

Article

Composition and Genesis of Dark Dolomite-Type Nephrite in the Kavokta Deposit, Middle Vitim Mountain Country, Russia

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Abstract

The Kavokta deposit in Russia contains gray and black dolomite-type nephrite, which is in high demand commercially. Although the fact that black nephrite has been found in several deposits, the reasons for its color are not well understood. The present study aims to identify the localization and mineral composition of gray and black nephrite, and to determine the reasons for its dark coloration. The mineral composition of nephrite was studied using a scanning electron microscope with energy-dispersive microanalysis (SEM-EDX) and X-ray phase analysis. Also, the isotopic composition of carbon in graphite in nephrite and in carbonates associated with nephrite in the surrounding strata was determined. The gray–black color in most samples from the southeastern part of the Kavokta deposit (lodes 17 and 28 of the nephrite-bearing zone 4 of the Medvezhy section and lode 6-1 of the nephrite-bearing zone 6 of the Levoberezhny section) is due to the presence of graphite. Syngenetic graphite formed both by the organic matter buried in dolomites and by the decomposition of carbon dioxide that is released during decarbonation under the influence of deep-seated hydrogen. The color of nephrite also depends on the iron content, changing from white to light green as the iron content increases. The gray color of tremolite–diopside nephrite is due to the development of chlorite aggregates that replace diopside and/or tremolite. The gray-green to black color of the nephrite in the northwestern part of the Kavokta deposit (lode 1 of the nephrite-bearing zone 1 of the Prozhachny section) is due to the high iron content in the tremolite–actinolite at the contact with the epidote–tremolite skarn formed after amphibolite. The identified patterns of black nephrite localization can be used in the process of geological exploration of similar deposits elsewhere in Russia and abroad.

Keywords: dolomite type nephrite; metasomatism; Kavokta deposit; black color; tremolite; actinolite; diopside; graphite; chlorite



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1. Introduction

Nephrite is a highly marketable semi-gem stone, a dense amphibole aggregate of the tremolite–ferroactinolite series, predominantly tremolite, with a distinctive tangled fibrous structure [1,2]. It is extremely valued in China, New Zealand, and on the Pacific coast of North America. Nephrite deposits are divided into two endogenous geological-industrial types. The first type is serpentinite type (S-type) in ophiolites. The second type is dolomite type (D-type) in tremolite–calcite magnesian skarns. The exogenous geological-industrial type is represented by placers, of which alluvial ones are the most productive [1,2].

As of 1 January 2024, Russia's State Reserves include 27 nephrite deposits [3]. The distributed reserves include 21 deposits. In 2023, six deposits were mined: Golyube, Kavokta (lodes 16, 18, 19–20, and 28 of Medvezhy (Bear) section, lodes 1 and 9 of Prozrachnyi (Transparent) section, Nizhne-Ollomi, Khayta (lodes 2, 5, 8, 8a, and 8b) of D-type nephrite, Ospa (lode 7), and Khamarkhudui of S-type nephrite, all located in Republic of Buryatia [3].

The color of S-type nephrite is characterized by various shades of green, and less often, brown (tobacco, swamp), and black. The color of D-type nephrite is characterized by a wide range of predominantly light colors, from white and gray to light green (salad), and less commonly brown (honey), and black [1,2]. The most valuable types of nephrite are bright blue-green with minimal chromite inclusions, white, and aglint “cat's eye” [1,2]. Alluvial pebbles and boulders of nephrite are highly valued, especially those with surface staining [4]. Black nephrite is also very popular. In China, it is believed that polished pieces of it resemble black lacquer-ware. It is used to make jewelry and ritual objects [5]. Black nephrite products are advertised as having medicinal or esoteric properties. However, they are often made of graphitized basalt or black shale instead of nephrite.

Traditionally, color of nephrite is determined by Fe content, and a high concentration of FeO makes it black [6–8]. Black D-type nephrite is found in Chinese deposits, such as Alamas [9] and the Karakash River (the river of black nephrite, [10,11]) in Hetian County in the nephrite-bearing area of the same name, and the Margou deposit in Qiemo (Cherchen) County in the Altyn Tagh nephrite-bearing area [12] in the Xinjiang Uyghur Autonomous Region; Sangpiyu in Liaoning Province [13]; and Dahua in Guangxi Zhuang Autonomous Region [5]. Grayish-purple nephrite has been found at the Sanchahe deposit in Qinghai Province [14]. Black D-type nephrite is known from the Cowell deposits in South Australia [15] and the Alpe Mastabia (Val Malenco) deposits in Lombardy, northern Italy [16]. Recently, there has been information about black nephrite in Somaliland [17].

The black color of nephrite at the Karakash River placer is caused, in some cases, by the predominance of actinolite with a high FeO content (2.90–4.39 wt. %). The black color is caused, in other cases, by graphite flakes up to 2 mm in size in tremolite with a low FeO content (0.31–1.97 wt. %) [10,11]. The black color of the Alamas nephrite is also explained by either graphite aggregates or films on cracks of iron hydroxides formed after pyrrhotite [9]. For the Margou nephrite, black color is defined by an increased Fe content—up to 6.29 wt. % FeO in actinolite [12]. At the Sangpiyu deposit, deep green and dark green nephrite contains abundant oriented graphite inclusions [13]. At the Dahua deposit, black nephrite consists mainly of tangled-fibrous actinolite or ferroactinolite with a high Fe content, 11.67–25.75 wt. % FeO, and a $Mg/(Mg + Fe^{2+})$ ratio of 0.765–0.343 [5]. However, there is also stilpnomelane (up to 25%), andradite (up to 5%), apatite (up to 3%), epidote (up to 5%), quartz (up to 8%), diopside (up to 15%), pyrrhotite, and pyrite (up to 30%) [5], which can also contribute to the coloration. The grayish-purple color of the Sanchahe nephrite is defined by presence of Mn^{2+} , and probably also Cu and Fe, in the tremolite structure [14].

D-type nephrite from the Cowell deposit in South Australia has a yellowish-green, greenish-black, and black color. Light greenish-yellow nephrite contains 0.60 wt. % FeO and 0.05 wt. % Fe_2O_3 , while dark green to black nephrite contains 4.75 wt. % FeO and 2.18 wt. % Fe_2O_3 [15]. At the Alpe Mastabia deposit, the gray to black color of nephrite is the result of uneven distribution of molybdenite and galena [16].

Black S-type nephrite has been found at the Gorlykgol deposit in the East Sayan nephrite-bearing region and the Khamarkhudui deposit in the Dzhida nephrite-bearing region. Its coloration is due to fine-grained graphite, which accounts for 1–3 vol. %, while the graphite content in the host rocks is significantly higher [18]. Black S-type nephrite has only recently become known abroad. It is found in the Kawakawa formation in

New Zealand, ranging from light to dark green, almost black, with small black opaque mineral inclusions [19]. Black nephrite boulders, composed of high-iron ferroactinolite, have been described on the coast of the Salish Sea in the southwestern area of the Canadian province of British Columbia and the northwestern area of the U.S. state of Washington [20]. Black hydrothermal nephrite, similar to the S-type one, has been described at the Sky Zone deposit in Wyoming, USA [21].

Unfortunately, previous works were not able to give reason for the black color of nephrite; they simply state the fact. Even if they point to an increased Fe content or presence of graphite, they do not explain the reason for this phenomenon. Therefore, the present study of the black nephrite problem is important for targeted searches for this valuable type of gemstone. The present study focuses on the newly discovered gray and black D-type nephrite at the Kavokta deposit in the Middle Vitim mountainous region, its possible genesis, and the reasons for its coloration.

2. Materials and Methods

Twelve polished half-core samples were studied. They were obtained by JSC “Trans-baikal Mining Enterprise” in the southeastern and northwestern areas of the Kavokta deposit during geological exploration. Visual petrographic and mineralogical studies were conducted under natural light using photofixation.

The mineral composition was studied using a LEO-1430VP scanning electron microscope (Carl Zeiss, Oberkochen, Germany) with an INCA Energy 350 energy-dispersive microanalysis system (Oxford Instruments, Abingdon, UK) at Multiple-access center “Geospectr” (Geological Institute of the Siberian Branch of the Russian Academy of Sciences (GIN SB RAS), Ulan-Ude, Russia). The research conditions are accelerating voltage of 20 kV, probe current of 0.3–0.4 nA, probe size of <0.1 μm , measurement time of 50 s (“live” time), and an analysis error of up to 2–4 mass. %, depending on the surface quality of the sample and its composition. An interactive software package developed at the GIN SB RAS was used to process the research results. The program implements an original method for identifying mineral phases based on mineral stoichiometry. The program’s output is a research report in the form of an Excel spreadsheet containing concentrations of elements and components, atomic percentages, and formulas calculated based on mineral identification. For a number of minerals (epidote, garnet, magnetite, phlogopite), the content of 2- and 3-valent Fe is calculated using an iterative fit to stoichiometry and a search for the golden ratio.

