Geology

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RARE METALS IN MINERALS OF STANNIFEROUS METASOMATITES FROM THE VERKHNEURMIYSKY ORE CLUSTER (FAR EAST, RUSSIA)

Viktor I. ALEKSEEV
Saint-Petersburg Mining University, Saint-Petersburg, Russia

This article is dedicated to the rare metal mineralization of stanniferous metasomatites of the Verkhneurmiysky ore cluster in the Far East of Russia. The mineral composition of metasomatites, formed during the five stages of the zwitter-tourmalineite stanniferous complex formation was studied. These stages were characterized as biotite-sericite, muscovite-quartz, siderophyllite-topaz, quartz-tourmaline, and chlorite-sericite. Rare metal-bearing minerals were selected and the concentrations of rare metals were estimated.

The ore and geochemical types of the studied metasomatites were determined. There was shown the presence of many rare metal-bearing minerals in the composition of stanniferous metasomatites in this region. The set of the rare metals (Nb, Ta, W, Y, REE (from La to Lu), Be, Li, Zr, Hf, In, Sc, Se, and Cd) is of strategic importance for the development of the Russia mineral resources base. Minerals concentrating rare metals were divided into two types: minerals, containing rare metals due to its stoichiometry and minerals (if vein and ore origin) with isomorphic impurities of rare metals.

There was traced the sequence of rare metal-bearing minerals formation and the evolution of their composition. Minerals of rare metals were formed throughout the history of the zwitter-tourmalineite formation, starting from the pre-ore stage of biotite feldspatholites to the post-ore of chloritites stage, including the zwitter ore stage. It was also shown a stepwise decrease in the intensity rare metal-bearing minerals formation and the evolution of the mineralization composition from lithophilic rare metals to chalcophylic ones: (LREE, Zr, Hf) → (W, Nb, Ta, Y, HREE, Sc) → (Sn, In, Cd, Se).

Magmatic, metasomatic and crystal chemical factors affecting the rare metal-bearing minerals formation in the Verkhneurmiysky ore cluster have been revealed. The ore cluster's prospects are related to the presence of lithium-fluoric granites of the Pravourmiyskiy complex, controlling the tungsten-stanniferous zwitter and tourmalinite with associated rare metal mineralization.

Key words: rare metals; Li-F granites; biotite; greisen; zwitter; tourmalinite; chloritite; Verkhneurmiysky ore cluster; the Far East of Russia

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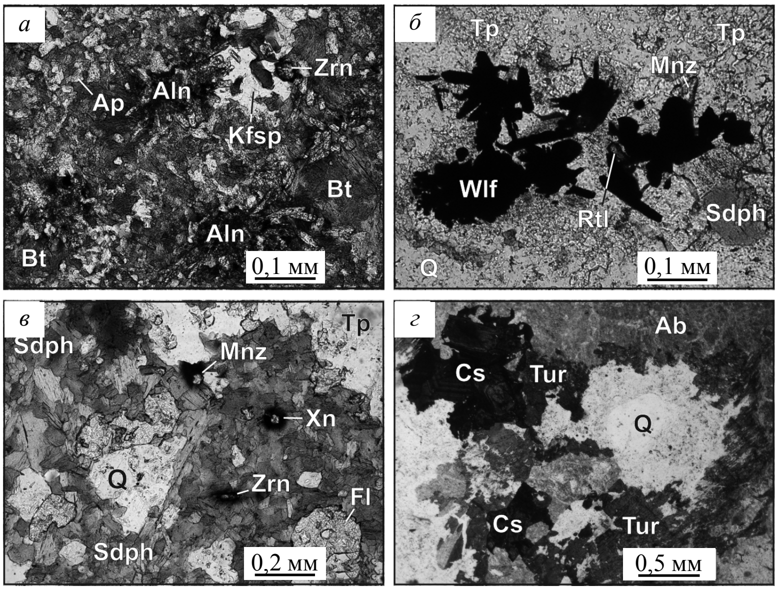
Introduction. The concept of «rare metals» is constantly changing, depending on the development of geological exploration and processing technologies and market conditions. Since the days of D.I.Mendeleyev and V.I.Vernadsky, low crustal abundance and technological progress stimulating demand for a chemical element have been constant criteria to determine «rare metal» [6, 16]. Russia has a significant resource potential of rare metals. Among the other sources of rare metals, there are deposits with rare metal granites. The mineralization of such deposits (columbite, pyrochlore, zircon, fergusonite, etc.) is associated with feldspatholites accompanying alkaline granites (Katugin, Transbaikalia; Ulug-Tanzek, Tuva; Ermakovskoe, Buryatia, etc.). While zwitters associated with subalkaline Li-F granites, bear tungsten-tin mineralization (Tigrinoe, Primorye; Odinokoe, Yakutia; Iultin, Chukotka, etc.) [15].

