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FEATURES OF FORMATION, MATERIAL COMPOSITION AND GEOLOGICAL STRUCTURE OF RARE METAL AND PEGMATITE DEPOSITS OF THE KALBA REGION ON THE EXAMPLE OF THE YUBILEINOE DEPOSIT

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The relevance *of the research is caused by the lack of knowledge on the behavior of rare metal in pegmatite ore formation in the Kalba region and the need to expand the rare-metal mineral resource base of the region and to establish geological and mineragenic mapping.*
The aim *of the research is to identify the features of geotectonic development, geological structure and material composition of the rare-metal deposit Yubileinoe (Kalba region).*
Study area: *large industrial rare metal deposit Yubileinoe and its mineral complexes.*
Methods: *detailed geological-geochemical and mineralogical study of the region of work, use of materials from works of previous years, stock literature, as well as laboratory studies (mass spectrometric, microprobe, geochronological and other studies). The structural relationships of minerals with each other, as well as the geochemical interpretation of the results of laboratory studies, were taken into account during diagnosing mineral complexes.*
Results. *Spatial and genetic relationship of rare-metal pegmatite deposit (Nb, Ta, Be, Cs, Li, Sn) with granites of the I phase of the Kalba complex P_1 (285 Ma), is distinguished. In the location of the Yubileinoe deposit, the leading ore-controlling role is given to the system of deep latitudinal faults of ancient origin, renewed in the Hercynian cycle. A geological and genetic model of rhythmically pulsating rare-metal pegmatite formation of the Yubileinoe deposit is presented, which reflects the zonal development of mineral complexes from oligoclase-microcline (barren) to albite, greisen, spodumene-containing and pollucite-bearing (ore) with an increasing concentration of mineralization. Information was obtained on the composition of pegmatite ores with the release of typomorphic minerals (clevelandite, lepidolite, colored tourmalines, spodumene, pollucite, ixiolite, etc.) and the main geochemical elements of rare metal ore formation (Nb, Ta, Be, Cs, Li, F, P, etc.).*

Key words:
Kalba region, granitoid, Yubileinoe deposit, rare metals (Nb, Ta, Be, Cs, Li, etc.), modeling, forecasting.

Introduction

The Kalba region is located in East Kazakhstan and, in terms of geotectonic zoning, is included in the general geostructure of the Great Altai (hereby GA) which is part of the Central Asian mobile belt [1, 2]. In the north-east it is limited by the Irtysh zone of crumpling, in the southwest along the Terekta fault it is separated from the West Kalba. The southeastern flank of the structure continues to China; in the northwest it is mainly overlain by a cover of loose deposits of the Kulunda depression. Kalba granitoid belt of the northwestern direction is formed in the Hercynian cycle in a post-collisional (orogenic) geodynamic setting – the spatial-genetic relationship of the leading geological-industrial type of rare-metal pegmatites deposits (Nb, Ta, Be, Cs, Li, Sn) with medium-coarse-grained biotite phase I granites of the Kalba complex ($P_{1,}$ 285 million years) [3, 4]. The study of the mineralogical composition of Kalba pegmatites was greatly contributed by A.I. Ginzburg, V.D. Nikitin, S.G. Shavlo, N.A. Solodov, V.I. Kuznetsov, Yu.A. Sadovsky, V.A. Filippov and others. In metallogenic terms, this is the major rare metal structure of East Kazakhstan, the prospects of which have not yet been exhausted. The features of the formation, material composition and geology of this structure will be considered on the example of the Yubileinoe deposit, located in Central Kalba and being a

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large industrial rare metal deposit. At present, the most important task is to forecast and search for new rare metal objects in order to strengthen the raw material base for rare metal production enterprises [5].

Materials and methods

The study included field and analytical work. Extensive materials of geological-surveying, prospecting and exploration works carried out in different years in the study area were used [6–8].

The samples for laboratory research were taken from ore-bearing rocks and rare-metal pegmatites of the Yubileinoe deposit (more than 200 samples). As a sample, fragments of samples, the remains of core samples were taken, the furrows of the ditches were retested. Analytical studies were carried out in the VERITAS laboratory of the D. Serikbaev East Kazakhstan Technical University (Ust-Kamenogorsk). The chemical composition of minerals were analyzed on the Agilent 7500cx ICP-MS mass spectrometer from Agilent Technologies (Agilent Technologies, Santa Clara, CA, USA) and an MC-46 Cameca microprobe (Cameca, Gennevilliers, France), which determined 73 elements with high sensitivity (Cu, Pb, Zn, Au, Ag, Cd, Pt, In, Ir, Y, Yb, TR, etc.), on Jeol-100C scanning electron microscopes with a Kevex-Ray energy-dispersive attachment and an ISM-6390 LV from Jeol with an INCA Energy attachment from OXFORD, which also studied fluid inclusions of ore and associated minerals, and also determined impurity elements (Au, Ag, Sb, As, Pt, In, U, etc.) in them.

Geochronological studies were carried out using the step heating method 40Ar/39Ar. The analyzes were performed at the Institute V.S. Sobolev (Novosibirsk, Russia). In total, more than 30 datings were performed. The isotopic composition of argon was measured on a Micromass Noble Gas 5400 mass spectrometer.

Geological structure of the Yubileinoe deposit

The largest rare-metal (Ta, Nb, Be, Li, Sn, W) deposits of the GA are located in the Kalba-Narym metallogenic zone [3, 9, 10]. The belt comprises the Shulba, Northwest Kalba, Central Kalba, and Narym ore districts. Central Kalba is the richest district, with many large pegmatitic rare-metal deposits (Bakennoe, Belaya Gora, Yubileinoe, etc.), which were operated by the Belogorsk Mining and Processing Combine before 1994 but have been suspended since then (Fig. 1).

Pegmatitic rare-metal mineralization in the Central Kalba district is spatially and genetically associated with Early Permian (P_1) postcollisional granite magmatism (Kalba complex) [4, 11–13]. The deposits occur in the zoned Ognev-Bakenny (Ognevskoe, Bakennoe, et.), Asubulak (Yubileinoe, Ungursay, Karmen-Kuus, etc.), and Belogorsk-Baimurza (Belaya Gora, Upper Baimurza, etc.) fields controlled by systems of W-E large faults with pinnate fractures and faults.

The Yubileinoe deposit was discovered in 1955 by G.I. Kazaryan, P.I. Vershkov and V.A. Filippov. Later it was studied by many geologists (K.I. Ivanova, E.P. Pushko, M.M. Ukolov, V.K. Remez, V.V. Lopatnikov, etc.). It is spatially located in the hanging side of the Asubulak ore field, controlled by a sublatitudinal deep fault (Fig. 1) [6–9].

