 : 1$ from the replaced dolomites. This ratio is observed in the zones of diopside skarn and nearby forsterite (\pm spinel) calciphyre [3]. Only the Chernushka deposit contains an additional zone of periclase marble after dolomite [3], which is restricted to local decompression zones but retains the Ca/Mg ratio of initial dolomites.

Deposits of lazurite rocks provide the color-stone industry with gem and cut stone. These deposits also supply material of unique color for the pant-and-varnish industry. The study of lazurite deposits of various geneses is of special interest in the light of probable

Table 3. Composition (wt %) of lazurite from deposits in Afghanistan, Burma, and Canada

Component	1	2	3 *	4 *	5	6	7	8	9	10	11
SiO ₂	32.52	31.34	35.99	36.49	33.7	34.5	36.37	32.7	33.9	33.06	33.46
TiO ₂	–	–	–	–	0.01	0.00	0.05	0.00	0.00	0.02	0.03
Fe ₂ O ₃	–	0.27	0.00	0.01	0.00	0.00	–	–	–	–	–
Al ₂ O ₃	27.61	26.27	26.45	26.68	26.3	27.9	24.22	26.6	27.3	27.84	27.51
MgO	–	2.47	–	–	0.00	0.00	0.39	0.01	0.00	0.17	0.09
CaO	6.47	7.97	5.12	4.97	4.7	4.4	5.06	7.7	4.6	7.18	8.05
Na ₂ O	19.45	15.75	18.39	18.08	19.2	20.3	18.81	17.5	19.2	17.61	16.35
K ₂ O	0.28	1.02	–	–	0.21	0.00	0.97	0.01	0.00	0.16	0.22
Co ₂	–	–	–	–	–	–	1.70	–	–	0.10	0.20
H ₂ O ⁺	–	–	–	–	–	–	1.90	–	–	1.26	2.07
H ₂ O [–]	–	3.87	–	–	–	–	0.25	–	–	0.24	0.36
SO ₃	10.46	8.71	10.86	11.31	10.44	10.38	7.31	12.53	9.67	11.06	10.67
Cl	0.47	0.78	0.75	0.99	0.53	0.19	1.19	0.19	0.21	0.37	0.30
S	2.71	1.84	–	–	0.26	0.53	1.18	0.75	1.97	0.77	0.41
Σ	99.57	100.29	97.55	98.53	95.35	98.20	99.40	97.99	96.88	99.84	99.72

Note: Sar-e-Sang deposit, Afghanistan: (1) [38], (2) [39], (3* and 4*) same, sample AC-04 and Ac-08; (5 and 6) Magok, Burma [36]; Lake Harbour, Baffin Island, Canada [36]; (7–9) Main Occurrence, (10 and 11) Northern Occurrence.

new finds of these stones. These are metasomatic deposits at contacts between dolomites and alkaline hypabyssal intrusions. The rare finds of authigenic lazurite represents another genetic type, which is, however, only of purely mineralogical interest.

HYPABYSSAL LAZURITE OCCURRENCES

Hypabyssal lazurite occurrences are characterized by the development of mineral assemblages containing abyssophobic minerals, which reflect the lower pressure and significant temperature variations of skarn formation during the prograde stage of dolomite metasomatism.

It was previously noted that, even at Precambrian lazurite deposits, the deformation-related local decompression during development of wall-rock magnesian skarns after Paleozoic dolomites [3] could produce periclase marbles along the periphery of the skarn bodies. This is observed at the Chernushka deposit in the southwestern Baikal area, whereas other lazurite deposits in this region belong to the abyssal metasomatic facies.

The other hypabyssal occurrence is the magnesian skarns after Paleozoic dolomites at the contact with the Zardalek multiple alkaline massif. It is located in the northern part of the High Foothills of the Turkestan–Alai Mountain system in southern Kyrgyzstan.