A possible avenue for the rare metals resources base development in Russia is the mineralogical and geochemical revaluation of previously known tungsten-tin deposits associated with Li-F-granites and located in the Russian Far East [2, 12]. It is necessary to find out which rare elements and in what concentrations are contained in certain minerals of these deposits, and which minerals are suitable for profitable rare elements extraction. This will ensure appropriate rare metals resources assessment of tungsten-tin deposits. Some rare metal-bearing minerals were found in the rocks of zwitter-tourmalineite metasomatic formation in Verkhneurmiysky copper-tungsten-tin ore cluster (Priamurye region). The mineralogical and geochemical evolution of these rare metal-bearing associations has also been studied in previous works [4, 5]. This article presents the study of the rare metal mineralization of five metasomatic formation stages, characteristic for the Verkhneurmiysky ore cluster: biotitite → muscovite greisens → zwitters → tourmalineites → chloritites [3, 11]. The objective of this work is to identify minerals containing rare metals in the composition of stanniferous metasomatites, to study the evolution of rare metal mineralization and to appraise its practical significance.

Methodology and techniques. The scientific basis of the work is a comprehensive research approach to the hydrothermal and metasomatic formations. The guiding principle of the research is the rational integration of structural geological, metasomatic, mineralogical, geochemical and ore zonation studies, based on the large-scale geological mapping [13]. Mineralogical study of metasomatites includes an assessment of their composition and structure, a finding of the indicative minerals and study of their forms and structures, as well as their role in petro- and ore genesis [2, 3, 11].

Special attention was given to ore and vein minerals containing rare metals. Metasomatites were sampled on the mineralization sites identified by geochemical mapping. Their petrographic and geochemical studies were carried out at the Center for Collective Use of the St. Petersburg Mining University with the help of emission and X-ray spectral fluorescence analysis (ED-2000, XRF-1800), as well as ICP-MS technique (ICPE-9000). The search for rare metal-bearing minerals was carried out under the electron microscope (JSM-6460LV, JSM-7001F, JIB-4500, Cameca MS-46) in the samples with a high bulk content of rare metals. The chemical composition of mica, fluorite, wolframite, cassiterite, and sulphides was determined by the wet-chemistry based, ICP-MS, and AAS analysis. The composition of microminerals was studied on electron probe micro-analyzers with a wave and energy-dispersive spectrometers (CamScan MV2300, JSM-7001F, JXA-8230).

Stanniferous metasomatites of the region. The Verkhneurmiysky ore cluster (VOC) is a part of the Badzhal ore region, located within the Khingano-Okhotsk volcanic belt [9, 10]. The Badzhal region is located in the epicentre of the largest asthenospheric dome, fixed by a negative gravity anomaly and intense heat flow of the lithosphere [2]. The structure of the VOC is characterized by the thick Cretaceous stratum of acidic volcanic rocks, permeated with subvolcanic and hypabyssal granitic intrusions. The VOC occupies the Verkhneurmiysky granite pluton and the adjacent Urmiyskiy ignimbrite volcanogenic area. Lithium- fluoric granites of the Pravourmiyskiy complex were identified in the Verkhneurmiysky pluton. These Li-F granites affected the formation of ore-bearing zwitter-tourmalineite metasomatites and the formation of the Pravourmiyskoe major tungsten-tin ore deposit occurred in the eastern near-contact zone of the massif [1-3, 10, 11, 14].