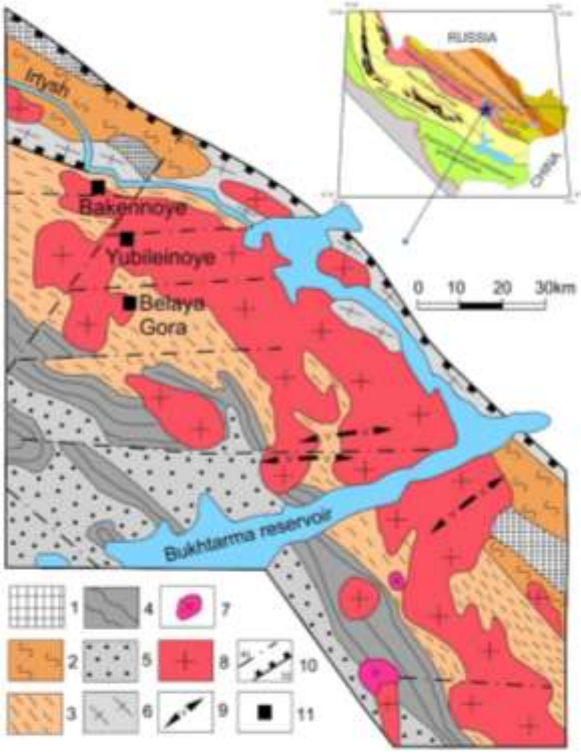

Fig. 1. *Simplified geology of the Central Kalba ore district. Performed on the material of B.A. Dyachkov [10]: 1 – amphibolites and gneisses (PR?); 2 – greenschist metamorphic rocks ($D_{1–2}$); 3 – carbonaceous sandstones, siltstones, and slates (D_3); 4 – carbonaceous-calcareous-clastic flysch ($C_1v_{2–3}$); 5 – siltstones, sandstones, and graywacke (C_1s); 6 – migmatites and gneiss granites (C_1); 7 – plagiogranites and granodiorites, C_3; 8 – granites of phase 1 Kalba complex (P_1); 9 – gabbro, dolerites, granites, and porphyry (P_2–T_1); 10 – faults that control mineralization (a) and boundary of Irtysh shear zone (b); 11 – pegmatite deposits*

Рис. 1. *Схема геологического строения Центрально-Калбинского рудного района [10]: 1 – амфиболито-гнейсовая формация (PR?); 2 – метаморфизованные «зеленосланцевые» отложения ($D_{1–2}$); 3 – углеродисто-песчаниково-алевролитовая, аспидная (D_3); 4 – флишоидная углеродисто-известковисто-терригенная ($C_1v_{2–3}$); 5 – граувакковая алевролито-песчаниковая (C_1s); 6 – мигматит-гнейсогранитовая (C_1) формации; 7 – плагиогранит-гранодиоритовая, C_3; 8 – граниты первой фазы калбинского комплекса (P_1); 9 – габбро-диабаз-гранит-порфировая формация (P_2–T_1); 10 – рудоконтролирующие разломы (a) и граница Иртышской зоны смятия (b); 11 – пегматитовые месторождения*

The pegmatite field is confined to large troughs of the roof of the Tastube and Priirtysh granite massifs, dissected by faults. The ore field is elongated in the sublatitudinal direction for 8–10 km with a width of 2–3 km. In its structure, hornfelsed sandstone-siltstone deposits of the slate formation (Takyr suite, D_3) and plagiogranites (C_3)

are fragmentarily fixed, but most of the ore field is occupied by granites of the Kalba complex (P_1), represented by two intrusive phases [3, 13–15]. The first phase is medium-coarse-grained porphyritic biotite granites, the second phase is medium-uniform-grained muscovitized (two-mica granites).The ores were deposited during multiple tectonic events under compression and extension cycles, which provided cyclic inputs of pegmatite-forming fluxes and metasomatic replacement of previous mineral assemblages in pegmatite veins [16, 17].

According to previous researchers (T.M. Nikitina, B.A. Dyachkov, A.E. Ermolenko, etc.), thickness variability and uneven distribution of rare elements (Ta, Li, Sn, etc.) along the strike and dip of ore deposits are revealed with the construction of horizontal plans and the calculation of isopowers and isoconcentrations of rare elements [4–9]. Based on this, a linear-nodal distribution of rare-metal mineralization is determined at the Yubileinoe deposit with ore concentration maxima in its thickened parts and at the intersection of ore-localizing fracture structures with the formation of ore-bearing bands or ore bands of northwestern strike (Fig. 2). The distance between the ore belts is 200–300 m, their inclination in the southeast direction at an angle of 20°.