X-ray diffraction (XRD) analysis was performed on a D8 Advance powder automatic diffractometer (BrukerAXS, Billerica, MA, USA) at the Multiple-access Center of the Baikal Institute of Nature Management of the Siberian Branch of the Russian Academy of Sciences (BINM SB RAS), Ulan-Ude, using the corresponding software with an angle-measuring speed of 2° per minute in the range from 5° to 70°.

Isotopic carbon analysis was performed using a Finnigan MAT 253 gas mass spectrometer (Thermo Fisher Scientific GmbH, Bremen, Germany) at Multiple-access center “Geospectr” (GIN SB PAH, Ulan-Ude). Graphite-containing samples were prepared using the Flash EA 1112 option. The samples were analyzed according to the international standards USGS 40 and USGS 24. The isotopic composition of carbon and oxygen in carbonates was measured by CO_2 in a continuous helium flow mode using the gasbench-mass spectrometer configuration. Decomposition of carbonates was carried out using the classical method in 100% orthophosphoric acid at 70 °C for 2–4 h. International calcite standards NBS-18 and NBS-19 were used for $\delta^{13}\text{C}$ calculation. The error of the obtained $\delta^{13}\text{C}$ values is $(1\sigma) \pm 0.2 \text{ ‰}$.

3. Geology of the Kavokta Deposit

The Kavokta D-type nephrite deposit is located in the Vitim nephrite-bearing region, in the Baunt Evenki district of the Republic of Buryatia. From 1984–1993, the Kavokta deposit with Prozrachnyi (Transparent) and Medvezhy (Bear) sections was explored in the upper reaches of the Kavokta River. The Medvezhy section area is 1.04 square km, coordinates are 55°10'14", 115°01'06"; 55°10'14", 115°01'55"; 55°09'30", 115°01'55"; 55°09'30", 115°01'38"; 55°09'45", 115°01'06". Prozrachnyi section area is 0.68 square km, coordinates are 55°08'19", 115°03'00"; 55°20'14", 115°03'38"; 55°07'59", 115°03'38"; 55°07'35", 115°02'59". Since 2007, the Dylacha family-clan Evenki community has been conducting mining and exploration operations. Since 2014, geological exploration and production have been carried out by "Zabaikalskoye Mining Enterprise". In 2021, the reserves of Levoberezhnyi (Left-Bank) section were put on the balance [22].

The Kavokta is the largest deposit of D-type nephrite in Russia: as of 1 January 2024, the raw nephrite reserves are 6034.88 tons, including 1257.13 tons of high-quality nephrite, which accounts for 13.61% of the total reserves of high-quality nephrite in Russia. In 2023, 367.20 tons of raw nephrite were mined, including 78.64 tons of high-quality nephrite, which accounted for 28.05% of Russia's total high-quality nephrite extraction [3].

The Kavokta deposit (Figure 1) is mainly composed of porphyritic and coarse-grained granites of the Middle-Late Carboniferous Vitimkan complex, which is part of the Angara-Vitim batholith. The granites contain various-sized xenoblocks of host carbonate and terrigenous rocks of the Talali suite of the Vitimkan series. The rocks are represented by meta-sandstones, crystal schists, amphibolites, and dolomite marbles. There are also diorites of the Atarkhan complex.

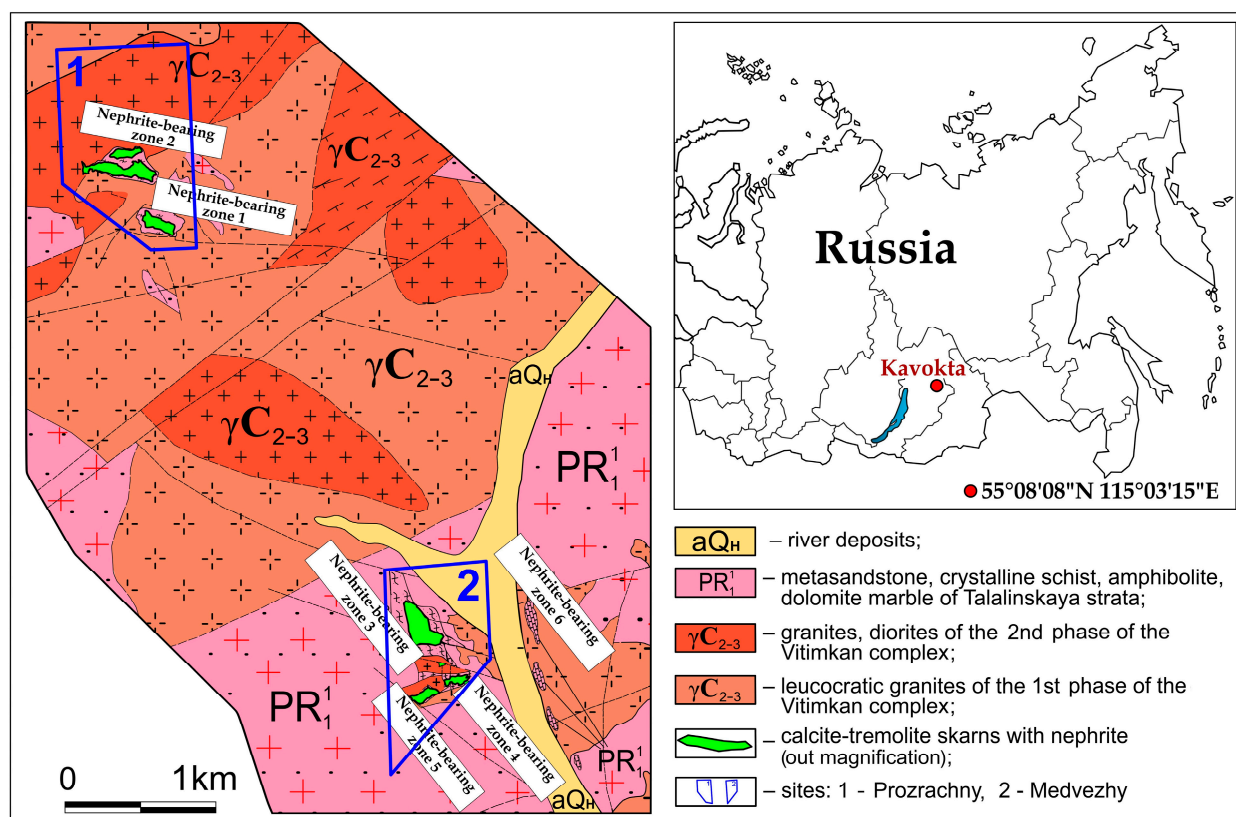


Figure 1. Geological map of Kavokta deposit based on the materials of JSC "Transbaikal Mining Enterprise".

Productive calcite–tremolite skarns with nephrite isolated bodies are formed at the contact between dolomite marbles and amphibolite at xenoblocks. The complete metasomatic zonation is dolomite marble–silicate marble–calcite–tremolite skarn with nephrite–epidote–tremolite skarn–amphibolite. Reduced versions of zonality are more common.

Nephrite bodies are small in size and have an extremely complex morphology with swellings, constrictions, and apophyses. Nephrite forms nodules, veins, nests, and lenses in the vein bodies of the calcite–tremolite skarn. The deposit is divided into three sections consisting of six nephrite-bearing zones (Figure 1), which include numbered nephrite lodes.

The nephrite texture is determined by uneven distribution of color and presence of inclusions. Nephrite is mostly massive, but it can also be spotted, banded, or brecciated. The structure is tangled and fibrous, with fibroblasts. The tremolite fibers that make up the nephrite are 0.01–0.1 mm long and 0.001–0.01 mm thick. Fibrous and needle-like tremolites are grouped into sheaf-like and panicle-like bundles of several dozen fibers. Shadow textures are characteristic due to replacement of broad-prismatic tremolite grains by parallel-fibered tremolite within the replaced grain. Less frequently, there are small veins of late cross-fiber tremolite up to several cm long and 1–2 mm thick.

The Kavokta nephrite deposit is characterized by a wide range of colors, defined by a variety of transitions between the three main colors: white, green, and brown. Gray and black colors have not been mentioned in the scientific literature, although such nephrite is used by “Oriental Way” LLC for various products (Figure 2).



Figure 2. Modern products using black nephrite from the Kavokta deposit.

4. Results

4.1. Geology of the South-Eastern Area of the Deposit

Most of the samples are from the southeastern area: the nearby nephrite-bearing zones 4 of Medvezhyi (Bear) section and 6 of Levoberezhnyi (Left-bank) section (Figure 3).