Rare metal-bearing minerals in the stanniferous metasomatites of the Verkhneurmiysky ore cluster (thin sections images, Leica DM750P):
a – K-feldspar-quartz-biotite metasomatite with allanite-(Ce), Hf-zircon, and Ce-apatite; *b* – siderophyllite-quartz-topaz zwitter with Nb-wolframite, Nb-W-rutile, and monazite-(Ce); *c* – topaz-quartz- siderophyllite zwitterwith Y-fluorite, monazite-(Ce), xenotime-(Y), and Hf-zircon; *d* – albite-quartz-tourmaline metasomatite with In-Nb-cassiterite. Minerals:Ab – albite, Aln – allanite-(Ce), Ap – apatite-(CaF), Cs – cassiterite, Fl – fluorite, Kfsp – feldspar, Mnz – monazite-(Ce), Sdph – siderophyllite, Tp – topaz, Tur – tourmaline, Q – quartz, Xn – xenotime-(Y), Zrn – zircon

The earliest tin-bearing formations of the region are hydrothermal rocks of *the biotite-sericite (first) stage*, represented by biotite-feldspar and biotite-sericite metasomatites. The pre-ore biotitites form steeply dipping zones with a thickness of 0.1-2 m and an extension of 2-200 m in the following ore fields: Osbadzhal (Wolfram-Makit, Dvoinoye), Pravourmiyskoe (Pravourmiyskoe, Dozhdlivoe, Alenushkino, Sulphidnoe), Wolframovoe (Lesnoye) and Synchuginskoe (Visokoe, Dlinnoe). Biotite feldspatholites are composed of biotite, muscovite, albite, K-feldspar, also containing quartz, garnet, and tourmaline in subordinate quantities. Accessory and ore minerals are presented by pyrrhotite, chalcopyrite, fluorite, apatite, rutile, scheelite. The biotitites contain rare metal-bearing minerals: allanite-(Ce), zircon, monazite-(Ce), xenotime-(Y), apatite-(F), ilmenite, thorite, and biotite (Fig. *a*).

The greisens of *the muscovite-quartz* (*second*) *stage* are superimposed on biotite metasomatites, with steeply dipping zones of 0.1-4.0 m (up to 20 m) and a length of 200-1800 m in the following ore occurrences: Grustnoe, Granitnoe, Ulun, and Wolfram-Makit (the Os-Badzhal ore field); Alenushkino, Yuzhnoe, Geophysicheskoe (the Pravourmiyskoe ore field); Lesnoe (the Wolframovoe field), Visokoe, Vetvistoe (the Synchuginskoe field). The muscovite-quartz metasomatites are permeated by veins containing quartz, muscovite, fluorite and sulphides. Ore minerals are cassiterite, wolframite, molybdenite, bismuthinite and arsenopyrite. Minerals containing rare metals in muscovite greisens are represented by cassiterite, wolframite, molybdenite and muscovite.

The siderophyllite-topaz (*third*) *stage* includes the formation of numerous bodies of tungsten-tin-bearing zwitters from the Pravourmiyskoe deposit and Wolfram-Makit, Dvoinoe (the Os-Badzhal ore field); Lesnoe (the Wolframovoe ore field), Visokoe (the Synchuginskoe ore field) ore occurrences [5, 9, 14]. The zwitters compose thick (up to 40 m) deposits and thin (*n* cm) halos in stockworks of topaz and quartz veins. The placement of metasomatites, composed of quartz, siderophyllite, topaz, and muscovite, is controlled by Li-F granites [2, 3]. The zwitters accessory and ore mineralization are composed of fluorite, cassiterite, wolframite, arsenopyrite, loellingite, beryl, scheelite, native bismuth, bismuthinite, etc. The rare metal-bearing minerals of stanniferous zwitters are fergusonite-(Y), euxenite-(Y), plumbopyrochlore, monazite-(Ce), xenotime-(Y), zircon, beryl, wolframite, cassiterite, scheelite, sphalerite, native bismuth, rutile , siderophyllite, muscovite, and fluorite (Fig. *b*, *c*).