According to Il'inskii [14], the massif is made up of gabbro–monzonites and predominant syenites, with rims and vein-shaped bodies of nepheline syenites at contacts with skarns. This rock series of diverse SiO₂ and alkalinity shows a decrease in plagioclase, pyrox-

ene, amphibole, and biotite amounts at an increase in the contents of K–Na-feldspar and nepheline (up to 60 vol %) or sodalite (up to 12%) and cancrinite (up to 16%). In addition, the magmatic rocks in the contact zone contain xenoliths of skarnized carbonate rocks with cancrinite and vishnevite.

The magnesian skarns in the host dolomites consist of a spinel–diopside zone, forsterite-bearing skarns, and calciphyres. The early metasomatic zoning in the outer contact was overprinted by wollastonite–, clinzoisite–, garnet–, chrysolite–, and phlogopite–pyroxene assemblages and magnetite during postmagmatic processes. Lazurite occurrences were found in the carbonate rocks near the southern contact of the massif [14]. Indigo blue equant grains of this mineral and pyrite are scattered throughout a carbonate matrix. It should be noted that the magnesian skarns of this region contain vesuvianite and even monticellite and melilite, which are typomorphic abyssophobic minerals of hypabyssal metasomatites [3].

In Europe, hauyne and lazurite are known to occur in alkaline rocks in France and Germany, as well as in metasomatically altered dolomitic xenoliths enclosed in the volcanogenic tuff–lava sequences of Vesuvius and Albani Hills, Lazio in Italy [6, 7, 15, 41]. Dolomites that host the magmatic chambers of these volcanoes experienced an intense skarn process and were entrapped by lava flows during eruptions.

The early associations involve magnesian–skarn metasomatites with high-temperature, abyssophobic assemblages (fassaite, forsterite, monticellite, melilite, and periclase) [3, 15, 41]. This indicates that lazurite could be formed during dolomite alteration at shallow

Table 4. Composition (wt %) of lazurite from hypabyssal deposits and afghanite

Component	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	33.85	34.7	31.7	32.9	34.1	33.4	31.95	30.8	32.10	31.8	32.96
TiO ₂	0.00	0.01	0.01	0.00	0.00	0.00	–	–	–	–	–
Al ₂ O ₃	25.8	24.0	26.4	26.3	28.3	28.7	26.58	25.0	27.00	25.2	25.45
MgO	0.06	0.83	0.06	0.00	0.00	0.00	–	–	–	–	–
FeO	0.00	0.03	0.00	0.01	0.01	–	–	–	–	0.03	–
CaO	8.6	8.9	8.2	4.65	7.3	5.7	11.66	16.5	12.34	11.7	11.98
Na ₂ O	11.45	14.2	16.2	19.15	18.4	18.6	13.26	12.6	12.43	13.3	12.52
K ₂ O	5.75	3.6	0.32	0.13	0.11	0.16	2.60	2.7	0.86	2.2	3.07
CO ₂	–	–	–	–	–	–	–	0.04	0.76	–	–
H ₂ O	–	–	–	–	–	–	–	0.7	2.11	–	–
SO ₃	11.73	13.3	12.14	10.80	11.98	9.69	10.99	8.5	9.21	10.5	10.82
Cl	0.08	0.27	0.14	0.03	0.07	0.08	4.35	4.6	4.54	3.6	3.98
F	–	–	–	–	–	–	0.04	–	–	–	0.04
S	0.67	0.00	1.95	2.20	1.45	3.59	–	–	0.23	–	–
Σ	97.99	99.84	97.12	96.17	101.72	97.99	101.43	101.8	100.46	98.33	100.78

Note: Lazurite: (1) Ariztia, Albani Hills, Italy [36]; (2) Monte Somma, Vesuvius, Italy [36]; (3) Italian Mountain, Colorado, United States [36]; (4 and 5) Cascade Canyon, California, United States [36]; (6) Ovalle, Chile [36]. Afghanite: (7 and 8) Sara-e-Sang, Afghanistan [40, 44], (9) Tultui, southwestern Baikal area [8], (10) Lyadzhvardara, Tajikistan [40], (11) Edwards, New York, United States [40].

depths. The postmagmatic stage is marked by the formation of phlogopite, humite, and endogenous borates (ludwigite, fluorborite, and others). The subsequent calc-skarn transformations were responsible for the formation of vesuvianite and garnet, as well as hauyne, lazurite, nepheline, and other minerals. The composition of lazurite from Lazio and Vesuvius (Table 4) is reported in [36, 41].