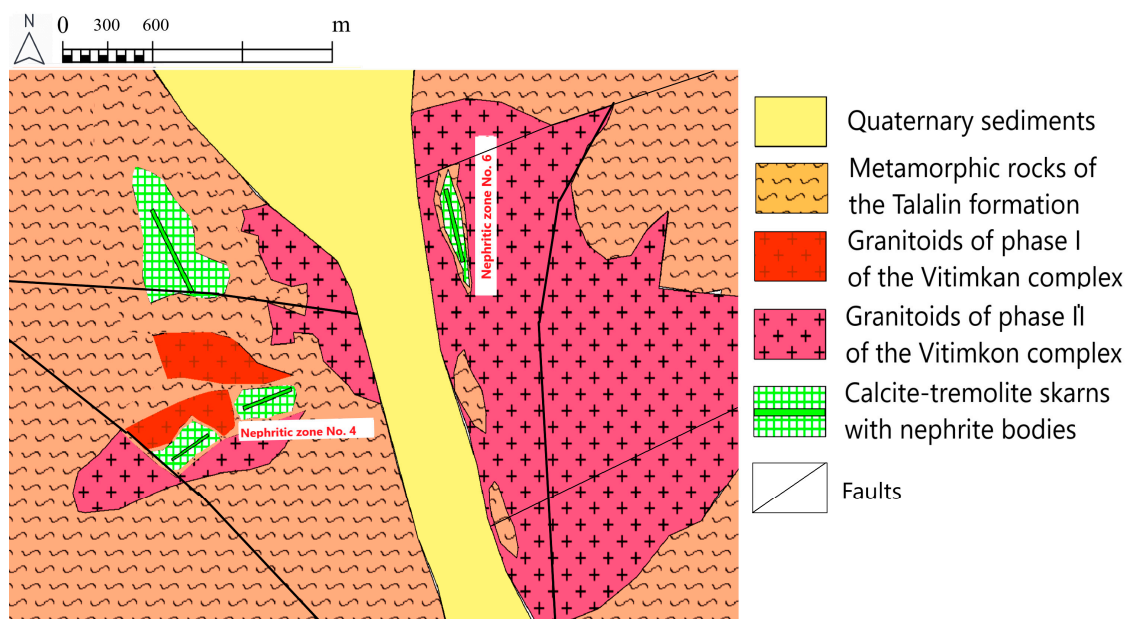


Figure 3. Geological map of the southeastern part of the Kavokta deposit based on the materials of JSC “Transbaikal Mining Enterprise”.

Samples 565901 and 585901 (Figure 4) were taken from lode 17 of nephrite-bearing zone 4 at the Medvezhyi (Bear) section. The nephrite deposit is associated with a north-west-trending layer of dolomite marbles in amphibolites (Figure 5). In the plan, the lode is represented by low-power (0.5–2 m) lens-shaped wavy bodies of calcite–tremolite skarns with nephrite, oriented in a north-west direction (azimuth 280–290°) with a north-eastern dip at an angle of 70–80°. The morphology of the skarn zones is variable, with swellings and power cuts, apophyses into host rocks, unpredictable thinning, and changes in dip angles. The lode is ~30 m long. The lode thickness varies from 0.2 to 1.6 m. The lode is characterized by areas of schistosity and fragmentation that range from a few tens of centimeters to a few meters in width. Cross-cutting veins and steeply dipping acidic dykes are widespread and tend to gravitate towards tectonically weakened zones. The nephrite is dense and has white, light green, or occasionally brown color. In some places, the nephrite is talc-coated, fractured, and contains flaky calcite aggregates. The deposit is productive: in 2023, 87.03 tons of raw nephrite were mined with a yield of 21.60%, and in 2024, 116.74 tons of raw nephrite were mined with a yield of 22.12%. As of 1 January 2024, the reserves amounted to 168.42 tons of raw nephrite, including 37.26 tons of high-quality nephrite [3].

Sample 952501 (Figure 4) was taken from lode 28, which is also located in nephrite-bearing zone 4. The lode has a complex morphology and is located at the contact of a marble lens with epidote–tremolite skarns after microcrystalline amphibolites (Figure 6). The lode extends in azimuth 25°, it is 14 m long, has an average thickness of 1.5 m, and has a subvertical dip in azimuth 115–120° at an angle of 85–90°. The lode is composed of calcite–tremolite skarns with nodules, veins (1–3 cm), and lenses (up to 1.2 m) of light green, yellowish-white, and white nephrite. In 2023, a gross sample of 77.10 tons of raw nephrite was taken from this deposit, with a yield of 21.32%. As of 1 January 2024, the reserves amounted to 1768.4 tons of raw nephrite, including 371.4 tons of high-quality nephrite [3].

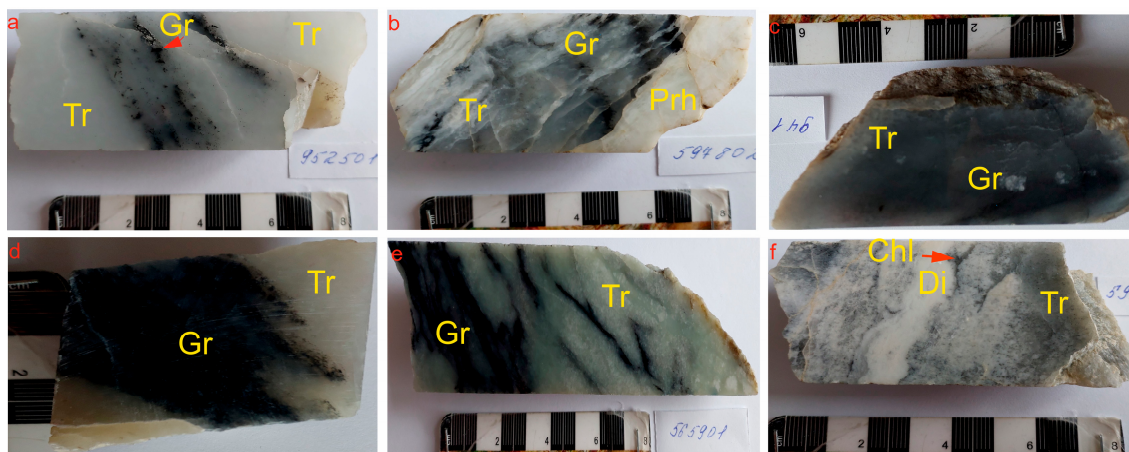


Figure 4. Nephrite samples from the southeastern part of the Kavokta deposit. (a)—952501, (b)—597802, (c)—941703, (d)—585901, (e)—565901, (f)—596803. Chl—chlorite, Di—diopside, Gr—graphite, Prh—prehnite; Tr—tremolite.

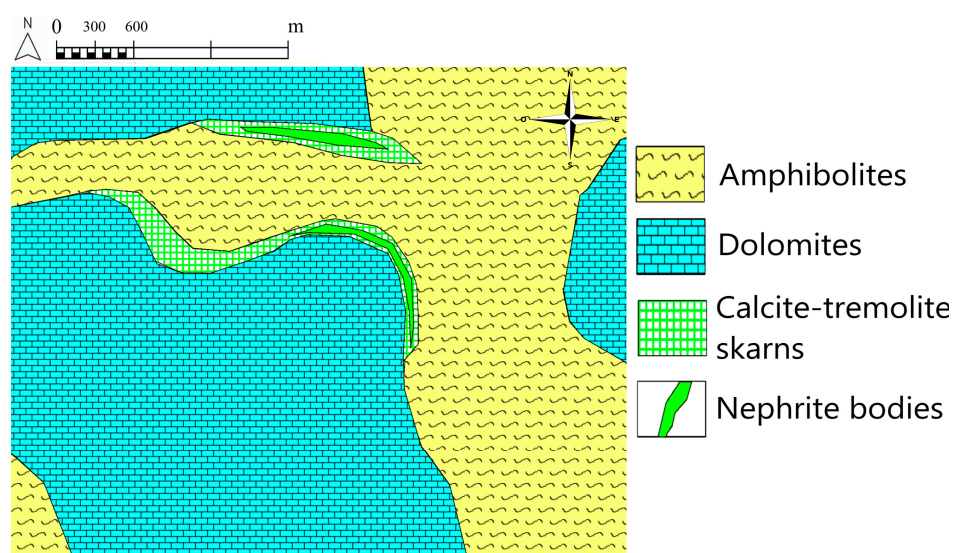


Figure 5. Geological map of lode 7 based on the materials of JSC “Transbaikal Mining Enterprise”.