The quartz-tourmaline (*fourth*) *stage* is characterized by the predominance of tourmaline metasomatic veins with a thickness of up to 40 cm and surrounding silicification, as well as an albitization of the host rocks. These veins are confined to the bodies of quartz-topaz and muscovite-quartz stanniferous greisens within the Pravourmiyskoe, Wolfram-Makit, Granitnoe, Lesnoe, and Vysokoe ore occurrences. The metasomatites surrounding veins play the key role in the steeply dipping zones of stanniferous tourmalineites with a thickness of 0.3-9 m and an extension of 500-600 m within Dvoinoye, Proskurnikova, Orokot, Omot-Makit (the Os-Badzhal ore field); Dozhdlivoe (the Pravourmiyskoe ore field); Dlinnoe, Vostochnoe (the Synchuginskoe ore field) ore occurrences. Tourmalinites are composed of quartz, sericite, albite (with an admixture of tourmaline), chlorite, and fluorite aggregates, also containing disseminations and veinlets with cassiterite, chalcopyrite and bornite. Such minerals as stannite, stannoidite, mawsonite, wittichenite, sphalerite, pyrrhotite, pyrite, native bismuth are less common. The rare metal-bearing minerals of tourmalineites are monazite-(Ce), zircon, scheelite, roquesite, cassiterite, wolframite, chalcopyrite, stannoidite, bornite, native bismuth, pyrite, epidote, and fluorite (Fig. d).

Metasomatites of *the chlorite-sericite* (*fifth*) *stage* are developed along high-angle faults and low-angle upthrow faults, forming zones of 0.1-83 m in thickness, 500-1600 m in extension and located at the Chloritovoye, Irungda-Makit (the Os-Badzhal ore field); Pravii Omot, Sulfidnoe (the Pravourmiyskoe ore field); Vostochnoe (the Synchuginskoe ore field) ore occurrences. Rock-forming minerals of the post-ore chlorities are chlorite, albite, sericite, and quartz, while secondary minerals are presented by epidote, calcite, tourmaline, prehnite, and zeolites. Accessory and ore minerals are fluorite, pyrite, sphalerite, galena, cassiterite, and antimonite. The rare metal-bearing minerals of chloritites are sphalerite, galena, fluorite, and epidote.

Rare metals in the minerals of stanniferous metasomatites of the Verkhneurmiysky ore cluster. In the metasomatites of *the biotite-sericite stage*, among all the rare metal-bearing minerals, allanite-(Ce) is of greatest interest (Fig. *a*). The allanite-(Ce) contains 4.76-17.52 of Ce_2O_3[*], 6.78-26.52 of ∑LREE (La, Ce, Nd), up to 3.93 of ThO_2, and up to 0.93 of SnO_2. Within the Sulfidnoe ore occurrence, there is a finding of allanite, containing up to 8.56 Y_2O_3. Microinclusions of monazite and xenotime occur in biotite-feldspar metasomatites. Monazite contains $LREE_2O_3$ (52.05-69.54), ThO_2 (0-10.45); xenotime contains Y_2O_3 (41.62-48.94), $HREE_2O_3$ (6.56-17.28),

[*] The content of all elements and minerals is specified in mass percentages.

ThO_2 (0-0.75), and UO_2 0-0.90. The zircon presence is also rather common. The content of ZrO_2 varies within 54.81-68.42, the rims are enriched with up to 2.15 of HfO_2, up to 1.58 of ThO_2, and up to 1.88 of UO_2. In rare cases, biotite metasomatites contain rare-earth (La, Ce, Nd) apatite-(CaF) ($LREE_2O_3$ 0.22-32.99, ThO_2 1.21-2.96), ilmenite (WO_3 3.62-5.56; Sc_2O_3 up to 1.24), and thorite (Y_2O_3 up to 6.65). The content of the biotite, concentrating rare elements, is: Li_2O 0,04-0,43; Rb_2O 0.06-0.32; Cs_2O 0,01-0,06; ZrO_2 0,02-0,20; WO_3 0-0,09; SnO_2 0-0,01; Y_2O_3 0-0,05.