At the territory of the United States, hypabyssal lazurite mineralization was found in Colorado and California. In the Italian Mountain, Gunnison county, Colorado [11, 36, 42], it is localized within a contact alteration zone of dolomites cut by melanogranodiorites, quartz monzonites, and diorites. The near-contact metasomatites are diopside–vesuvianite–garnet rocks, which can be regarded as formed by the calc-skarn replacement of hypabyssal magnesian skarns. Optically isotropic grains and crystals of lazurite (Table 4) replaced by tompsonite are scattered in diopside–forsterite calciphyre bearing Ba phlogopite. The sulfides are pyrite, pyrrhotite, and sphalerite.

In the North Italian Mountain, high-quality dark blue lazurite was found only in lode A (Anderson Prospect), while sky blue to pale blue and light colored lazurites were found in lodes B and C (Christopher Prospect). At Italian Mount, 1.5 km south of the Anderson lode, bands of high-quality lazurite of constant composition (2.5 cm wide and 30 m long) were found in lodes U, M, and L (Table 4). According to Hogarth and Griffin [11], lazurite in Colorado was formed at 600°C and 250 bar, i.e., in hypabyssal environments.

Two lazurite occurrences are known in California: Cascade Canyon in the San Bernardino County [12] and the Big Horn deposit (the largest in the United States) in the vicinity of Los Angeles, San Gabriel Mountains [13]. In the former, lazurite occurs as thin beds in a diopside rock, which occasionally contains calcite, colorless phlogopite, and small pyrite crystals. The blue lazurite is isotropic ($N = 1.503 \pm 0.003$) (Table 4) [35], whereas its light greenish varieties have insignificant birefringence.

High-quality intensely colored lazurite with dissemination of goldish pyrite is mined at the Bighorn deposit [13]. The lazurite does not contain calcite and is comparable with Afghan lazurite in quality. However, no data are available on its petrology and composition.

The largest Chilean deposit is located in the Andes, at the border with Argentina [7, 10]. The geology of this region is poorly studied. Lazurite bodies are localized in marbles, which are underlain by schists and overlain by magnetite–garnet rocks. The Chilean lazurites are light blue and greenish blue, with the subordinate development of blue and bright blue varieties. The composition of dark blue lazurite (Table 4) from the Caren occurrence at the Cazadero River, a tributary of the Rio Grande (Department of Ovalle, Chile) was studied by Hogarth and Griffin [36]. The mineral was found in altered marbles in association with wollastonite and scapolite, suggesting its formation under wollastonite-facies conditions.

The above data indicate that lazurite can be formed in a wide range of the physicochemical parameters of metasomatic alteration of S- and Cl-bearing dolomitic

rocks in contact with aluminosilicate rocks and under the effect of alkaline magmas. The presence of its economic contents at abyssal (Baikal area in Russia, Pamirs in Tajikistan, Hindu Kush in Afghanistan, Baffin Island in Canada, and Andes in Chile) and hypabyssal (Bighorn and other deposits in the United States) deposits, as well as its finds in Italian skarns confirm this fact.

An interesting genetic fact is the presence of lazurite in sedimentary sequences. Authigenic lazurite was found in halite-bearing saliferous sequences with thin trona intercalations in Sweetwater County, Wyoming [43]. The detrital minerals were pyroxene (acmite), hornblende, quartz, and feldspar. Lazurite was found as scattered small isotropic cubic crystals ($N = 1.515$) of a bright blue color in aggregates of talc, chlorite, and smectite-group minerals, which are typical of the sequence of Green River Formation. The rocks also contained pyrite. The authors argue that these rocks are of evaporite origin and were formed by interaction between brines and silicates contained in the saliferous sequence [43].