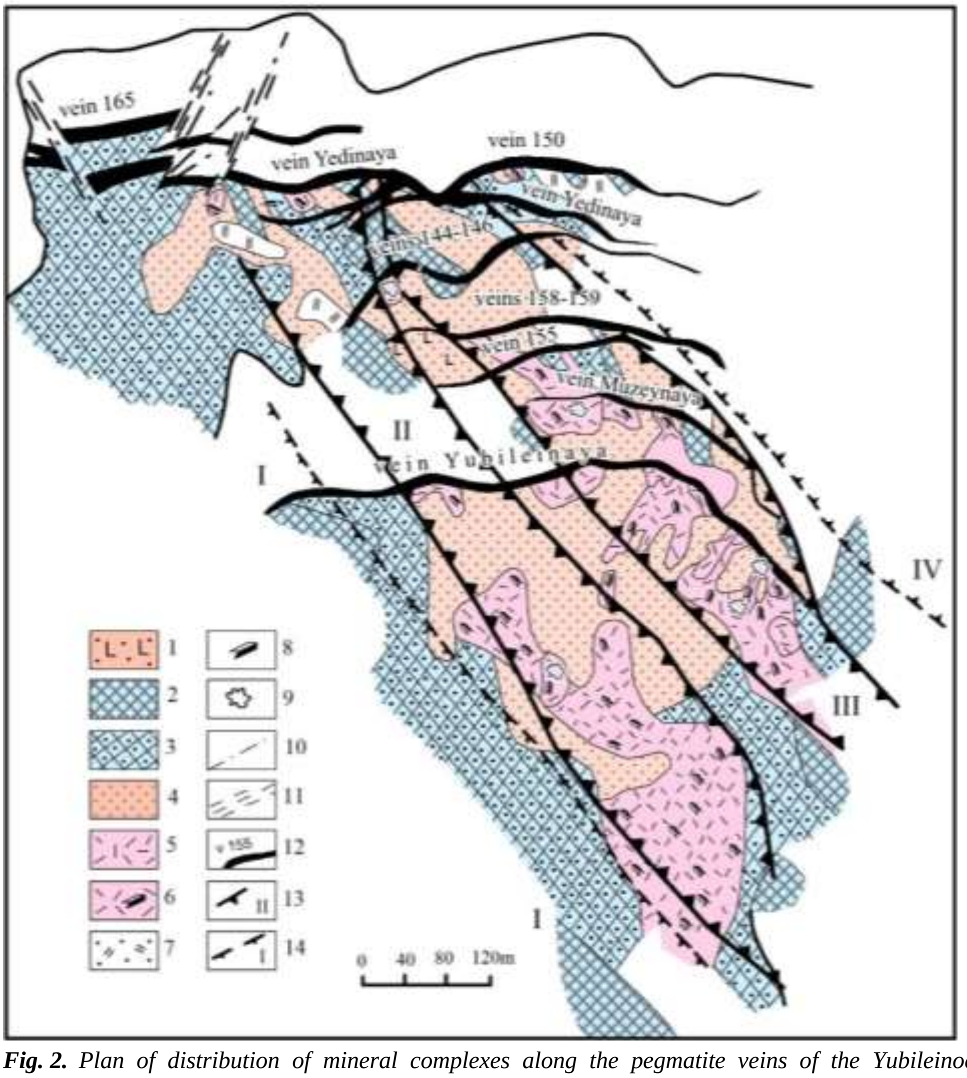

Fig. 2. Plan of distribution of mineral complexes along the pegmatite veins of the Yubileinoe deposit. Performed by T.A. Oitseva based on materials [6]. Mineral complexes: 1 – microcline oligoclase with albite; 2 – microcline; 3 – microcline-albite; 4 – albite; 5 – spodumene-bearing; 6 – spodumene-clevelandite-quartz; 7 – quartz-albite-muscovite (greisen). Minerals: 8 – spodumene; 9 – lepidolite in association with pollucite, petalite, colored tourmalines; 10 –discontinuous violations (post labor); 11 – zones of increased fracturing; 12 – ore veins and their names. Ore belts: 13 – installed; 14 – alleged, and their numbers

Рис. 2. План распределения минеральных комплексов по пегматитовым жилам Юбилейного месторождения. Выполнено Т.А. Ойцевой по материалам [6]. Минеральные комплексы: 1 – олигоклаз микроклиновый с альбитом; 2 – микроклиновый; 3 – микроклин-альбитовый; 4 – альбитовый; 5 – сподумен-кварцевый; 6 – сподумен-содержащие; 7 – кварц-альбит-мусковитовый (грейзеновый). Минералы: 8 – сподумен; 9 – лепидолит в ассоциации с поллуцитом, петалитом, цветными турмалинами; 10 – разрывные нарушения (пострудные); 11 – зоны повышенной трещиноватости; 12 – рудные жилы и их названия. Рудные ленты: 13 – установленные; 14 – предполагаемые, и их номера

Results of the study of leading mineral complexes

The zonal distribution of mineral complexes in pegmatites of Yubileinoe deposit is clearly manifested, which was noted in the works of N.A. Solodov, V.A. Filippov, D.Ya. Aizderzis, E.P. Pushko, A.M. Smirnov and other researchers. The characteristics of the leading mineral complexes are given [3, 9, 18, 19].

The *albite complex* is widely developed. It is composed mainly of albite (95 %) with an insignificant admixture of quartz (up to 5 %), muscovite, tourmaline, garnet and other minerals. Outwardly, it is a rock of massive appearance, white, composed mainly of fine-grained and sugary albite (Fig. 3, *a*). They contain tantalite-columbite in the form of fine dissemination (up to 0,5 mm in size), prismatic crystals of dark brown and black color. Less commonly, cassiterite crystals of a dipyramidal-prismatic appearance of various colors from reddish-brown and pale green to colorless are observed. A distinctive feature of the complex is its enrichment with phosphates of Li, Mn, Fe, forming nests, lenses and black spots (Fig. 3, *b*).

The varieties of this complex are found in the central parts, hanging and recumbent sides of pegmatite veins. In crusts, they contain (in grams per ton): tantalite-columbite (263), cassiterite (452,8), minerals of the samarskite-fergusonite group (33,7). Apatite, garnet, tourmaline (scherl and verdelite) and phosphates of Li, Mn, Fe are also characteristic. Spodumene, zircon, sphalerite, corundum, fluorite and biotite are also noted. In lithium phosphates, the contents of P, Li, Mn (more than 1 %) and rare elements (wt. %) are increased: Ta (0,08–0,1), Sn (0,01–0,3), Be (up to 0,01), significant contents of Mo, As, Sb, Zn are noted. According to the results of mass spectrometric analysis, albite is slightly enriched in rare elements (in grams per ton): Ta (26,33), Sn (22,88), Nb (67,43). The content of rare alkalis reaches: Li (112,3), Rb (381,4) and Cs (19,6).

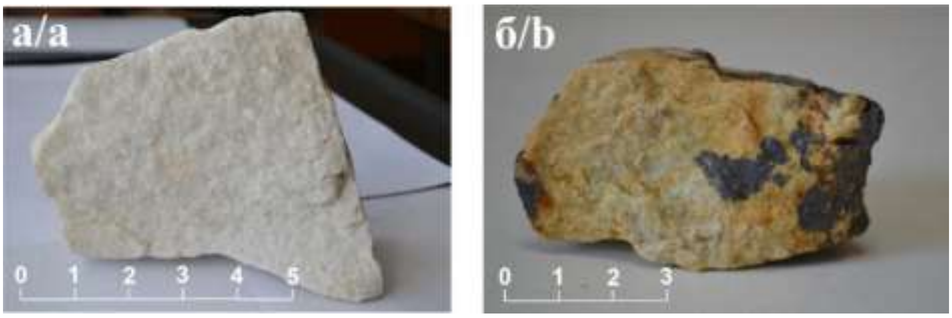

Fig. 3. *Typomorphic minerals of the albite complex: a) massive sugar albite; b) with phosphates of lithium and manganese*

Рис. 3. *Типоморфные минералы альбитового комплекса: а) сахаровидный альбит массивного облика; б) с фосфатами лития и марганца*

In albitized pegmatites with spodumene, the concentrations of Li (3664) and Sn (up to 110 grams per ton) are increased. BSE images in pegmatites with lithium and manganese phosphates are dominated by albite; inclusions of fluorapatite containing scheelite impregnation (WO_3 –59,85 %) are characteristic. Quartz, muscovite, tourmaline and sphalerite are also noted (Zn –50,27 %). Among the lithium-bearing manganese minerals of the triphilite-lithiophyllite group – $Li(Fe_2+Mn_2)[PO_4]$, syclerite ($LiMn_2+PO_4$) was first discovered. New formations of sodium and calcium-containing manganese phosphates were determined: firefeldite $Ca_2Mn(PO_4)_2$, natrophyllite (P_2O_5 – 40,88; MnO – 29,27 и Na_2O – 10,16 %) and beusite (Ca – 34,47; P – 13, 48 %) associated with albite, pyrolusite, and quartz.