In the greisens of the muscovite-quartz stage, the main rare metal-bearing ore minerals are: cassiterite (WO_3 0.02-0.56, Nb_2O_5 0.02-0.18, Sc_2O_3 0.001-0.004) and wolframite (Nb_2O_5 0.05-1.25, Ta_2O_5 0-0.91, Sc_2O_3 0.01-0.27, La_2O_3 0-0.007). The molybdenite with the content of Nb_2O_5 varying from 0 to 0.05 and Ag_2O ranging between 0 and 0.04 is relatively rare. The main impurities in muscovite are Li_2O 0.01-0.56, WO_3 0-0.02, and SnO_2 0-0.01.

Minerals containing rare metals are particularly diverse in ore zwitters of *the siderophyllite-topaz stage* (Fig. *c*). The rare metal-bearing minerals in the ore zwitters are: fergusonite (Nb_2O_5 49.18-54.16; Y_2O_3 22.15-32.50; $HREE_2O_3$ 9.27-34.41; $LREE_2O_3$ 0-2.71), euxenite (Nb_2O_5 52.99-62.81; Y_2O_3 9.88-22.12; WO_3 9.52-13.72), plumbopyrochlore (Nb_2O_5 44.56-56.22; Y_2O_3 0-13.98; WO_3 10.34-18.54), monazite ($LREE_2O_3$ 49.28-66.86; ThO_2 0.48-10.71; UO_2 0.37-2.14), xenotime (Y_2O_3 35.75-51.45; $HREE_2O_3$ 14.34-25.67; $LREE_2O_3$ 0-2.38; ThO_2 0-1.63; UO_2 0.58-3.73), and zircon (ZrO_2 55.38-70.11; HfO_2 0.29-1.98; ThO_2 0-0.41; UO_2 0-1.48) [4]. Findings of beryl are described in the metasomatites of the Verkhneurmiysky massif and the Pravourmiyskoe deposit.

The main ore minerals, wolframite and cassiterite (Fig. b), contain 66.41-77.77 and 0-0.94 of WO_3, 0-2.15 and 0.01-0.13 of Nb_2O_5, 0-1.41 and 0.001-0.012 of Sc_2O_3, respectively. Wolframite also contains 0-0.07 of Y_2O, while cassiterite is enriched with 0-0.001 of In_2O_3. The highest content of rare elements is characteristic to minerals in the western part of the VOC, located in the granites of the Verkhneurmiysky massif [4, 8]. The minor ore minerals are also enriched in rare elements: scheelite contains 69.66-87.53 of WO_3 and 0.36-10.46 of MoO_3; sphalerite has 0-1.04 of CdO. In some cases, enrichment in rare metal of native bismuth (SeO_2 up to 1.50); rutile (MoO_3 up to 1.30, WO_3 up to 4.17), ilmenite (WO_3 up to 2.84) is observed. Sufficient quantities of rare metals are preserved in such zwitters vein minerals as fluorite, siderophyllite and muscovite [8]. Fluorite from zwitters is enriched in Y_2O_3 (up to 0.47), and also contains all HREE (up to 0.14) and LREE (up to 0.07). The content of siderophyllite is: Li_2O 0.05-1.53, Rb_2O 0.12-0.60, Cs_2O 0.01-0.15, SnO_2 0.01-0.62, WO_3 0.001-0.015. Muscovite contains the following se of elements: Li_2O 0.01-0.65, Rb_2O 0.03-0.11, Cs_2O 0-0.01, SnO_2 0-0.03, WO_3 0.01-0.18.