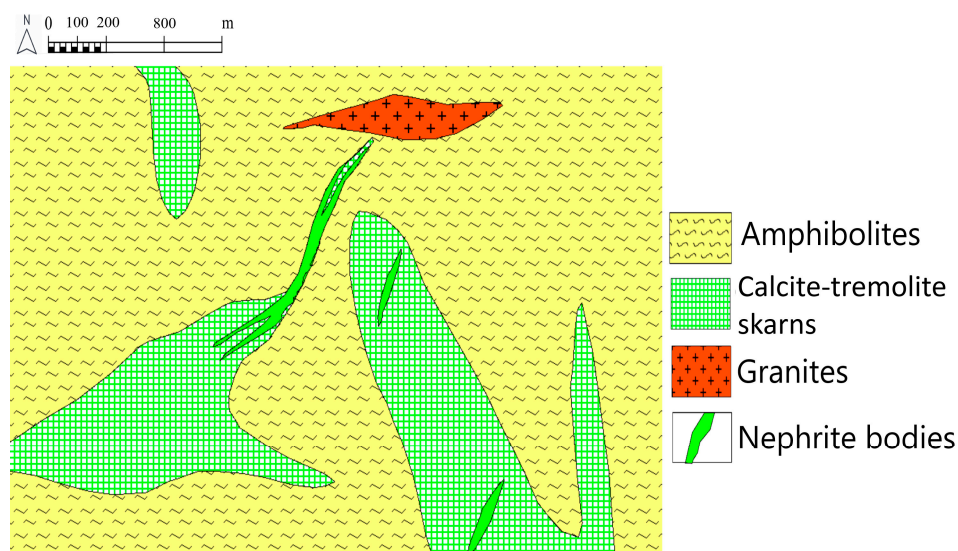


Figure 6. Geological map of lode 28 based on the materials of JSC “Transbaikal Mining Enterprise”.

Samples 596701, 596803, 597802, 934402, 934502, 941703, 941705, and 941705-1 (Figure 3) were taken from lode 6-1 of nephrite-bearing zone 6 at Levoberezhnyi (Left-Bank) section. Lode 6-1 consists of four parallel zones of skarns associated with marble xenoliths (Figure 7). Xenoliths are complex-shaped with steeply dipping contacts of 70–90°. The structures extend to the north-west and are traced for 106 m in the western and for 90 m in the eastern areas of the deposit. The bodies of nephrite-bearing skarns are located both in the contact parts of the xenoliths, parallel to the contact, and in their inner parts. The thickest skarn bodies tend to be associated with amphibolites. In the inner part of the xenolith, vein-like, stair-like (escalated) bodies of skarns have a lower thickness and limited distribution. The overall location of productive lodes is sub-vertical. The thickest skarn bodies are accompanied by zones of fragmentation. The structure of the bodies is complicated by the cutting sub-horizontal and gently dipping dike-like apophyses of the Vitimkan complex granites. The nephrite of the deposit is white, yellowish-white, light green, gray, and black. Previously, this was an area of intensive illegal mining, known as the “six”. As of 1 January 2024, the reserves of lode 6-1 were composed of 1280.2 tons of raw nephrite, including 131.96 tons of high-quality nephrite [3].

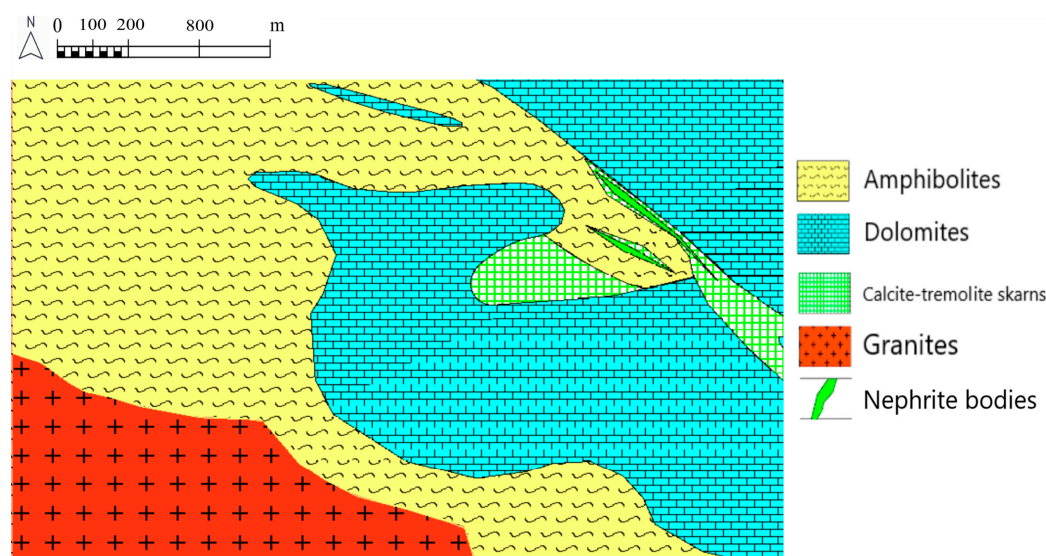


Figure 7. Geological map of the northeastern part of lode 6-1 based on the materials of JSC “Trans-baikal Mining Enterprise”.

4.2. South-Eastern Area Nephrite Petrography, Minerals Chemistry, and Carbon Isotope Ratios

Most of the samples taken for the study are white with black streaks, gray to black stripes, or a mixture of white, gray, and black areas (Figure 4). In sample 952501, black dots and grains are grouped into sub-parallel streaks on a white background (Figure 4). The translucency of the samples ranges from 1 to 5 cm.

Two samples are different from the others. Sample 596803 has stripes and spots of both white and gray of varying intensity, sometimes black, and translucency up to 0.5 cm (Figure 4). Sample 565901 is of heterogeneous light green color with thin, sub-parallel, but winding gray–black streaks, with a translucency of up to 1 cm (Figure 4).

All samples are dominated by tremolite of various morphology, which form isometric grains and tangled-fibrous aggregates that do not differ in composition (Figure 8, Table 1). In all samples, Fe content in tremolite is below the detection limit or is detected in individual grains, up to 0.77 wt. %. In the light green sample 565901, FeO content is significantly higher: 0.48–0.87 wt. %. Single tremolite grains of the studied samples contain up to 0.36 wt. % Na₂O, 0.45 wt. % K₂O, and 1.57 wt. % F.

In sample 596803, diopside forms monomineral fine-grained aggregates: white, slightly translucent layers (Figure 8b). This is an intermediate formation between tremolite–nephrite and diopside–nephrite, known as “karkaro” [1]. The diopside of this sample contains up to 1.13 wt. % Al_2O_3 and 0.61 wt. % Fe_2O_3 (Table 1). There are isometric or corroded relic grains of Fe-free diopside, with rare impurities up to 2.57 wt. % Al_2O_3 and 0.93 wt. % Na_2O observed in the remaining, but not all, samples. Some diopside grains contain graphite inclusions, and there are also intergrowths with tremolite, quartz, and graphite (Figure 8a,d–g). Sample 596803 contains chlorite that corresponds to clinohlorite in composition (Table 1, the total amount is underestimated due to the small size of the grains), forming interlayers and filling the interstices between diopside crystals (Figure 8b). Only two of the remaining samples contain single chlorite grains (Figure 8g).

Graphite is found in all samples except 596803, forming flattened crystals, elongated to vein-like grains, and inclusions in diopside and quartz, and it contains calcite inclusions (Figure 8a,c–l,o). Sample 952501 has graphite–calcite intergrowths; this explains the visible black grains. The presence of graphite was confirmed by X-ray phase analysis of samples 952501 and 941703 (Figure 9).