Ore minerals are represented by microinclusions of tantalite (ferrotantalite), in which Ta_2O_5 prevails over Nb_2O_5 (4,59 times), and the FeO content (13,64 %) is significantly higher than MnO (1,58 %). Beryl forms crystals (more than 300 microns in size), which are intersected by quartz and contain inclusions of pyrolusite and muscovite. In general, the albite complex is geochemically specialized in Nb, Ta, Be, Sn, Li, in practical terms it is accompanied by ordinary ores (Ta_2O_5 of about 100 grams per ton), accounting for about 12 % of the total reserves of rare metals in the Yubileinoe deposits.

The *quartz-albite-muscovite (greisen) complex* occurs locally in different parts of the veins. In the inner zones, it is associated with the albite-spodumene complex. Outwardly, it is a coarse-grained greisen of greenish color, consisting mainly of muscovite (more than 50 %), quartz and albite (Fig. 4).

Typomorphic indicator minerals are green muscovite, fluorapatite, apatite, and green tourmaline (verdelite). Spodumene is rare. Ore minerals are represented by dissemination of tantalite, ixiolite $(Ta, Nb, Sn, Fe, Mn)_4O_8$, uranium-bearing microlite (Ta – 31,33; U – 4,46–6,57), cassiterite, zincite and others. Tantalite-columbite forms lamellar and tabular black crystals. Apatite in crushes is noted in the form of fragments of prismatic crystals of various colors (2458 grams per ton), fine-crystalline apatite with an impurity of Li_2O – 0,54 %. A distinctive feature of the greisen complex is its enrichment in tantalum (the average Ta_2O_5 content is more than 0,3 %). According to spectral analyzes, the Ta content reaches 0,5–1 %, and in tantalite crushes – 4460 grams per ton. In the greisens of the vein, the single concentration of tantalite is 2564,3 grams per ton. Abnormal contents of tantalum in greisens have been established at other pegmatite objects: Ungursai (Ta_2O_5 – 1500 grams per ton, Nb_2O_5 – 125 grams per ton) and Kvartsevo in North-West Kalba (Ta_2O_5 up to 0,225 %).

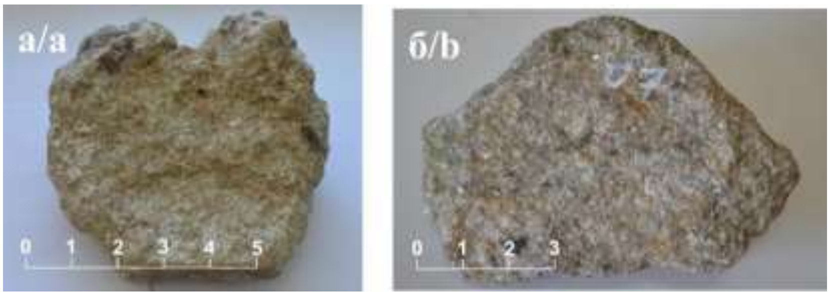

Fig. 4. *Typical samples of quartz-albite-muscovite (greisen) complex in the Yubileinoe deposits: a) greisen of greenish-gray color; b) greisen with muscovite and impregnated tantalite*

Рис. 4. *Типичные образцы кварц-альбит-мусковитового (грейзенового) комплекса на Юбилейном месторождении: а) грейзен зеленовато-серой окраски; б) грейзен с мусковитом и вкрапленностью танталита*

Spodumene-bearing complexes are the main concentrators of rare-metal mineralization. New research results show that the most productive are quartz-clevelandite-spodumene-lepidolite (colored) and quartz-clevelandite-lepidolite-pollucite complexes and their varieties [10, 20, 21]. Similar pegmatites are widespread in other rare-metal provinces [22–27]. The main feature is the complexity of the composition of pegmatites containing unique minerals of several generations (clevelandite, lepidolite, spodumene, petalite, amblygonite, pollucite, colored tourmalines, cassiterite, tantalite-columbite, manganotantalite, microlite, etc.) and rich complex ores (Sn+Ta+Cs+Li). The following minerals are among the most leading indicators of rare metal pegmatite formation.

Micas are widespread in all mineral complexes of the Yubileinoe deposit and other rare-metal objects of Kalba. An increased lithium content of micas was found not only in lepidolite, but also in transparent muscovites. They are also enriched in Ta, Nb, Be, Rb, Cs, Sn, W and are prospecting indicators of rare-metal mineralization.

Greenish lithium-bearing muscovites (in association with fluorapatite and verdelite) indicate the enrichment of the quartz-albite-muscovite (greisen) complex with tantalum at the level of hurricane values (up to 0,3 % and more). On a scanning microscope in muscovites, fluid microinclusions of tantalite, cassiterite, fluorapatite, ilmenite and galena (in the first units and tens of microns) are observed. Cryptocrystalline varieties of muscovite (gilbertite) of the Karmen-Kuus ore occurrence are enriched in rare alkalis (Li+Rb+Cs=12576 grams per ton) with the content of Sn (149 grams per ton) and Ta (18,5 grams per ton).

Lepidolite is the main indicator of a productive quartz-clevelandite-lepidolite (colored) complex (Fig. 5, *a*). It is represented by two varieties: 1) large- and medium-scaled, forming large aggregates in association with clevelandite and quartz; 2) fine-hidden scaly, fixed in the form of metasomatic quartz-lepidolite nests among other minerals.