In the tourmalineites of *the quartz-tourmaline stage*, the minerals, containing rare-metals as the main cations are rare. The inclusions of monazite ($LREE_2O_3$ 49.20-51.04; ThO_2 3.17-3.95), zircon (ZrO_2 61.68-70.73; HfO_2 0.13-3.04; ThO_2 0.09-1.00; UO_2 0.20-1.25), and scheelite (WO_3 86.90) were found in tourmaline. The roquesite (In_2O_3 51.26-56.91; CdO 0.55-0.99; SnO_2 0.75-1.16; Ag_2O 0.34-0.99) was described among the other sulfides. There is a wide range of the minerals, containing the impurities of rare metals in the tourmaline-bearing metasomatites (Fig. d). Among them, the main ore minerals are cassiterite (WO_3 0.07-0.18; Nb_2O_5 0-0.07; Sc_2O_3 0-0.01; In_2O_3 0-0.002), wolframite (Nb_2O_5 0.05-0.53; Sc_2O_3 0.01-0.03; Y_2O_3 0.001-0.002), chalcopyrite (SnO_2 0.12-3.17; In_2O_3 0.01-0.94; Ag_2O 0-0.53), stannoidite (SnO_2 24.42-26.89; In_2O_3 0-0.67; CdO 0-0.37; Ag_2O 0-0.74), bornite (SnO_2 0-3.75; In_2O_3 0-0.54; Ag_2O 0-0.33), native bismuth (SnO_2 0-0.83; CdO 0-0.63; Ag_2O 0-0.67), and pyrite (WO_3 1.69-4.35; SnO_2 0-0.17). Minor minerals of tourmalineites, containing impurities of LREE (La, Ce, Nd), yttrium and other rare metals, are: epidote ($LREE_2O_3$ 15.84-21.21; ThO_2 0-0.99; SnO_2 0-0.69) and fluorite Y_2O_3 0.01-0.07; $LREE_2O_3$ 0-0.06; $HREE_2O_3$ 0-0.02; Sc_2O_3 0-0.001; SnO_2 0.002-0.007).

Chlorite metasomatites of *the post-ore chlorite-sericite stage* do not contain rare metals minerals. However, in the polymetallic sulphide mineralization, characteristic for this stage, impurities of In, Cd, Se and other rare metals are observed: sphalerite (CdO 0.09-2.12; In_2O_3 0.003-1.085; SnO_2 0-0.79; Ag_2O 0-0.01) and galena (SeO_2 1.57-10.83; SnO_2 0-0.07; In_2O_3 0-0.001; Ag_2O: 0.01-6.78). Fluorite from chloritites contains 0-0.64 of Y_2O_3; 0-0.02 of $HREE_2O_3$; 0-0.03 of $LREE_2O_3$, and 0-0.01 of SnO_2. There is also an epidote with the impurities of SnO_2 varying from 0.44 to 6.40.

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Discussion. The study shows the presence of many rare metals-bearing minerals in the composition of the stanniferous metasomatites of the Verkhneurmiysky ore cluster. The present set of the rare metals (Nb, Ta, W, Y, REE (from La to Lu), Be, Li, Zr, Hf, In, Sc, Se, and Cd) is of strategic importance for the development of the Russia mineral resources base. This fact causes the research objectives, aimed at the study of the origin and evolution of rare metal mineralization, as well as the assessment of its practical importance. Magmatic and metasomatic conditions, and crystal chemical properties are the key factors affecting the rare metal-bearing minerals formation [8, 10-13, 15, 16].

The magmatic and metasomatic conditions of rare metal mineralization of the VOC were studied earlier. The Pravourmiyskiy rare metal-granite complex is identified within the studied area. This complex is associated with the formation of large-scale tungsten-tin ore deposits bearing rare-metal mineralization [1, 2, 5]. Hydrothermal and metasomatic conditions of the rare metals-bearing minerals formation have been supplemented with the mineral composition of tin-bearing metasomatites. The multi-stage pneumatolytic-hydrothermal process, determining the formation of the tungsten-tin zwitter-tourmalinite complex in VOC, has been specified [1, 3, 8, 11, 14].