COMPOSITION OF LAZURITE

The presence of Cl^- , OH^- , SO_4^{2-} and S^{2-} ions significantly complicates the calculation of the chemical formula of lazurite, since microprobe analysis does not determine the hydroxyl ion and the sulfate and sulfide ions are measured as total S. The content of sulfate S varies from 6 to 13 wt %, while that of sulfide S, from 0 to 2.6–3.5 wt %. Isomorphic substitution between these ions in combination with conjugate variations in SiO_2 , Al_2O_3 , CaO , and Na_2O causes differences in the interpretation of its chemical composition (Tables 1–4).

The works of Belov [4] and Platonov [5] showed that lazurites ubiquitously contain sulfide S, which determine the color of the mineral and its intensity. The photoluminescence of such framework silicates as lazurite and afghanite showed that the absorption bands of molecular ion radicals (S^{2-}) representing paramagnetic centers at ~400 nm cause the appearance of a yellow color, the appearance of bands at 400 and 600 nm related to the presence of S^{2-} and S^{3-} is correlated with the appearance of a green color, while the presence of S^{3-} associated with a band at 600 nm produces a blue color [5]. The same radical ions of sulfide S determine the color of heated afghanite.

The generalization of our and literature data on lazurite composition shows that the mineral typically has a light blue and blue, occasionally spotty color. This is mainly related to the presence of the S^{3-} ion. The existence of combined modes of sulfide sulfur led to the appearance of a green color.

In spite of facies differences, lazurites from abyssal and hypabyssal deposits (Tables 1–4) are generally similar, including the ratio of their sulfate to sulfide S.

The maximum amounts of the latter (up to 3.5 wt %) are typical of bright blue varieties. It was noted that heating causes the partial transition of sulfate S to the sulfide mode.

CANCRINITE-SERIES MINERALS IN LAZURITE ROCKS

The lazurite deposits considered above are abundant in syngenetic feldspathoids of the sodalite and cancrinite groups [8, 44–48]. The latter are typically afghanite $(\text{Na,Ca,K})_8(\text{Si,Al})_{12}\text{O}_{24}(\text{SO}_4,\text{Cl},\text{CO}_3)_3 \cdot \text{H}_2\text{O}$ (Table 4), which was described at the Sar-e-Sang deposit in Afghanistan [44], Tultui, Pokhabinsk, and Malaya Bystritsa deposits in the southwestern Baikal area [8, 16, 45–48], at the Lyadzhvardara deposit in the Pamirs, the Edwards Mine in the United State [40], and at Lazio province [15] and Vesuvius Volcano (Monte Somma) [41]. Afghanite composes zones in the diopside- and calcite-bearing rocks of the Malaya Bystritsa deposit, pervasively replaces lazurite, and has a bluish green or pale blue color. Lazurite relics are preserved in diopside crystals. In the forsterite calciphyres of the Tultui occurrence, afghanite and lazurite show no reaction relations, but the former mineral is locally replaced by phlogopite, zeolites, or calcite [16, 45].

The minerals newly found in association with lazurite are bystrite and tounkite (Table 5), which are known only at deposits in the western Baikal area [8, 16]. Bystrite, $\text{Ca}(\text{Na,K})_7(\text{Si}_6\text{Al}_6\text{O}_{24})(\text{S}_3^{2-})_{1.5} \cdot \text{H}_2\text{O}$ [15], is a trigonal mineral, which forms platy hexagonal yellow crystals and occurs in two generations in association with diopside, lazurite, and calcite [7, 8, 46].

Tounkite $(\text{Na,Ca,K})_8[\text{Al}_6\text{Si}_6\text{O}_{24}](\text{SO}_4)_2\text{Cl} \cdot \text{H}_2\text{O}$ was found in diopside-lazurite rocks at the Malaya Bystritsa and Tultui deposits. It is associated with diopside, apatite, pyrite, and calcite, being replaced by phlogopite [7, 8, 47, 48]. According to [48], its ordered and disordered modifications are similar in composition, except for differences in K and Cl contents: 0.62 and 6.46 wt % K_2O , and 4.05 and 2.90 wt % Cl, respectively.