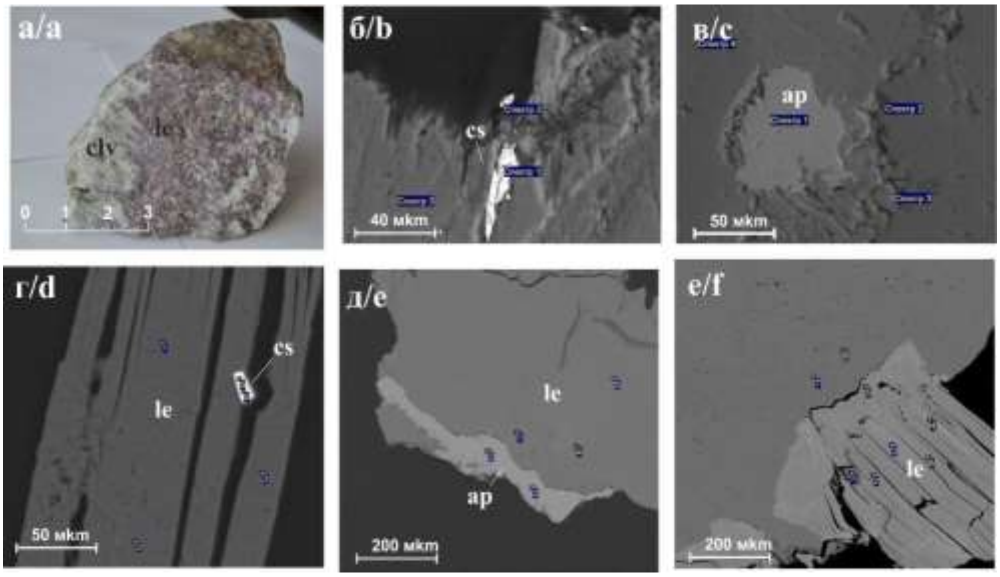

Fig. 5. *Microinclusions of minerals from the greisen complex of the Yubileinoe deposit. Analyst I.V. Aborneva. a) replacement of lamellar clevelandite by lepidolite; b) larger micrograins of vein-shaped cassiterite in lepidolite; c) relict grain of apatite corroded by albite and lepidolite; d) inclusion of cassiterite in lepidolite; e) micrograin apatite in the rim of lepidolite; e) lepidolite plate*

Рис. 5. *Микровключения минералов грейзенового комплекса Юбилейного месторождения. Аналитик И.В. Аборнева. а) замещение лепидолитом пластинчатого клевеландита; б) более крупные микрозерна касситерита прожилковой формы в лепидолите; в) реликтовое зерно апатита, разъедаемое альбитом и лепидолитом; г) включение касситерита в лепидолите; д) микрозерно апатита в оторочке лепидолита; е) пластинка лепидолита*

Lepidolite is characterized by a high Li content (up to 16240 grams per ton); at the micro level, inclusions of cassiterite, fluorapatite, apatite and scheelite are noted in it (Fig. 5, *b–f*). In this complex, according to the results of mass spectrometry, anomalous contents (grams per ton) were determined: Nb (1940), Ta (248,7), Rb (4746), Li (7160), P (3357), Sn (80,54), at low values of W (2,44) and Mo (1,2). Significant contents of Ag (0,51), Sb (2,9), Au (0,30), Pd (0,12), Bi (0,34), Tl (7,82), In (0,24). According to the BSE microanalysis, the complex consists (%) mainly of SiO_2 (49–52), Al_2O_3 (24–28), K_2O (10,9), F (5,6–6,4), impurity WO_3 (1,35–3,25) and other components.

Spodumene from the pyroxene group (Li, Al[Si_2O_6]) is one of the major indicator minerals of rare metal pegmatite formation. It forms prismatic crystals of a plank appearance (up to 0,5 m in size) of yellowish-white and beige color, glassy luster, with secondary changes acquiring a pinkish color. Aggregate clusters with an oriented distribution of spodumene crystals associated with quartz, clevelandite, and amblygonite are noted (Fig. 6). The main crystallographic faces of the spodumene prism m {110} and the pinacoid a {110}.

At the microlevel, it contains inclusions of cassiterite (Sn – 34,51 wt. %), scheelite with tantalum impurity (W – 45,67; Ta – 10,27) and native iron (with Zn impurity – 13,38; Pb – 7,53) (Fig. 7).

According to the ICP-MS results, rare earths in spodumene are represented mainly by the lanthanide group of elements (12 grams per ton). The content of chalcophilic elements reaches (grams per ton): Cu (107,3), Zn (116,4), Pb (410,6), Sb (40,3), Ag (17,5), Au (0,35), Pd (0,31). Above-high values of B, Ga, Ge, Tl were determined. Among the alkaline elements, Na (10722 grams per ton) is sharply prevalent. Content of Li (up to 16240 grams per ton), Sn (up to 448.87) with an uneven distribution of Ta, Nb, Be. In terms of high concentration, Li approaches the Koktogai deposit (China). The noble metal group of elements is represented by Ag (17,52), Au (0,22), Sb (40,30). Studies have shown that spodumene contains a wide range of rare elements (Li, Ta, Nb, Sn, W) and is one of the main indicator minerals of rare metal pegmatite formation.

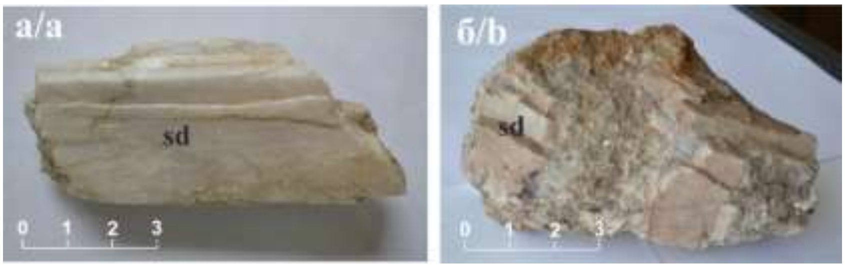

Fig. 6. *Typomorphic samples of the spodumene lepidolite-spodumene-clevelandite complex: a) prismatic crystal of spodumene with glass luster; b) metasomatic replacement of spodumene with quartz-albite-mica vein*

Рис. 6. *Типоморфные образцы сподумена лепидолит-сподумен-клевеландитового комплекса: а) призматический кристалл сподумена со стеклянным блеском; б) метасоматическое замещение сподумена кварц-альбит-слюдистым прожилком*