There are three independent *crystal chemical conditions* affecting the rare metal-bearing minerals formation: a) presence of rare elements, incompatible with rock-forming elements in the parental melts and consequent accumulation of such elements in residual melts and fluids; b) formation of polytypic structures by rare metals in combination with related elements (Ti, Al, Mn, Fe, Sn); i.e. independent crystallization of rare metals-bearing minerals [7]; c) isomorphic substitution of main cations by rare metals in the composition of ore and vein minerals. The first condition is satisfied by the magmatic system of the VOC, which ensured a large-scale pneumatolytic-hydrothermal alteration of the strata containing the Li-F granites, with the participation of fluids saturated with F, Nb, Ta, Li, Zr, Be, Y, and REE [1, 2, 4 , 5, 8-11, 14]. As it is shown in the article, two last conditions are realized in the region under study: there are minerals with the stoichiometric amount of rare metals (fergusonite, euxenite, plumbopyrochlore, allanite, zircon, monazite, xenotime, and roquesite) and minerals with the impurities of rare metals (ore minerals: wolframite, cassiterite, sulfides of Cu, Sn, Fe, Zn, Pb, Mo, scheelite, rutile, ilmenite, and native bismuth; vein minerals: fluorite, siderophyllite, muscovite, and epidote). The in situ analysis made it possible to determine the presence of isomorphic impurities and the absence of microinclusions of the rare-metal phases.

Pneumatolytic-hydrothermal rare metal deposits are usually characterized by the multistage mineral formation and the evolution of rare metal associations. The data given in the article allow us to conclude that rare metals-bearing minerals were formed during the entire history of the zwitter-tourmalineite formation in the VOC, beginning from the pre-ore stage of biotite feldspatholites and ending up with the post-ore chloritites stage, including the zwitter ore one. The first alkaline stage is accompanied with the accumulation of zirconium and rare earth elements, the greisens of the second and third acidic stages show the high concentrations of the yttrium, niobium and tungsten, while the subalkaline metasomatites of the fourth and fifth stages are enriched with cadmium, indium and tin. The sequence of impurities accumulation can be presented as follows: (LREE, Zr, Hf) → (W, Nb, Ta, Y, HREE, Sc) → (Sn, In, Cd, Se). The transition from early to late stages is traced by the change of lithophile rare metals by chalcophile ones and the decrease in the intensity of rare metal mineral formation. The minerals with the stoichiometric content of rare metals are crystallized mainly at the early pneumatolytic stages.

Thus, it has been determined that a complex multistage rare metal mineralization of the VOC occurred due to the intrusion of rare-metal Li-F granites. Magmatic, metasomatic and crystal chemical factors affecting the rare metal-bearing minerals ore formation in the VOC have been revealed. Among the main future challenges are the correlation study between rare metals and main ore components (Sn, W, Cu) in ores; the finding of rare metal-bearing minerals in metasomatites of various stages; the study of rare metal-bearing minerals distribution within the area of interest and specific ore occurrences.

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Conclusions

1. The presence of minerals, containing a set of strategic rare metals (Nb, Ta, W, Y, REE (the entire spectrum from La to Lu), Be, Li, Zr, Hf, In, Sc, Se, and Cd) are revealed in the composition of the stanniferous metasomatites of the Verkhneurmiysky ore cluster. Two forms of concentration of rare metals are distinguished: minerals with the stoichiometric amount of rare metals (fergusonite, euxenite, plumbopyrochlore, allanite, zircon, monazite, xenotime, and roquesite) and minerals with the impurities of rare metals (ore minerals: wolframite, cassiterite, sulfides of Cu, Sn, Fe, Zn, Pb, Mo, scheelite, rutile, ilmenite, and native bismuth; vein minerals: fluorite, siderophyllite, muscovite, and epidote).

2. The rare metals-bearing minerals were formed during the entire history of the zwitter-tourmalineite formation. The transition from early to late stages is traced by the change of lithophile rare metals by chalcophile ones and the decrease in the intensity of rare metal mineral formation. The sequence of impurities accumulation can be presented as follows: (LREE, Zr, Hf) → (W, Nb, Ta, Y, HREE, Sc) → (Sn, In, Cd, Se).

3. Magmatic, metasomatic and crystal chemical factors affecting the rare metal-bearing minerals formation have been revealed. This may indicate the associated rare-metal mineralization within the deposits of the Verkhneurmiysky ore cluster.