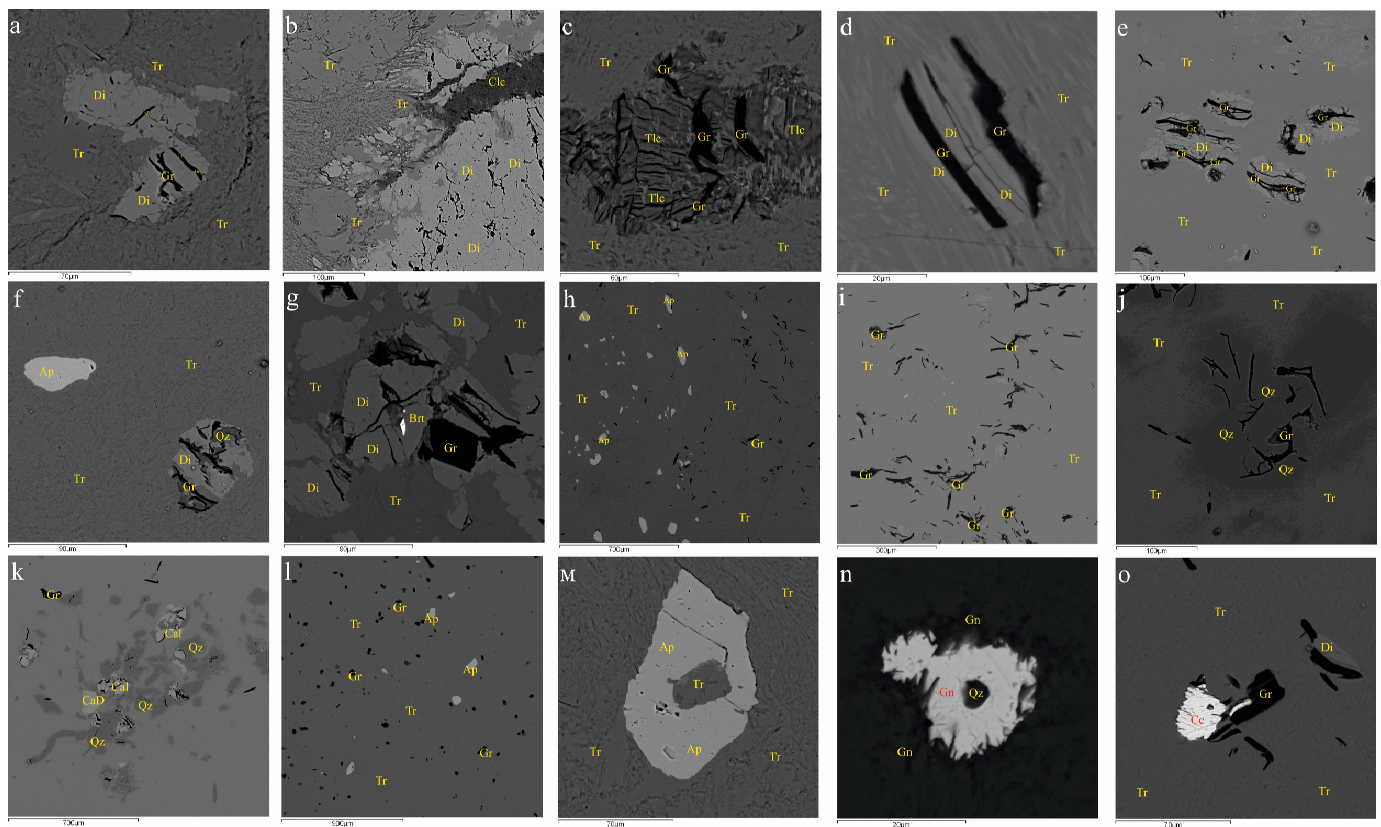


Figure 8. Mineral composition of nephrite. (a)—diopside grains with graphite inclusions, surrounded by prismatic and entangled fibrous tremolite, 941703; (b)—diopside grain corroded by tremolite, veinlets of clinohlore, 596803; (c)—talc aggregate with graphite inclusions replaces tremolite, 941705; (d)—corroded diopside intergrowth with graphite, diopside relics in tremolite, 597802; (e)—diopside–graphite aggregates in tremolite, 934402; (f)—grain of diopside, tremolite, quartz, graphite, another grain of apatite on the side, 585901; (g)—intergrowths of diopside, graphite, and barite in tremolite, clinohlore develops, 596701; (h)—apatite and graphite in tremolite, 565901; (i)—graphite flakes in tremolite, diopside relics, apatite grains, 934402; (j)—quartz with graphite, 952501; (k)—grains of calcite, quartz, and graphite at the predominant tremolite, 952501; (l)—apatite and graphite in tremolite,

565901; (m)—apatite with tremolite inclusion, subordinate diopside, around tremolite, 941703; (n)—galena grain with quartz inclusion, 952501; (o)—chalcocite with graphite, diopside grain, 585901. Ap—apatite, Brt—barite, Cc—chalcocite, Clc—clinocllore, Di—diopside, Gn—galena, Gr—graphite, Qz—quartz, Tlc—talc, Tr—tremolite.

Table 1. Chemical composition of minerals of investigated nephrite, wt. %.

	Tremolite <i>n</i> = 96		Diopside <i>n</i> = 60		Chlorite <i>n</i> = 9		Prehnite <i>n</i> = 12		Talc <i>n</i> = 6	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
SiO ₂	58.24	55.20–62.02	55.29	52.16–58.32	31.95	34.12–36.90	43.86	41.41–44.31	54.08	51.37–56.99
Al ₂ O ₃	0.56	0–2.14	0.78	0–2.83	14.87	12.92–16.74	24.51	23.41–25.32	3.36	2.46–4.14
FeO	0.08	0–0.87	0.01	0–0.37	0.42	0–0.68	0	0	0.12	0–0.39
Fe ₂ O ₃	-	-	0.04	0–2.23	-	-	-	-	-	-
MnO	0	0	0	0	0.03	0–0.28	0	0	0	0
MgO	23.49	21.56–26.05	18.04	16.40–20.23	33.87	31.49–35.35	0.42	0–1.04	27.73	26.52–30.56
CaO	13.49	11.67–14.89	25.89	20.27–27.75	0.57	0–2.15	27.78	27.12–28.64	2.23	1.34–3.79
Na ₂ O	0	0–0.36	0.01	0–0.77	0	0	0	0	0	0
K ₂ O	0.02	0–0.45	0	0	0	0	0	0	0	0
V ₂ O ₃	0	0	0	0	0	0	0.03	0–0.35	0	0
F	0.07	0–1.57	0	0	0	0	0	0	0.29	0–1.73
Cl	0	0–0.17	0	0	0	0	0	0	0	0
Total	95.95		100.06		81.71		96.60		87.81	

n—number of analyses. 0—below detection limit, dash—not calculated. Concentrations of other elements in these minerals are below the detection limit.

Quartz is found in large amounts in three samples, forming grains and spot-like aggregates, often with graphite inclusions (Figure 8f,j,k,n), and does not contain impurities above the detection limit of an electron microscope. Calcite was found in association with graphite in two samples in large quantities (Figure 8k), both free of impurities above the detection limit and containing Mg and, less frequently, Mn.

The apatite is detected in eight samples in large quantities. It forms crystallographically faceted to irregular grains, sometimes case-like (Figure 8f,h,i,l,m). Fluorapatite prevails; 37 grains analyzed were found to be pure fluorapatite. Five fluorapatite grains contain 0.24–0.34 wt. % Cl, and another grain contains 0.47 wt. % SO₃. One grain contains only 0.17 wt. % Cl. The apatite is associated with graphite.

Prehnite with a considerable amount of Mg (Table 1) was found in sample 597802, forming elongated grains and veins. Four irregularly shaped zircon grains with rare hafnium impurities are associated with graphite, and one of them contains a relic of baddeleyite. Talc with small amounts of Al, Fe, and Ca (Table 1, the total amount is underestimated due to the small size of the grains) substitutes tremolite in three samples and contains graphite grains, and, less frequently, grains of apatite and galena (Figure 8c). Barite with 0–14.65 wt. % SrO grow together with diopside and graphite (Figure 8g). Goethite is found in tremolite.

Molybdenite (a single grain), galena (six grains in six samples, Figure 8n), and chalcocite (six grains in two samples, Figure 8o) form xenomorphic grains and do not contain impurities detectable by an electron microscope. One grain of galena contains an inclusion of crystallographically faceted quartz, and tremolite crystals are found on the periphery (Figure 8g). The only pyrite grain is idiomorphic.

The analysis of sample 585901, which contains 0.50 wt. % C after acid etching to remove calcite, resulted in $\delta^{13}\text{C}$ isotopic composition of -14.2‰ . For comparison, samples of dolomite marble core DH-1083-35.1 and DH-10466-41.85, taken at Medvezhyi (Bear) section, were analyzed, resulting in $\delta^{13}\text{C}$ values of $+3.2\text{‰}$ and $+5.2\text{‰}$, $\delta^{18}\text{O}$ values of $+20.8$ and $+26.1\text{‰}$, respectively [23].