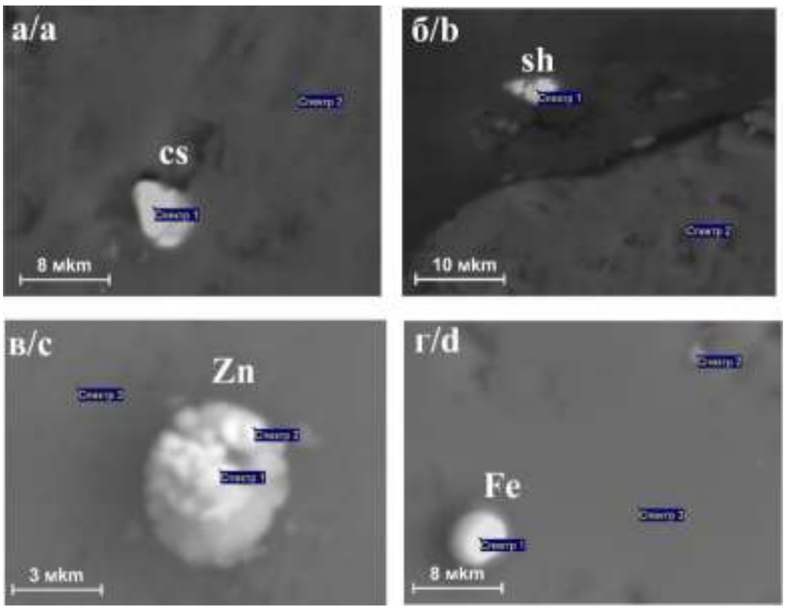

Fig. 7. *Micro-inclusions in the spodumene of the Yubileinoe deposit. Analyst A.V. Rusakova. a) micrograin lumpy cassiterite; b) inclusion of scheelite; c) native iron with zinc admixture; d) native teardrop-shaped iron*

Рис. 7. *Микровключения в сподумене Юбилейного месторождения. Аналитик А.В. Русакова. а) микрозерно касситерита комковидной формы; б) включение шеелита; в) самородное железо с примесью цинка; г) самородное железо каплевидной формы*

Ambigonite $LiAl[PO_4]$ F is noted in the form of large prismatic crystals (up to 10–15 cm in size) with well-defined pinacoid faces. It is a typical lithium mineral of the colored complex, associated with clevelandite, lepidolite, spodumene, pollucite and quartz, forms idiomorphic aggregates. When weathered, it becomes brownish-pink in color (Fig. 8).

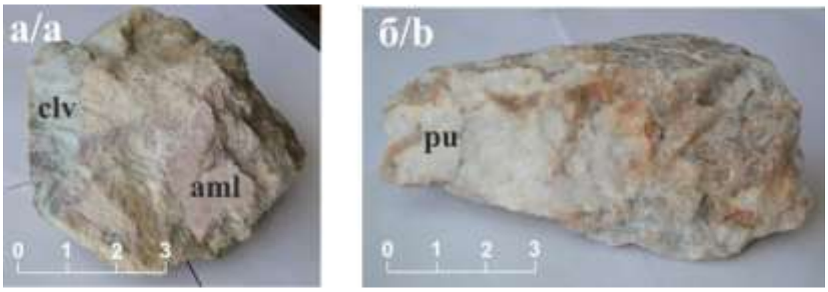

Fig. 8. *Typical samples of amblygonite and pollucite of the colored complex: a) relict amblygonite crystal corroded by quartz and fine-flaked lepidolite; b) nest of white pollucite*

Рис. 8. *Типичные образцы амблигонита и поллуцита цветного комплекса: а) реликтовый кристалл амблигонита, корродируемый кварцем и мелкочешуйчатым лепидолитом; б) гнездо поллуцита белой окраски*

Colored tourmalines are also informative minerals, differing in color, morphological characteristics and chemical composition. Black tourmalines (sherl) with a low content of trace elements reflect pegmatites of simple composition. The colored mineral complex contains aggregates of dark green tourmalines of variable color, blue indigolite crystals, polychrome tourmalines, and pink rubellites (Fig. 9). Colored tourmalines are associated with clevelandite, lepidolite, pollucite and are indicators of rich rare metal ores (Ta, Nb, Be, Sn, Li, Cs).

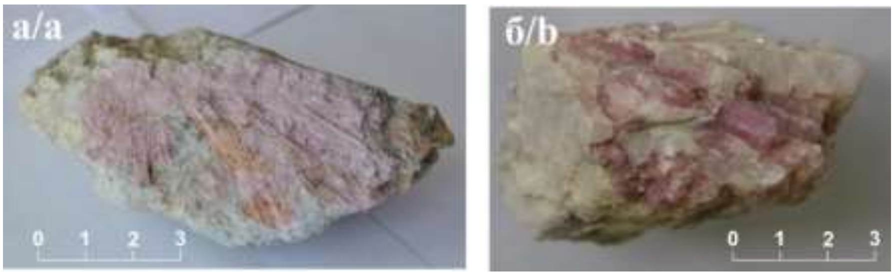

Fig. 9. *Rubellite crystals in pegmatites of the Yubileinoe deposit: a) radiant accumulations of rubellite; b) crystals of rubbelite in quartz*

Рис. 9. *Кристаллы рубеллита в пегматитах Юбилейного месторождения: а) лучистые скопления рубеллита; б) кристаллы руббелита в кварце*

Clevelandite forms curved large-lamellar crystals of bluish-gray color, associated with quartz, lepidolite, spodumene, petalite, and other minerals (Fig. 10).

According to the BSE image data, clevelandite consists (in %) of Na_2O (11,48), Al_2O_3 (20,1), SiO_2 (67,28), P_2O_5 (0,37), K_2O (0,16), CaO (0,18). It is characterized by a patchy openwork and veinlet dissemination of fluorapatite (F – 5,33; P_2O_5 – 34,33; CaO – 47,47 %). According to the results of mass spectrometry, increased contents (grams per ton) were found in clevelandite: Li (348,15), Sn (353,3), Ta (17,59). The amount of rare earths is low (5,46 grams per ton) with a maximum Dy value (3,07 grams per ton). Other elements are represented (in grams per ton) mainly Fe (5573), Mn (110), Ti (87) and Cr (66).

