Introduction

Minerals of the columbite — tanta\l{}ite (Col-Ta) group are the most important in commercial aspect minerals of tantalum: more than 50% of the world reserves of this rare metal is connected with these minerals.

The main suppliers of tantalum are the deposits connected with granite pegmatites and rare metal granites of subalkalic type. Due to the known tendency of working out of rich in tantalum pegmatite deposits, great in reserves but poor in tantalum content and hardly enriched deposits connected with rare metal granites become more and more significant.

There are two such deposits in the Eastern Transbaikalia, Russia (Orlovskoe and Aetykinskoe) connected with the same names rare metal granite massifs. The Orlovskoe deposit was intensively exploited up to the end of the 1980s (its ore was gravity enriched at the neighboring Orlovsky mining-and-processing combine). At that time, the Aetykinskoe deposit was prepared for exploitation introducing, but failed; only recently, tantalum production was initiated in moderate volumes with consequent processing by gravity enrichment at the Pervomaysky mining-and-processing factory. At these deposits, a significant part of tantalum is contained in the minerals of the Col-Ta group along with pyrochlore — microlite (Prch-Mcr) and, to a lesser degree, with cassiterite (Css) being the main tantalum-bearing minerals. As it is known from the literature devoted to these deposits, the spatial distribution of these minerals with concentration of Prch-Mcr in the granite massifs endocontact zones and relatively even occurrence of Col-Ta and Css (Lugovskoy et al., 1972) allows to predict the increase of importance of the columbite — tanta\l{}ite type ores in the tantalum balance as these deposits quarry mining.

That is why it is so important and actual to investigate Col-Ta group minerals from this type deposits and reveal their typomorphic features effecting the values of the ore technological processing during the exploration and estimation of such deposits.

The work was based on the materials obtained by the author as well as submitted for the investigation by S.M. Beskin, V.N. Pavlova, and A.E. Tsyganov (Institute of Mineralogy, Geochemistry and Crystal Chemistry of Rare Elements, Moscow), V.V. Matias (All-Russian Institute of Mineral Resources, Moscow), B.A. Levichev (Orlovsky Mining-and-Processing Combine, Chita oblast), A.M. Grebennikov and I.I. Kursinov (Pervomaysky Mining-and-Processing Combine, Chita oblast), Yu.K. Lebedev and A.N. Fedorov (Aetyinskaya Geological-and-Exploration Party, Zolotorechensk, Chita oblast).

Altogether there were investigated 224 disintegrated and panned samples from different phases and facia of the following rare metal amazonite — albite granite massifs containing Col-Ta group minerals: Orlovsky and Aetykinsky (Eastern Transbaikalia) and Maykul’sky (Southern Kazakhstan).
The massifs investigated are close to each other by the following several features: a) Late Hercynian age of formation; b) formation affiliation and connection with a unified extended Urals—Mongol—Okhotsk geosyncline belt and zones of tectono—magmatic activation of intermediate massifs; c) asymmetrical—fungiform (graptolitic) intrusion shape with intersecting interrelations with enclosing significantly silicate rocks; d) wide development of postmagmatic autometasomatic processes of albitionization and greisenization; e) assembly and quantitative correlations of rock-forming, accessory, and ore minerals; f) increased concentrations of the lithophile rare elements in comparison with their clarkes. Composite geological characteristics of the mentioned granite massifs have been described in our paper (Povarennykh, 1994) and numerous publications of the other researchers (Zalashkova, 1969; Lugovskoy et al., 1972; Alexandrov, 1989; Zaraysky, 2004; A. Rub, M. Rub, 2006; Beskin, 2007).

Analyses and determination of mineral features have been performed by the author and scientific researchers of several geological institutes and Lomonosov Moscow State University.

**Chemical typomorphism of the columbite tantalite group minerals**

Variations of chemical composition of these minerals reflect the complete isomorphism between two pairs of species-forming elements: Mn and Fe, Ta and Nb. The following several mineral species belonging to the columbite—tantalite group are nowadays distinguished: ferrocolumbite Fe2+Nb2O6, ferrotantalite Fe2+Ta2O6, manganocolumbite (Mn,Fe2+)(Nb,Ta)2O6, and manganotantalite MnTa2O6. Continuous isomorphic series exist between these mineral species. Concentrations of other isomorphic impurity elements are regularly insignificant and reach as follows: Ti (<12.8% W (<4.56%), Sn (<2.5%), TR (<2%), Al (<1.5%), Sc (<1.34%), and U (<0.5%) (Povarennykh, 1966; Voloshin, 1993; Povarennykh, 1983, 1991, 2008; A. Rub, M. Rub, 2006).