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REFERENCES

1. Alekseev V.I. Far East belt of lithium-fluoric granites, ongonites and stanniferous zwitters. *Zapiski Gornogo instituta*. 2015. Vol. 212, p. 14-20 (in Russian).
2. Alekseev V.I. Lithium-fluoric granites of the Far East. St. Petersburg: Natsional'nyi mineral'no-syr'evoi universitet «Gornyi», 2014, p. 244 (in Russian).
3. Alekseev V.I. Metasomatic zoning of ore fields of the Badzhalsky District (Amur River region). *Zapiski Vsesoyuznogo mineralogicheskogo obshchestva*. 1989. Iss. 5, p. 27-37 (in Russian).
4. Alekseev V.I., Sukhanova K.G., Marin Yu.B. Niobium minerals as indicators of consanguinity of stanniferous zwitters and lithium-fluoric granites in Verkhneurmiysky massif (Amur River region). *Zapiski Rossiiskogo mineralogicheskogo obshchestva*. 2018. N 1, p. 85-100 (in Russian).
5. Alekseev V.I., Sukhanova K.G., Gembitskaya I.M. Evolution of the mineral forms of rare elements concentration in ore-bearing granites and metasomatites from Verkhneurmiysky ore cluster (Amur River region). *Zapiski Gornogo instituta*. 2017. Vol. 224, p. 149-155. DOI: 10.18454/PMI.2017.2.149 (in Russian)
6. Bykhovskii L.Z., Tigunov L.P., Temnov A.V. Defining the concept «rare elements» («rare metals»): historical and terminological aspects. *Mineral'nye resursy Rossii. Ekonomika i upravlenie*. 2015. N 3, p. 32-38 (in Russian).
7. Voloshin A.V. Tantalum-niobates. Systematics, crystal chemistry and evolution of minerals formation in granite pegmatites. St. Petersburg: Nauka, 1993, p. 298 (in Russian).
8. Gavrilenko V.V., Panova E.G. Geochemistry, genesis and typomorphism of the minerals of tin and tungsten deposits. St. Petersburg: Nevskii kur'er, 2001, p. 260 (in Russian).
9. Geodynamics, magmatism and metallogeny of the Russian East: V 2 kn. / Pod red. A.I.Khanchuka. Vladivostok: Dal'nauka, 2006. 981 (in Russian).
10. Gonevchuk V.G. Tin-bearing systems of the Far East: magmatism and ore genesis. Vladivostok: Dal'nauka, 2002, p. 297 (in Russian).
11. Marin Yu.B., Skublov G.T., Gul'bin Yu.L. Mineralogical and geochemical criteria of local forecasting of rare metal deposits. Mineralogicheskoe kartirovanie i indikatory orudeneniya. Leningrad: Nauka, 1990, p. 67-94 (in Russian).
12. Bortnikov N.S., Volkov A.V., Galyamov A.L., Vikent'ev I.V., Aristov V.V., Lalomov A.V., Murashov K.Yu. Mineral resources of strategic metals in Russia: performance and prospects. *Geologiya rudnykh mestorozhdenii*. 2016. Vol. 58. N 2, p. 97-119 (in Russian).
13. Plyushchev E.V., Shatov V.V., Kashin S.V. Metallogeny of hydrothermal and metasomatic formations. St. Petersburg: Izd-vo VSEGEI, 2012, p. 560 (Trudy VSEGEI. Novaya seriya. Vol. 354) (in Russian).
14. Semenyak B.I. About «zwitters» of Verkhneurmiysky ore cluster. *Rudnye mestorozhdeniya Dal'nego Vostoka*. Vladivostok: DVNTs AN SSSR, 1983, p. 20-25 (in Russian).
15. Beskin S.M., Marin Yu.B., Matias V.V., Gavrilova S.P. So what is «rare-metal granite»? *Zapiski Vsesoyuznogo mineralogicheskogo obshchestva*. 1999. Iss. 6, p. 28-40 (in Russian).
16. Rare Earth and Critical Elements in Ore Deposits / Ed. by Ph.L.Verplanck, M.W.Hitzman; Society of Economic Geologists, Inc. Broomfield, CO, USA, p. 365 (Reviews in Economic Geology. 2016. Vol. 18).

Author: **Viktor I. Alekseev**, *Doctor of Geological and Mineralogical Sciences*, *Professor*, *Alekseev_VI@pers.spmi.ru* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*).
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