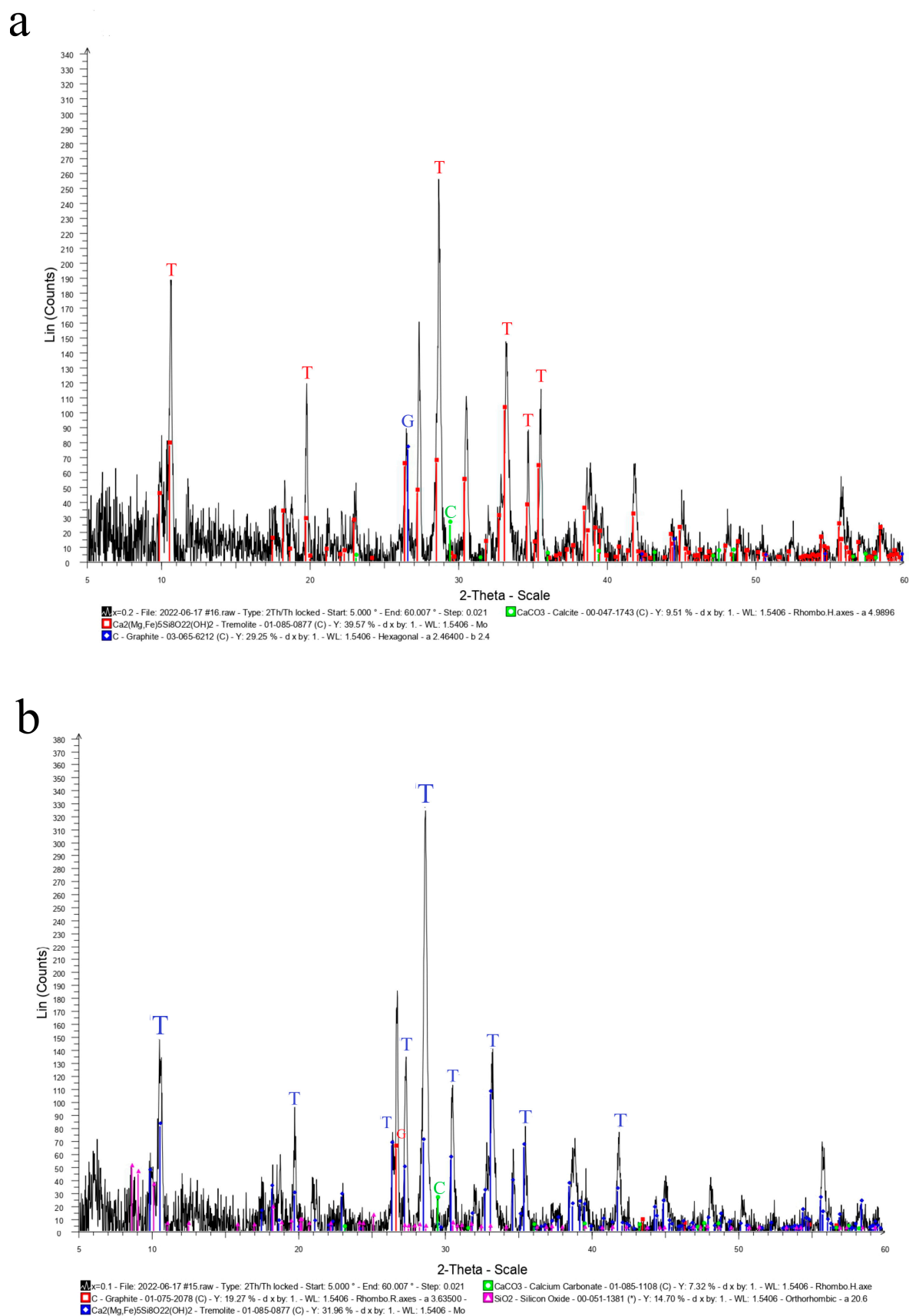


Figure 9. X-ray images of nephrite samples. (a)—sample 952501; (b)—sample 941703.

4.3. Geology of the North-Western Area of the Deposit

Prozrachnyi (Transparent) section is in the northwest of the Kavokta deposit. It includes nephrite-bearing zones 1 and 2. The sublatitudinal zone 1 is located on the southern flank of the section and includes lodes 1, 4, and 9 (Figure 10).

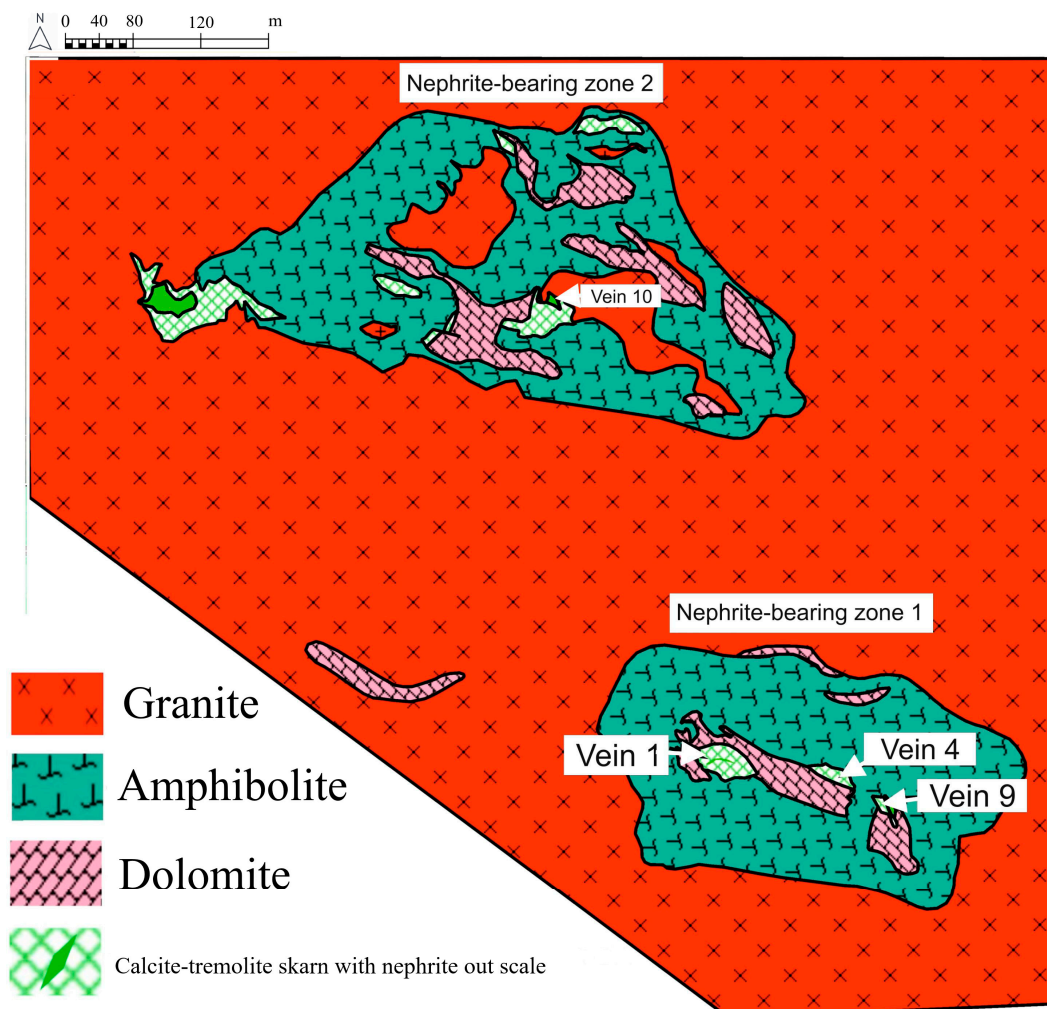


Figure 10. Geological map of Prozrachnyi section based on the materials of JSC “Transbaikalsk Mining Enterprise”.

Lode 1 is a nephrite body of complex morphology with pinches and swellings at the contact between dolomite marbles and amphibolites (Figure 11). The lode is 15 m long and 0.2–2.8 m thick, with a steep southwest dip of 60–70°. It is opened to a depth of 15 m [22]. A small area of the deposit was exposed by erosion. It was traced by drilling wells, the core of which was used in this work, and then exposed by a quarry. The deposit is productive: in 2022, 53.19 tons of raw nephrite were mined with a grade yield of 15.4%; in 2023, 82.2 tons with a grade yield of 14.68%; and in 2024, 25.08 tons with a grade yield of 14.51%. As of 1 January 2024, the reserves amounted to 165.7 tons of raw nephrite, including 24.06 tons of high-quality nephrite [3].

Distribution of nephrite in skarn bodies is very uneven. The most characteristic feature is the veined and lenticular shape of nephrite isolated bodies, which range in thickness from a few millimeters to a few centimeters, with gradual transitions to calcite–tremolite skarns. Larger nephrite isolated bodies usually have tectonic contacts with calcite–tremolite skarns, often with sliding mirrors with long-fiber tremolite formed along them. Two systems of steeply dipping sublatitudinal and north-west-extending fractures divide the nephrite

and host rocks into 5–15 cm thick and 70–80 cm long flat-parallel blocks. The nephrite color is grayish-white, light green, grayish-green to green, and grayish-brown, and, rarely, black [22].