The aforementioned data on feldspathoids of the sodalite and cancrinite groups in lazurite rocks of the Baikal area (Table 5) point to their close geochemical relation, which is expressed in their similar composition, crystal structure, and formation sequence [48]. It was shown [8, 46–48] that lazurite is replaced by either bystrite or tounkite, but these minerals are not associated with each other. Lazurite rocks also contain nepheline (Table 5).

Lazurite universally occurs at contacts with pyroxene skarns. Diopsides at the Canadian deposits (Table 6) are low-Fe to high-Mg varieties with low Al_2O_3 contents (up to 2–5 wt %) [9].

The sulfur isotope composition of carbonate and lazurite-bearing rocks at deposits of the Baikal area, Pamirs, and Hindu Kush [22, 32] indicates that the

Table 5. Composition (wt %) of feldspathoids and lazurite-bearing rocks

Component	1	2	3	4	5*	6	7*	8*	9*	10	11
SiO ₂	33.37	30.71	36.74	37.62	33.94	37.6	46.47	45.08	43.51	42.9	43.1
TiO ₂	–	–	–	0.17	–	–	–	–	–	–	–
Al ₂ O ₃	26.76	25.43	31.96	29.07	28.51	30.5	32.43	33.55	32.41	34.3	34.35
MgO	–	–	–	0.23	0.01	0.00	0.01	0.01	0.00	0.01	0.01
FeO	–	–	–	–	–	–	0.01	0.00	0.02	–	–
CaO	5.10	10.82	0.11	1.58	0.05	0.11	0.92	1.47	1.21	1.33	0.74
Na ₂ O	14.42	10.25	25.95	25.27	23.90	24.6	15.75	15.63	15.65	17.2	15.5
K ₂ O	7.63	6.46	–	0.84	0.02	0.00	4.58	5.23	5.56	4.0	6.05
CO ₂	0.32	0.00	–	–	–	–	–	–	–	–	–
H ₂ O	1.62	0.77	–	–	–	–	–	–	–	–	–
SO ₃	0.50	13.28	0.00	0.00	–	0.53	0.03	0.13	0.00	0.00	0.00
Cl	0.25	2.90	7.11	4.03	8.04	5.9	0.01	0.01	0.01	0.00	0.00
F	–	–	–	0.08	0.01	0.00	0.02	0.00	0.00	–	–
S	12.03	–	–	0.03	0.10	0.00	–	–	–	–	–
Σ	99.92	99.96	100.04	99.95	94.61	99.24	100.23	101.10	98.36	99.74	99.75

Note: Bystrite: (1) Malaya Bystritsa deposit [16]. Tounkite: (2) Tultui deposit [16]. Sodalite: (3) Slyudyanka deposit [8], (4) Malyi Bystryi deposit [8], (5*) Tultui deposit, sample BT-262, Baikal area, (6) Baffin Island, Canada [9]. Nepheline: (7* and 8*) Slyudyanka deposit, Sample BC-038, (9*) Tultui deposit, Sample BT-0262, Baikal area; (10 and 11) Baffin Island, Canada [9].

Table 6. Composition (wt %) of pyroxenes in the lazurite rocks

Component	1*	2*	3*	4*	5*	6*	7*	8*	9	10	11
SiO ₂	53.87	53.61	54.83	54.17	55.20	53.90	54.25	52.58	55.0	54.9	53.4
TiO ₂	–	–	–	–	–	0.00	0.00	–	0.22	0.56	0.61
Al ₂ O ₃	0.26	0.57	0.93	1.35	1.25	1.80	2.32	3.72	2.9	2.5	5.3
MgO	18.67	18.51	19.23	19.57	17.91	17.99	17.45	18.84	17.0	17.2	15.9
FeO	1.10	1.46	0.41	0.11	0.53	0.12	0.08	0.00	0.12	0.10	0.19
CaO	24.41	23.48	23.37	25.13	25.05	24.76	25.15	22.91	23.7	23.6	23.8
Na ₂ O	0.17	0.29	0.57	0.11	0.36	0.41	0.39	1.91	1.3	1.2	1.4
K ₂ O	0.02	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00
SO ₃	–	–	–	–	–	–	–	–	0.07	0.00	0.02
Cl	0.02	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00
F	0.00	0.00	0.16	0.00	–	–	–	–	–	–	–
S	0.01	0.03	0.02	0.01	0.01	0.00	0.00	0.01	–	–	–
Σ	98.54	97.97	99.52	100.68	100.35	98.98	99.68	99.31	100.12	100.06	100.62