Specimens of the Col-Ta group minerals from the objects belonging to the following row of different formation types "carbonatites — alkaline rare metal granites — subalkalic rare metal granites — granitic pegmatites" are significantly distinguished from one another by content of the main species-forming cations (Ta, Nb, Fe, and Mn) and tantacl and manganiferous characteristic relations (Ta/(Ta + Nb) and Mn/(Mn + Fe), respectively). Within this row, average values of the tantacl characteristic relation in Col-Ta specimens gradually increases from 0.02 (central type carbonatites) to 0.93 (granitic pegmatites), and average values of the manganiferous characteristic relation vary approximately in the same limits.

Specimens of Col-Ta from the Maykul’sky massif of subalkalic rare metal granites (Southern Kazakhstan) are characterized by the following features of chemical composition: a) values of manganiferous characteristic relation Mn/(Mn + Fe) vary from 0.28 to 0.37; b) values of tantacl characteristic relation Ta/(Ta + Nb) vary from 0.04 to 0.17; c) rather high concentrations of impurity elements (in mas. %): titanium (1.00 TiO2), tungsten (0.46 WO3), scandium (0.28 Sc2O3), and tin (0.17 SnO2). Contents of impurity elements in Col-Ta have been determined by microprobe analysis (Camebax), INAA and with the help of X-ray radiometric method (“Quant” device).

Variations of the main species-forming cations (in mas. %) and their correlations in the Col-Ta specimens from the Orlovsky massif (Aginsky Buryatsky autonomous okrug, Eastern Transbaikalia) are as follows: Ta2O5 15.7—65.1, Nb2O5 26.6—47.8, FeO 0.9—4.6, MnO 12.2—21.5, Ta/(Ta + Nb) 0.2—0.94 (average 0.44), and Mn/(Mn + Fe) 0.49—0.97 (average 0.89). These specimens are characterized by rather high average contents (in mas. %) of tungsten (0.75 WO3), titanium (0.6 TiO2), scandium (0.15 Sc2O3), and tin (0.2 SnO2). Specimens of Col-Ta from the Aetykinsky massif of rare metal granites (Eastern Transbaikalia) are characterized by the following variations of chemical composition and correlations of the main species-forming cations (by bulk samples of great weight 250—300 kg, in mas. %): Ta2O5 3.31—40.01, Nb2O5 39.26—75.67, FeO 1.94—11.18, MnO 7.93—16.00, Ta/(Ta + Nb) 0.04—0.53 (average 0.2), and Mn/(Mn + Fe) 0.29—0.9 (average 0.66). Concentrations of impurity elements vary in the following intervals (in mas. %): TiO2 0.11—4.76, Sc2O3 0.06—1.34, WO3 0.31—4.56, SnO2 0.04—0.86, and UO2 0.0—1.57.

In comparison with the values of tantacl and manganiferous characteristic relations of Col-Ta from the Maykul’sky and Orlovsky massifs, these parameters of Col-Ta from the Aetykinsky massif occupy intermediate position. Scandium is the most characteristic impurity element for the Col-Ta specimens from the Aetykinsky massif: its average content is very high (0.54 mas. % Sc2O3). Titanium, tungsten, and tin are also very

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**New Data on Minerals. М., 2008. Volume 43**
common for these Col-Ta specimens (average contents, in mas. %): TiO₂ 1.15, WO₃ 0.85, and SnO₂ 0.14.

Within the massifs investigated, Col-Ta is regularly distinguished by chemical composition depending on different phase and facies (autometasomatically altered and greisenized) varieties of rare metal granites and remoteness from endocontact. So in the Aetykinsky massif, the early phase with lower contents of tantalic relation \(\frac{Ta}{Ta + Nb} = 0.44\), and relatively increased contents of the following impurity elements (in mas. %): SnO₂ 0.03, Sc₂O₃ 0.42, WO₃ 0.48, and TiO₂ 0.48. Col-Ta from the later rare metal facia with higher content of tantalic relation \(\frac{Ta}{Ta + Nb} = 0.07\). They also contain lesser amounts of the following elements (in mas. %): tin (SnO₂ 0.2), scandium (Sc₂O₃ 0.75), tungsten (WO₃ 1.52), and titanium (TiO₂ 2.11). Within the limits of the same phase and facies of the Aetykinsky massif belonging to the same rare metal granite facies, the following definite vertical zonality occurs: more niobian and ferruginous Col-Ta varieties are found in the deeper sites and more tantalic and manganiferous Col-Ta specimens are found closer to the endocontact or paleo-surface.