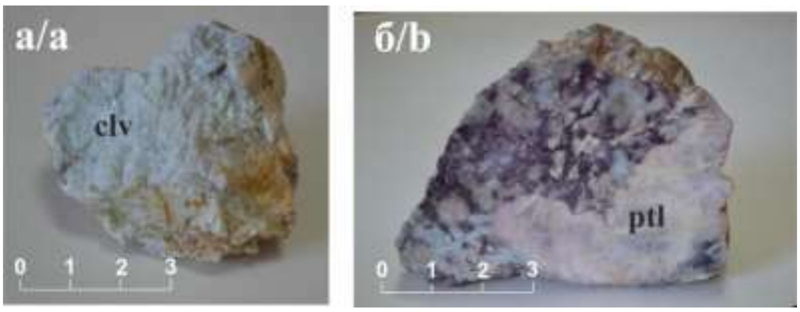

Fig. 10. *Klevelandite varieties in quartz-spodumene-lepidolite (colored) complex: a) aggregates of bluish-gray clovelandite; b) clevelandite in association with quartz, large-lamellar lepidolite, and spotted petalite*

Рис. 10. *Разновидности клевеландита в кварц-сподумен-лепидолитовом (цветном) комплексе: а) агрегаты клевеландита голубовато-серого цвета; б) клевеландит в ассоциации с кварцем, крупнопластинчатым лепидолитом и петалитом пятнистой окраски*

Pollucite $Cs[AlSi_2O_6]$ belongs to the latest pegmatite minerals, closely associated with lithium-bearing micas, amblygonite, petalite, colored tourmalines, fluorapatite, cassiterite, and quartz. It is observed in the form of solid masses of milky white, fine and fine-grained structure, often of a sugar-like appearance. It is the main mineral of cesium ores, which were mined at the Yubileinoe deposit. The SEM image shows relatively large grains of pollucite (up to 100 µm in size), which are intersected by microlite and late generation cassiterite (Fig. 11).

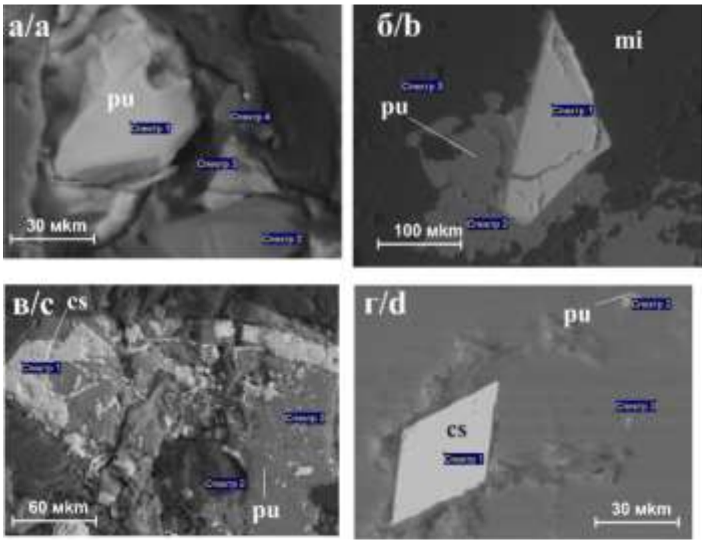

Fig. 11. *Microinclusion of rare-metal minerals in pegmatites of the non-ferrous complex: a) micrograins of pollucite; b) intergrowth of tantalum-bearing microlite and pollucite; c) nested and vein accumulations of cassiterite in pollucite; d) cassiterite crystal in a Q-Al matrix*

Рис. 11. *Микровключение редкометалльных минералов в пегматитах цветногокомплекса: а) микрозерна поллуцита; б) сросток танталоносного микролита и поллуцита; в) гнездовидные и прожилковые скопления касситерита в поллуците; г) кристалл касситерита в Q-Al матрице*

Tantalite is the main ore mineral, represented by large black crystals and forms a fine dissemination (5–8 mm) in quartz, clovelandite, lepidolite, spodumene and other minerals. It is also noted in the form of irregular grains or short-prismatic and tabular crystals of brownish-black color (Fig. 12). Several morphological varieties have been identified, differing in the appearance of crystals, chemical composition and distribution of impurity elements.

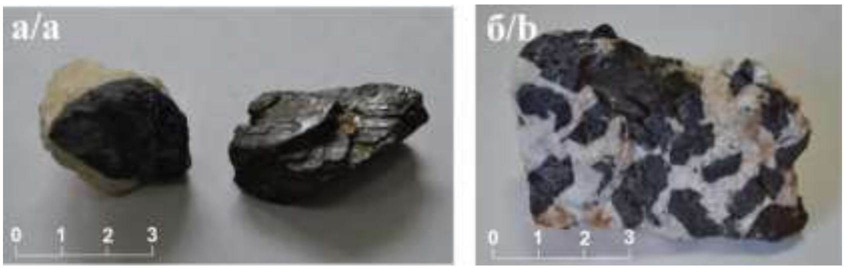

Fig. 12. *Tantalum-bearing minerals of rare metal pegmatites: a) tantalite crystals; b) nested cluster of tantalite crystals in granular bud-shaped quartz*

Рис. 12. *Танталоносные минералы редкометалльных пегматитов: а) кристаллы танталита; б) гнездовидное скопление кристаллов танталита в зернистом почковидном кварце*

Based on the results of analyzes at the Yubileinoe deposit, the following types of tantalites were identified: 1) manganotantalites – $Mn(Ta,Nb)_2O_6$, enriched in manganese (Mn/Fe ratio=10,3–16,9); 2) tapiolites of increased iron content – $Fe(Ta, Nb)_2O_6$; 3) ixiolites with increased Sn content (more than 10 %) and 4) fluorine-containing microliths $(Ta, Nb, Li, Sn, Fe, Mn)_4O_8$. Tantalites are characterized by sodium alkalinity (Na/K=1,5–11,3), which in association with the composition of clevelandite and spodumene reflects the alkaline environment of ore deposition. The increased manganese content of tantalum-bearing minerals is confirmed by the results of BSE analyzes, the average MnO content (16,33 %) sharply prevails over FeO – 0,71 % (23 times).

The varieties of tantalum-bearing minerals at the micro level are shown in Fig. 13. Columbite is represented by columnar crystals (Nb/Ta>2,2 times). In the microlite, the Ta content is 52,23 wt. %, the W impurity content is 5,80; Ca – 4,07; F – 0,04 (Fig. 14, *b*). Uranium-bearing tantalite (Ta – 55,76; Nb – 3,18 wt. %), revealed Pb impurities – 8,09; U – 9,37), nanodispersed dissemination of Ta, W, U, Pb, Hf, Ca, Au are recorded, uranium rings are clearly manifested (Fig. 14, *c*). In a lumpy grain of manganotantalite (Fig. 14, *d*), the ratio of Mn, Nb and Ta is

1:2:3,2. In ixiolite, the weight contents of Ta (39,50), Sn (27,02), and Au (1,17 wt. %) were determined.