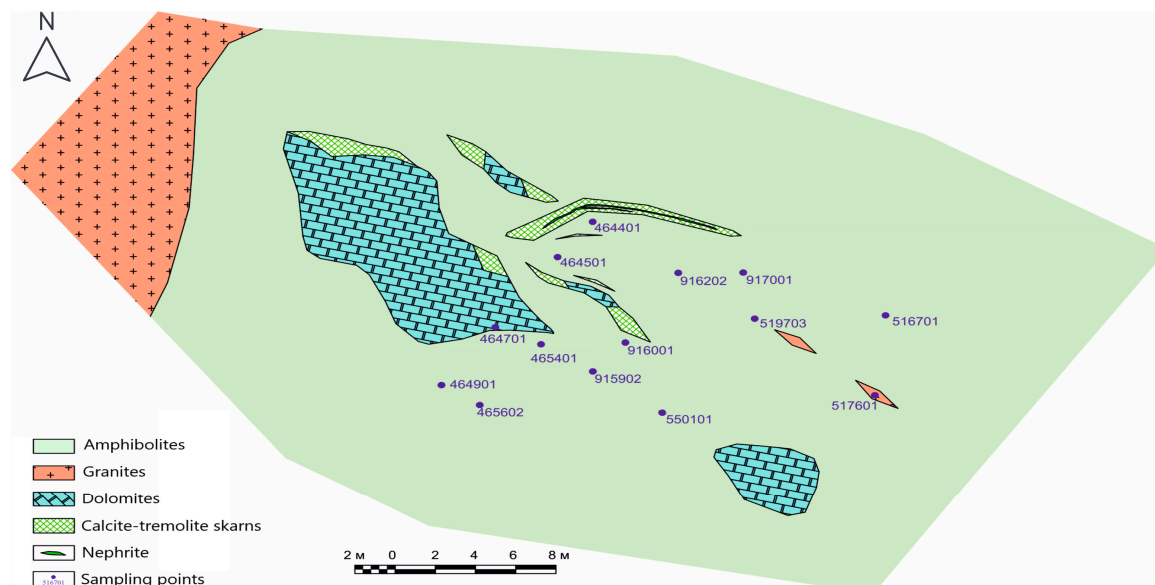


Figure 11. Geological map of lode 1 based on the materials of JSC “Transbaikal Mining Enterprise”. The numbers of the samples are marked.

4.4. North-Western Area Nephrite Petrography and Minerals Chemistry

Sixteen samples were studied [24,25]. No FeO was found in 12 tremolite samples of different colors. The grayish-salad colored nephrite samples are 550101 (0–1.45 wt. %) and 519703 (0–4.64 wt. %), and the grayish-green nephrite samples are 915902 (0.78–1.24 wt. %), 916202 (0.82–3.91 wt. %).

Sample 916202 differs from the other samples in its transitions from dark green to almost black (Figure 12). In one black section of the sample, mottled aggregates of actinolite with 14.23% FeO are adjacent to tremolite, with a content of 0.82 wt. % FeO (Figure 13a). In another black area, all three analyses correspond to actinolite, with 5.18–7.19 wt. % FeO. This sample also contains relict diopside with 1.23 wt. % Fe_2O_3 (Figure 13a), xenomorphic titanite with 2.17 wt. % Al_2O_3 (Figure 13c), idiomorphic magnetite with 4.87 and 10.64 wt. % Cr_2O_3 (Figure 13b), fluorapatite, dolomite (Figure 13b), and irregular to xenomorphic chlorite aggregates (Figure 13d). Titanite and chromium magnetite are not found in other samples of the lode.

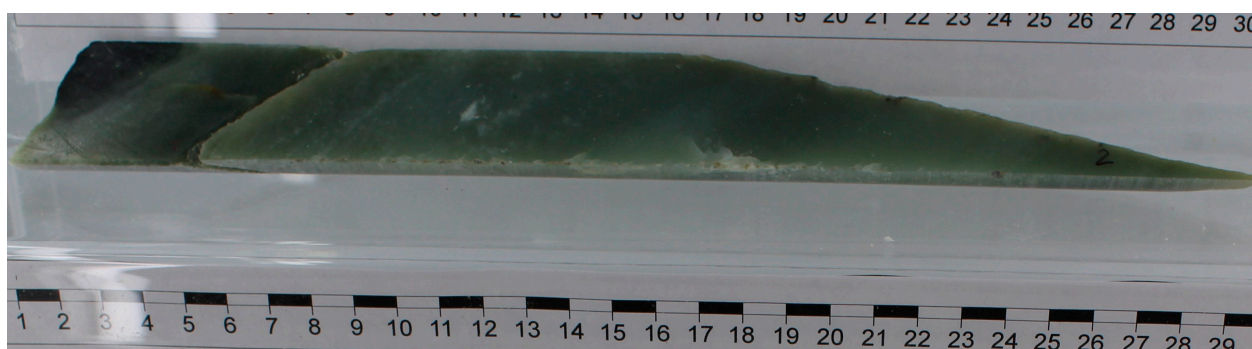


Figure 12. Green–black nephrite, sample 916202.

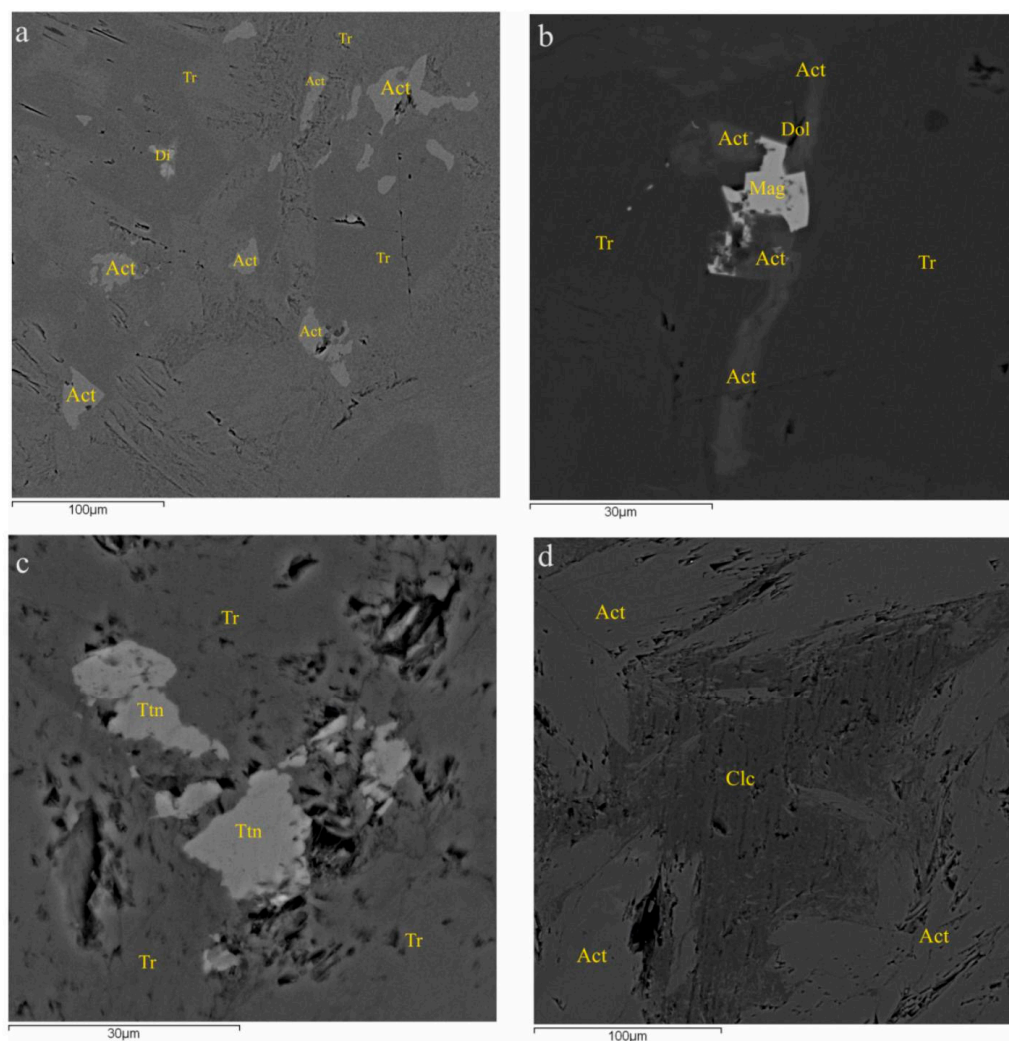


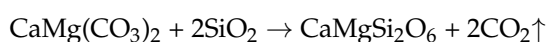
Figure 13. Mineral composition of sample 916202. (a)—spot-like aggregates of actinolite in tremolite, relics of diopside; (b)—Cr-enriched magnetite, grains and veins of actinolite, dolomite in tremolite; (c)—grains of titanite in tremolite; (d)—chlorite in tremolite—aggregates of irregular to xenomorphic shape. Act—actinolite, Clc—clinochlore, Di—diopside, Dol—dolomite, Mag—magnetite, Tr—tremolite, Ttn—titanite.