For the Orlovsky massif, the character of zonality in distribution of Col-Ta with different chemical composition is close, to a first approximation, to those described for the Aetykinsky massif. So, the specimens of Col-Ta from the later rare metal granite facies (small-grained structure, lepidolite–amazonite–albite composition) are enriched with tantalum and manganese in comparison with those from the earlier facies (middle-grained structure, cryophyllite–amazonite–albite composition): values of tantalic characteristic relation \(\frac{Ta}{Ta + Nb} = 0.45\) and 0.23, and values of manganiferous relation \(\frac{Mn}{Mn + Fe} = 0.94\) and 0.73, respectively in the first and second cases. However, the most tantalic Col-Ta specimens do not occur immediately close to the endocontact, but in a 30–40 (up to 60) meter distance from it. They are characterized by tantalic relation value \(\frac{Ta}{Ta + Nb} = 0.7\) and rather decreased value of manganiferous characteristic relation \(\frac{Mn}{Mn + Fe} = 0.78\). Presence of such specific zone of tantalic "secondary enrichment" of Col-Ta specimens in the Orlovsky massif may be explained, in our opinion, by the action of the following two factors: 1) redistribution of tantalum between its two main tantalic-bearing minerals Prch-Mcr and Col-Ta (their simultaneous occurrence is observed only at the mentioned distances from endocontact where tantalum is spent for Prch-Mcr formation with synchronous depletion of Col-Ta in this element), 2) wave-like character of acidity–basicity conditions evolution of mineral formation during the post-magmatic high-temperature autometasomatically altered granite by albitization and greisenization processes.

Specimens of Col-Ta from the Maykulsky massif belonging to the same phase of rare metal granite (small-middle-grained structure, amazonite–albite with protolithionite–zinnwaldite) become more and more tantalic and manganiferous with approaching to the endocontact with quartzite of the Maykulian suite O₂mk \(\frac{Ta}{Ta + Nb} = 0.04–0.172\) and \(\frac{Mn}{Mn + Fe} = 0.284–0.367\). Col-Ta specimens from the small-grained albite granites of additional intrusions occurring within the amazonite–albite granites in the form of narrow lenticular xenolith-like bodies are distinguished by decreased values of tantalic characteristic relation \(\frac{Ta}{Ta + Nb} = 0.07\). They also contain lesser amounts of the following elements (in mas. %): tin (SnO₂ 0.06 and 0.19), titanium (TiO₂ 0.4 and 1.01), scandium (Sc₂O₃ 0.15 and 0.33), and tungsten (WO₃ 0.26 and 0.44) (greater concentrations correspond to Col-Ta from the main phase granite).

Trends of Col-Ta chemical composition variations in the investigated Transbaikalian massifs in comparison with those from several other amazilite–albite massifs of the Urals–Mongol–Okhotsk belt are shown on Fig. 1. These trends coincide in directivity with the geochemical ones revealed by G.P. Zaraysky for these massifs according to Zr–Hf relation (Zaraysky, 2004) and mineragenic established by S.M. Beskin (Beskin, 2007). Distinct discreteness of figurative spot fields of Col-Ta group minerals in the investigated amazonite–albite Transbaikalian massifs with the presence of the unified trend may be interpreted as an indication of the following two great Col-Ta generations occurrence: earlier primary magmatic (ongonitic), and later high-temperature, hydrothermal–autometasomatically genetically connected
with the ore–magmatic system development from the unified magmatic chamber without external matter introduction.

**Typomorphism of morphology (properly typomorphism)**

Morphology of crystals of the Col-Ta group minerals varies greatly in deposits of different genetic types. The simplest morphology is observed in Col-Ta crystals from the granitic pegmatites (12 – 15 simple forms). The most complicated morphology is observed in ferro-columbite crystals from carbonatites (40 – 50 simple forms). According to our data and other information from the literature, including the data for the Ukrainian Priazov granitic massifs, Col-Ta specimens from the rare metal granites...
occupy an intermediate position: maximal amount of simple forms identified by us with the help of two-circle reflecting goniometer GD–1 on manganocolumbite crystals from the Orlovsky massif reachs 19 (Povarennykh, 1988, 1991, 1994; Matias et al., 1984).