According to mass spectrometry data, the Ta/Nb coefficient in tantalum-bearing minerals varies from 0,36 to 5,92. The content of rare earths is low (REE up to 30 grams per ton) with a predominance of the light group of elements over the heavy (1,9–6,4 times). In microlites, characteristic impurity elements (grams per ton): Zr (up to 28140) and Hf (up to 8887), B (up to 320), Hg (11,03), U (up to 895) and In (up to 266,2) (for account of the admixture of cassiterite). For the first time, according to the results of electron microscopy in tantalites, the weight contents of noble metal elements (Au, Ag, Pt, Ir, Cd, Sb), in particular Au, more than 50 grams per ton, were determined. Thus, in the course of the evolution of the pegmatite process, there was a change in the composition and an increase in the varieties of tantalum-bearing minerals from columbite and ferritantantalite to tantalite-columbite, manganotantalite, ixiolite and microlite with an increased concentration of tantalum in later mineral complexes.

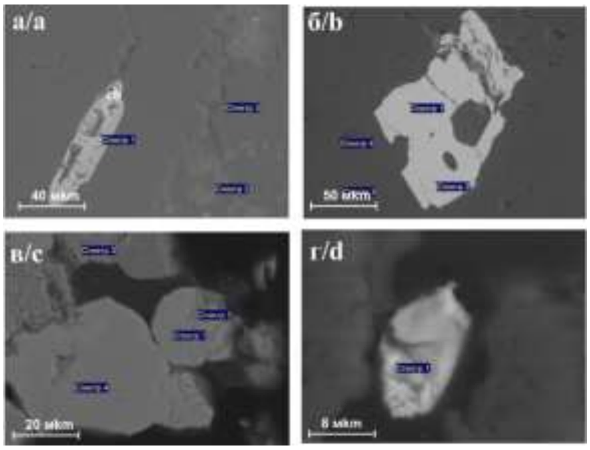

Fig. 13. *Microinclusions of tantalum-bearing minerals in rare metal pegmatites: a) columbite crystal; b) micrograin microlite; c) uranium-bearing tantalite; d) submicroscopic inclusion of manganotantalite*

Рис. 13. *Микровключения танталоносных минералов в редкометалльных пегматитах: а) кристалл колумбита; б) микрозерно микролита; в) ураноносный танталит; г) субмикроскопическое включение манганотанталита*

Conclusion

New data have been obtained on the formation patterns, features of the material composition of ores of Yubileinoe rare-metal pegmatite deposit and its geological structure. Based on geological, geochemical and mineralogical studies, information was obtained on the composition of pegmatite ores with the release of typomorphic minerals (clevelandite, lepidolite, colored tourmalines, spodumene, pollucite, ixiolite, etc.) and main geochemical elements of rare metal ore formation (Nb, Ta, Be, Cs, Li, F, P, etc.).

New studies of the material composition of pegmatites were carried out by the authors using modern laboratory methods to study typomorphic minerals and geochemical elements of a rare-metal pegmatite formation of the Yubileinoe deposit as an example. Rare metal pegmatites were formed as a result of the multistage development of metasomatic processes: microclinisation, accompanied by the formation of block microcline pegmatites and mineral paragenesis (block quartz and microcline, large-lamellar muscovite, columbite and beryl); albitisation, which is associated with the formation of albite-microcline and albite mineral complexes, which are the matrix of rare-metal pegmatite veins with ordinary beryllium-tin-tantalum ores; greisenisation, fixed by a quartz-albite-muscovite complex, in the inner parts of pegmatite veins; typomorphic minerals – green lithium-bearing muscovite, fluorapatite, verdelite, tantalite-columbite, and cassiterite; spodumenisation, manifested by new formation of the most productive mineral complexes (quartz-spodumene, quartz-spodumene-clevelandite, quartz- clevelandite-spodumene-lepidolite, etc.).

The general evolution of pegmatite formation was accompanied by a more complex shape and increase in the thickness of pegmatite veins, increase in the amount of ore and accompanying minerals, concentration of rare metal mineralization (Ta, Li, Sn) and increase in the contents of Zr, Hf, U, TR.

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ОСОБЕННОСТИ ФОРМИРОВАНИЯ, ВЕЩЕСТВЕННОГО СОСТАВА И ГЕОЛОГИЧЕСКОГО СТРОЕНИЯ РЕДКОМЕТАЛЛЬНЫХ ПЕГМАТИТОВЫХ МЕСТОРОЖДЕНИЙ КАЛБИНСКОГО РЕГИОНА НА ПРИМЕРЕ ЮБИЛЕЙНОГО МЕСТОРОЖДЕНИЯ

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Актуальность *исследования обусловлена недостаточной изученностью поведения редких металлов в процессе образования пегматитовых руд в Калбинском регионе, а также необходимостью расширения минерально-сырьевой базы редкометалльных месторождений региона с постановкой геологического и минерагенического картирования.*
Цель: *выявление особенностей геотектонического развития, геологического строения и вещественного состава редкометалльного месторождения Юбилейное (Калбинский регион).*
Объекты: *крупное промышленное редкометалльное месторождение Юбилейное и его минеральные комплексы.*
Методы: *детальное геолого-геохимическое и минералогическое исследование региона работ, использование материалов работ прошлых лет, фондовой литературы, а также проведение лабораторных исследований (масс-спектрометрические, микрозондовые, геохронологические и другие исследования). При диагностике минеральных комплексов учитывались структурные взаимоотношения минералов между собой, а также геохимическая интерпретация результатов лабораторных исследований.*
Результаты. *Выделяется пространственно-генетическая связь редкометалльно пегматитового месторождения (Nb, Ta, Be, Cs, Li, Sn) с гранитами I фазы калбинского комплекса P_1 (285 млн лет). В размещении Юбилейного месторождения ведущая рудоконтролирующая роль придается системе глубинных широтных разломов древнего заложения, подновленных в герцинский цикл. Приводится геолого-генетическая модель ритмично-пульсационного редкометалльного пегматитообразования Юбилейного месторождения, отражающая зональное развитие минеральных комплексов от олигоклаз-микроклиновых (безрудных) до альбитовых, грейзеновых, сподуменсодержащих и поллуцитоносных (рудных) с возрастающей концентрацией оруденения. Получена информация о составе пегматитовых руд с выделением типоморфных минералов (клевеландит, лепидолит, цветные турмалины, сподумен, поллуцит, иксиолит и др.) и главных геохимических элементов редкометалльного рудообразования (Nb, Ta, Be, Cs, Li, F, P и др.).*

Ключевые слова:
Калбинский регион, гранитоиды, Юбилейное месторождение, редкие металлы (Nb, Ta, Be, Cs, Li, и др.), моделирование, прогнозирование.

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