5. Discussion

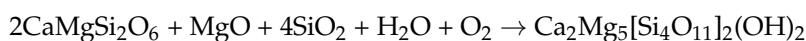
The present study shows that the gray color of sample 596803 is due to chlorite aggregates, which have not been previously observed in gray nephrite. The gray–black color of the remaining samples from the southeastern area of the Kavokta deposit is caused by presence of graphite.

Sulfides, according to their pure chemical composition, were formed during the late low-temperature hydrothermal stage. Their rare small grains did not contribute to the nephrite color.

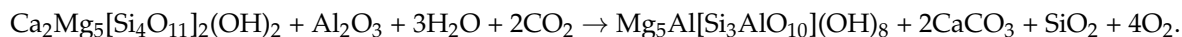
As evidenced by the corrosion of diopside grains, it can be assumed that diopside initially forms at the contact between dolomite and amphibolite:



At the retrogressive stage, diopside is replaced by tremolite:



Sample 596803 belongs exactly to this stage—it still contains a lot of diopside, but it also contains tremolite. As the retrogressive process continues, chlorite replaces both tremolite and diopside:



It has been previously shown that the light green color of the Kavokta nephrite is defined by presence of Fe in tremolite, with an average FeO content of 0.46–0.96 wt. %, in contrast to white nephrite, where Fe is mostly not observed in tremolite or has an average FeO content of less than 0.31 wt. % [22]. The results of this study confirm these conclusions.

High Fe content is derived from rocks with higher Fe content, such as crystalline schists and amphibolites, which participate in nephrite formation. Light-colored nephrites are located closer to the contact with marbles. The nephrite turns green, as it is closer to the contact with aluminosilicate metamorphic rocks [22]. Another possibility should also be taken into account: an involvement of not only granite/granodiorite intrusions in the formation of nephrite-forming fluids, but also an involvement of intermediate, mafic to ultramafic intrusions in the fluids formation [26]. The gabbro and diorites of the Atarhan complex are noted in the area of the deposit, but at a fairly large distance from the nephrite-bearing areas.

The studied samples, except light green 565901, consist of white tremolite. Thus, the gray and black varieties of nephrite, whose color is defined by graphite, are located closer to the contact with dolomite and have been less affected by aluminosilicate rocks. That is why graphite is preserved in nephrite.

This is also consistent with the association of graphite with minerals such as quartz, apatite, and calcite in significant quantities. Quartz is generally not characteristic of the nephrite from the Kavokta deposit, and calcite and apatite usually form single small grains [24,25]. Quartz reflects presence of a terrigenous impurity in the dolomite, after which the nephrite was formed. Formation of apatite is explained by organic matter of animal origin. Relict calcite reflects a less significant transformation of the original dolomites.

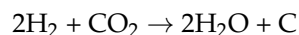
Graphite could have been formed as a result of metamorphism of organic matter of plant origin that formed an impurity in dolomite. This is based on the morphology of layers enriched with graphite to varying degrees, which is similar to sedimentary rocks. The syngenetic formation of graphite corresponds to the presence of graphite inclusions in early minerals such as diopside and quartz.

The question arises: was there enough organic matter in such ancient deposits? The Talali host sequence was assigned to the Lower Proterozoic by analogy with the Lower Proterozoic formations of the adjacent territory. Based on the results of isotopic U-Pb analysis of zircon monofractions from granitoids that intrude the Talali sequence, it was determined that the zircon contains an inherited ancient crustal (1.9 billion years old) component. The folded structures of the stratum have a completely different orientation compared to the folded structures of the Amalat plateau. These data allowed us to consider the age of the Talali sequence as Early Proterozoic [27].

At the same time, the Devonian (Frasnian–Famennian) age of the sedimentary rocks containing the Vitimkan complex of granitoids was determined using the spore-pollen method [28]. The deposits of the Devonian–Lower Carboniferous Vitimkan–Tsipa zone of the Baikal–Vitim folded system are similar to those of the Bambuika–Olingda subzone located to the north. The carbonate Bambuika, terrigenous Chulegmin, and terrigenous–carbonate Kadalin formations are assigned to the Devonian. The Devonian carbonate complex was formed in calm conditions of a shallow, warm shelf sea [29]. There are

similar nephrite deposits in the Bambuika region: Burom, Nizhnee Ollomi, Sergeevskaya lode, and Golyube. Thus, the age of the Talali sequence can be considered Devonian.

Another explanation is participation of a deep hydrogen flow in the graphite formation. The nephrite-containing zone 4 and Levoberezhnyi (Left-Bank) sections are located on steep slopes facing each other in a straight section of the Kavokta River. The riverbed likely follows a deep fault. This fault may have supplied deep-seated hydrogen, which is believed to have been involved in the nephrite formation [18,30]. During dolomite metasomatism, its replacement by tremolite (directly, or more likely with intermediate diopside), carbon dioxide should have been released. In this case, hydrogen reacted with carbon dioxide to form water and graphite.



The carbon isotopic composition can give an answer. The analysis of sample 585901, which contains 0.50 wt. % C after acid etching to remove calcite, resulted in an isotopic composition of $\delta^{13}\text{C}$ —14.2‰. Similar values are typical for calcite from nephrite and skarn of the Zloty Stok deposit in Poland ($\delta^{13}\text{C}$ from −16.0‰ to −9.1‰) and nephrite of the Yurungkash River deposit in China ($\delta^{13}\text{C}$ = −14.9‰), which is explained by the influence of organic matter from the host dolomites [26].

The ratio of carbon isotopes in organic matter ranges from −40‰ to −17‰ [31], with an average value of −27‰ [32]. Metamorphism can make the isotopic composition of organic matter heavier by removing methane from it. But the impact is small. The isotopic composition of carbon in contact-metamorphic graphite from the Kureika deposit is −23.5 ÷ −25.0‰, which is comparable to the composition of coal from the Tungusky coal basin, which is −22.6 ÷ −25.5‰. At the same time, a slight increase in the $\delta^{13}\text{C}$ composition from −23.5 to −25.0‰ towards the intrusive contact is observed in the graphite layer [33].

$\delta^{13}\text{C}$ values for marine carbonate rocks are generally relatively heavier, ranging from −2‰ to +4‰ [34,35]. As a result of the analysis of dolomite marble core samples DH-1083-35.1 and DH-10466-41.85, taken near the Medvezhyi (Bear) section, an even heavier isotopic composition of $\delta^{13}\text{C}$ +3.2‰ and +5.2‰ and oxygen isotope compositions $\delta^{18}\text{O}$ +20.8 and +26.1‰ were obtained [23].

Compared to marine carbonates, mantle-derived carbon has a slightly lower carbon isotopic composition ($\delta^{13}\text{C}$ = −5‰ ± 2‰; [36]). However, there is no evidence of fault-related graphitization at the deposit.

Thus, we come to the conclusion that the graphite nephrite of the southeastern area of the Kavokta deposit is a combination of two sources of carbon: organic matter buried in dolomites and carbon dioxide decomposed by hydrogen.

The cause of the black nephrite color in the northwestern area of the deposit, the Prozrachnyi (Transparent) section, is different in general, for the Kavokta deposit. It has been shown that the green color is determined by a Fe impurity in actinolite: as Fe content increases, the tone becomes more saturated, which was noted earlier [22]. The black color of sample 916202 is a result of high Fe content, which is caused by its close contact with amphibolite. This sample is the only one that contains titanite and Cr-enriched magnetite. The black spots are composed of either tremolite and actinolite with an extremely uneven distribution of Fe, or only actinolite with a more stable Fe content.

Previously, it was believed that nephrite at the Kavokta deposit should be sought in connection with dolomites, as it has the purest white color [22]. However, it has now been discovered that black nephrite, which is also in high demand, is associated with amphibolites.

6. Conclusions

Dark dolomite type (D-type) nephrite was found at the Kavokta deposit at Middle Vitim Mountain Country, Russia.

Dark D-type nephrite is most typical of the southeastern area of the deposit: nephrite-bearing zone 4 of Medvezhyi (Bear) section and lodes 6-1 of Levoberezhnyi (Left-Bank) section.

The gray–black color of most samples is defined by presence of graphite. Graphite is syngenetic: it is formed both by organic matter buried in dolomites and by decomposition of carbon dioxide that appears during decarbonization under the influence of deep-seated hydrogen.

The gray color of tremolite–diopside nephrite is defined by formation of chlorite aggregates that replace diopside and/or tremolite.

The gray-green–black color of the nephrite in the northwestern area of the Kavokta deposit, lode 1 of Prozhachnyi (Transparent) section, is caused by high Fe content in actinolite on the contact with the after-amphibolite epidote–tremolite skarn.

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