Col-Ta specimens from carbonatites are distinguished by the often presence of complication simple forms such as \{321\}, \{211\}, \{342\}, \{121\}, \{151\}, \{161\}, and other as well as roundness of edges and tops (Povarennykh, 1990). Crystals of Col-Ta from rare metal alkaline granites are characterized by the presence of the following simple forms facets: \{010\}, \{111\}, \{130\}, \{110\}, \{150\}, and other. Along with the presence of simple forms common to the Col-Ta crystals from the rare metal alkaline granites, the specimens from the rare metal amazonite–albite subalkalic (the so called persilic) granite massifs investigated by the author, Orlovsky and Aetykinsky, also contain the following habitus simple forms: \{021\}, \{031\}, \{051\}, \{230\}, and \{170\}. For crystal face indexing, we have used goniometer GD – 1 as well as modified for this purpose Fedorov’s stage and photogoniometer with laser exposer (Institute of Geochemistry and Physics of Minerals, Kiev, V.M. Krochuk). Drawing of crystals has been conducted manually by the known method or with the help of computer ES-1033 and adopted japanese program of crystal drawing KRISTAL.

The widest variation of Col-Ta crystal habitus types has been observed in the specimens from the Orlovsky massif. According to their occurrence in different age phase and facial varieties of the amazonite–albite granites, evolution row of Col-Ta crystal habitus forms has been constructed (Fig. 3). Col-Ta crystals in this massif vary in morphology from columnar–needle-shaped elongated by [001], plate-like flattened by [010] and elongated by [001] through tabular and thick tabular, tabular–columnar flattened by [010] and elongated by [001] to isometric and short columnar shortened by [001].

Simple forms and habitus types’ spectrum of Col-Ta crystals from the Aetykinsky massif is not so wide in comparison with those from the Orlovsky massif: a) amount of simple forms does not exceed 15, b) crystals distinct elongation by [001] has not been observed, and c) share of columnar – needle-shaped and thick tabular crystals is significantly lower.

Spectrum of simple forms (up to 11) and habitus types of Col-Ta crystals observed in specimens from the Maykyl’sky massif is much more poor. Tabular, plate-like, and thick tabular flattened by [010] Col-Ta individes are the most abundant in this massif. Columnar – needle-shaped and thick tabular crystals occur rarely with minor occurrence of more isometric crystal forms.

The following regularities of Col-Ta crystal morphology has been observed for the investigated rare metal granites: 1) more isometric form crystals are connected with apical parts of massifs or their endocontacts, and anisometric form crystals are connected with more deep massif parts; 2) more late facial varieties of granites contain, as a rule, more isometric form crystals; 3) for the same facial variety of granites, more isometric form crystals occur in the upper horizons, and anisometric ones for lower horizons.

**Typomorphism of inner structure (structure typomorphism)**

According to the structure degree of ordering of the Col-Ta group minerals, very wide variation occurs for the specimens belonging to different genetic type’s deposits. Ferrocolumbites from carbonatites are commonly most ordered, normally rhombic. Most unordered up to ixio-

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**Fig. 3. Schematic evolution row of habitus forms of the Col-Ta group minerals of the Orlovsky rare metal granite massif (Transbaikalia) (Povarennykh, 1991, 1994). Habitus types: I (columnar–needle-shaped and lamellar crystals) \{010\}+\{130\}+\{hk0\}; II (tabular crystals) \{010\}+\{110\}+\{011\}; III (thick tabular crystals) \{010\}+\{110\}+\{111\}; IV (tabular–columnar crystals) \{010\}+\{001\}+\{hk0\}+\{hk\}; V (isometric and short columnar crystals) \{001\}+\{010\}+\{0k1\}+\{hk0\}+\{h0l\}.**
erals: 1) albite (no. 0–5 polysynthetically associated* with the following rock-forming minerals, Col-Ta group minerals are paragenetically zonal–sectorial anatomy structure predominant and more often third type of minerals from the Orlovsky massif; crystals with sectorial does not practically occur in the Col-Ta specimen facia. First type zonal–sectorial picture Ta monocrystal characteristic to the later granite composition change in different sectors of Col-Ta are distinctly determined: early, pre-microlite, and later, post-microlite. First generation Col-Ta is presented by small grains (0.05–0.15 mm along elongation) with composition corresponding to manganiferous ferrocolumbite (Ta₂O₅ 5.88–8.78%, FeO 7.89–11.16%, MnO 8.4–10.9%). In quantitative sense, it strongly predominates, and in granites it is distinctly replaced by pyrochlore-microlite containing 8.5–35 mas. % Ta₂O₅ and 41–69 mas. % Nb₂O₅. Second generation Col-Ta is more coarse-grained (0.25–1.0 mm along elongation), more tantalic