Note: Diopside: (1*) Slyudyanka deposit, sample BC-038, (2*–4*) Tultui, sample BT-0262, (5*) Malaya Bystritsa, sample MB-024. Al-bearing diopside: (6* and 7*) Lyadzhvardara, Tajikistan, sample PL-07, (8*) Sar-e-Sang, Afghanistan, sample AC-04, (9–11) Baffin Island, Canada [9].

lazurite incorporated sulfate S (gypsum, anhydrite) from the host rocks. The modes of sulfur occurrence varied during the metasomatic alterations: minerals of the sodalite and cancrinite groups contain the sulfate

ion, whereas lazurite contains both sulfate and sulfide sulfur, and bystrite possesses only the sulfide ion. The presence of sulfide S is inferred for afghanite [5]. The feldspathoids were formed under the effect of H₂S. This

caused the syngenetic and later precipitation of pyrite and its later replacement by pyrrhotite. The studies [22, 32] showed that elementary S found in the marbles and lazurite rocks is of exogenic origin.

CONCLUSIONS

Our data and their correlation with literature information showed that lazurite rocks and their deposits everywhere postdate the magnesian-skarn alteration of the dolomitic carbonate rocks. This is evident from their bimetasomatic alteration during ultrametamorphism, which also affected interbeds of granite gneisses and their boudined blocks, or from the metasomatic alteration of dolomites at contacts with an intrusion of granitoid or more mafic composition and lavas of increasing alkalinity.

The metasomatic zoning of exoskarms is characterized by a primitive structure, being represented by diopside skarn and nearby forsterite calciphyre grading into dolomites. In zones of decompression under hypabyssal conditions, it is complicated by the development of an outer aureole of periclase marbles or by the presence of high-temperature abyssophobic minerals (monticellite, melilite, and others) in skarns, depending on the T - P conditions of the prograde metasomatism of dolomites.

Lazurite and its host rocks are polygenetic, forming both abyssal and hypabyssal, including subsurface, deposits and occurrences. Lazurite can even be authigenic.

Lazurite deposits of the abyssal facies are associated with saliferous sequences of sedimentary dolomites, bearing haloids, sulfates, and phosphates. The latter include apatite, which is present in the rocks of the Baikal area. This is less typical of contact-metasomatic lazurite occurrences, at which S and Cl needed for lazurite formation were supplied by postmagmatic alkaline solutions and gases.

Lazurite deposits ubiquitously contain no early Fe-bearing minerals, and the skarns and metasomatites contain their high-Mg varieties. These are pyroxenes (mainly diopside), forsterite, amphiboles, phlogopite, and carbonates. The lazurite-bearing rocks contain genetically close feldspathoids of the sodalite and cancrinite groups, as well as afghanite, tounkite, bystrite, and late zeolites. The presence of these minerals in lapis lazuli, together with other minerals, changes the color of the lazurite rocks, which is widely used in the stone-cutting and jewelry industry. Iron sulfides ubiquitously developed in lapis lazuli only during final stages. Disseminated pyrite imparts an unusual appearance to the Afghanian lazurite rocks, which is termed in the stone-cutting production as the "Badakhshan night."

In conclusion it should be noted that magnesian-skarn deposits are unique sources of semiprecious stones. Noble spinel, sapphire, ruby, serendibite, sinha-

lite, and other gem and semi precious stones, including ornamental high-quality calciphyres, nephrites, and brucites have been known since ancient times and were also formed by metasomatic alteration of dolomites.

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