* Paragenetic association was determined visually with a binocular microscope due to the presence of induction surfaces of cooperative growth as well as with the help of a raster electron microscope JSMT-20 under 1000–2000 magnifications.
and manganiferous (can be classified as manganocolumbite), and contains more high concentrations of such admixture elements as titanium, tungsten, tin, and scandium. Col-Ta group minerals are distinctly connected with different age subphases of granites (facia on degree of albization and greisenization): ferrocolumbite is connected with the early rocks, and manganocolumbite to the later rocks. Coarse-grained Col-Ta crystals (0.5–1.5 cm) of isometric or tabular—columnar habitus close in composition to the second generation Col-Ta occur in pegmatoid quartz—amazonite and Li-mica quartz—amazonite veins intersecting middle-grained and fine-grained amazonite—albite with light Li-mica granites. Within the middle-grained amazonite—albite apical massif part granites of homogeneous and tectonic texture $\gamma_3$, incomplete apomanganocolumbite pseudomorphosises of wolframite (huebnerite) occur (Povarennykh, 1991, 1994, Povarennykh et al., 1990). Mutual overgrowths of manganocolumbite and pyrochlore—mircolite occur in the later facia.

The Maykul’sky massif is characterized by the occurrence of regular intergrowths of ferrocolumbite with fersmite and samarskite as well as its apopyrochlore pseudomorphosises. Presence of induction surfaces of cooperative growth between ferrocolumbite, amazonite, and lithium-containing biotite (raster electron microscope JSMT-20 under 200-fold magnification) indicates close synchronism of their formation in the granite. According to the presence of replacement products correlation, the following row of the occurrence succession of the main ore tantalum-bearing minerals of the Maykul’sky massif has been established: fersmite — samarskite — ferrocolumbite (Povarennykh, 1994).

Resistant characteristics of Col-Ta have been investigated with the help of PMT – 3 device with indenter loading varying from 20 to 100 g. Microhardness of the Col-Ta specimens from the investigated granite massifs varies within the limits 320–970 kg/mm². Relation between the microhardness and Ta content is nonlinear and represents a broken line. Col-Ta specimens with 5–15% $\text{Ta}_2\text{O}_5$ content occupy the part of this broken line with a steep incline, and Col-Ta specimens with 15–60% $\text{Ta}_2\text{O}_5$ occupy its part with a gentle incline. We have found the inverse proportion between the values of microhardness and mircobritleness of the investigated Col-Ta specimens. Col-Ta from the later granite subphases rather often shows microhardness anisotropy of the I and II types (Povarennykh, 1991, 2008).

Crystal morphology mapping of the Col-Ta group minerals has been conducted at the rare metal granite massifs Orlovsky and Aetykinsky (Transbaikalia). Tantalum deposits are connected with these massifs, and the Col-Ta role in the balance of tantalum in these deposits is predominant in comparison with the pyrochlore-mircolite. Col-Ta crystals shape and habitus have been used as elements of mapping (Povarennykh, 1988). We construct histograms of distribution of different habitus type crystals of Col-Ta in series of samples in every borehole and in surface mining workings (quarries, open pits, trenches), series of boreholes in profiles, series of profiles in the block, and in the massif as a whole. With the help of the data of the preceding researchers, we construct block-diagrams showing the correlation between the Col-Ta concentration in the granites and peculiarities of its crystal morphology.

For explanation of the established crystal morphology regularities, the author has used morphogenetic hypothesis (A. Povarennykh, 1966) in addition with the universal principle of Curie on the influence of the environment symmetry onto the individual symmetry. As a result, we could gain an impression of the crystal genesis conditions (if for no other reason than the symmetry of feeding environment) due to the observed natural distribution of the Col-Ta individuals of different habitus type. It also allows reconstructing the former geological conditions and estimating respectively the modern level of erosion shear of granite massif. Thus, according to the distribution in the granite samples of Col-Ta crystals belonging to the different habitus types and members of the evolution row of habitus forms, the minimal erosion shear level occurred in the western apical nose of the Aetykinsky massif roof (in reality does not day outcropping). The values of the erosion shear level have been respectively estimated as negligible (0–50 m) for the Orlovsky massif, moderate (100–200 m) for the main cupola of the Aetykinsky massif, and significant (300 m and more) for the Maykul’sky massif. These estimates of the erosion shear level are in well correspondence with those made in accordance with the geological data by Yu.I. Temnikov for the Orlovsky massif, A.A. Sitnin and V.V. Sunkinzian for the Aetykinsky massif, and P.V. Koval’ for the Maykul’sky massif (Beskin, 2007).

Thus, along with the other typomorphic signs, crystal morphology of the Col-Ta group minerals can be successfully used during the geological prospecting for the survey and estimation of the tantalum ore occurrences in the
massifs of the subalkaline type rare metal amazonite–albite granites. It can be also used at the stage of the detailed and exploitation exploration during conduction of the mineralogical—technological mapping of tantalum deposits in such massifs.

References


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