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Columbite–Tantalite of the Kester Deposit (Eastern Yakutia)

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Abstract—Three mineral types of the columbite group have been revealed at the Kester Deposit (Eastern Yakutia), that is, columbite-(Fe), columbite-(Mn) and tantalite-(Mn), which are part of rare-metal granites, ongonites, albitites, and greisens. Columbite-(Mn) prevails: $Ta/(Ta + Nb) = 0.30$, and $Mn/(Mn + Fe) = 0.64$. The generalized formula of columbite–tantalite of the deposit is $(Mn_{0.61}Fe_{0.34})_{0.95}(Nb_{1.37}Ta_{0.58}Ti_{0.04}W_{0.03}Sn_{0.01})_{2.03}O_6$. Columbite–tantalite forms polymineral individuals with concentric growth zonality (from the core to the rim): columbite-(Fe) → columbite-(Mn) → tantalite-(Mn) + uranmicrolite → columbite-(Mn). In columbite of the Kester Deposit, WO_3 is a typomorphic impurity, which is 2.67%, on average (formula coefficient, apfu is 0.04); the maximum value is 7.12% (apfu is 0.11). The isomorphic replacement of cations in the B position is assumed according to the following scheme: $2(Nb, Ta)^{5+} \leftrightarrow W^{6+} + Ti^{4+}$. In tantalite, SnO_2 is a typomorphic impurity, which is 1.01%, on average (apfu is 0.03); the maximum value is 3.74% (apfu is 0.21). The paragenesis of the columbite group minerals includes albite, topaz, lepidolite, Nb-Ta-bearing cassiterite, wolframoixiolite, wolframite, U-Hf-bearing zircon, and strüverite. At the Kester Deposit, the evolution of columbite–tantalite is accompanied by an increase in Ta/Nb, Mn/Fe, and Sn/W ratios manifested in the change of columbite by tantalite both in the process of the formation of ore-bearing rocks and in the rock series: rare-metal granites → albitites → greisens. The variation limits of Ta/(Ta + Nb) and Mn/(Mn + Fe) ratios are 0.07–0.74 and 0.16–0.96, respectively. The diversity and evolution of the columbite group minerals of the Kester Deposit indicate their belonging to the rare-metal ore-magmatic system, which includes ore-bearing rare-metal granites, albitites, and greisens. The presence of small intrusions of rare-metal granites and ongonites in the deposit area allows the forecasting of new objects with bedrock and placer columbite–tantalite mineralization.

Keywords: columbite, tantalite, rare-metal granites, ongonites, albitites, greisens, Kester, Eastern Yakutia

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INTRODUCTION

The Development of Industry and Strengthening of its Competitive Capacity State Program suggests provision of industrial enterprises with rare-metal raw materials by preparing new ore reserves. Increasing rare metal recovery from explored ore deposits, which is comparable with the discovery and development of new deposits, is an effective way of resolving this problem [16]. In particular, the major prospects are linked to the Far Eastern tin-ore deposits, such as Tigrinoe (Primorye), Pravourmiyskoye (Priamurye), Odinokoe and Polyarnoye (Yakutia) and others [1, 4, 6].

At the Kester rare-metal tin-ore deposit located in Eastern Yakutia, ore minerals in granites and metasomatites are cassiterite, amblygonite, wolframite, and Sn, Fe, Cu, and Zn sulfides. Potentially commercial columbite group minerals and the attendant tantal–niobaths, which are wolframoixiolite, microlite, strüverite, and ilmenorutile, are also widely developed [2, 8, 18]. The goal of this paper was to classify and characterize the columbite group minerals of the Kester Deposit.

THE GEOLOGICAL CHARACTERISTICS OF THE DEPOSIT

The Kester tin–rare metal deposit, which was discovered by P. P. Epifanov in 1937, is located in Eastern Yakutia between the Yana and Borulakh rivers. The deposit is related to the Ege–Khaysky tin-ore–placer cluster localized in the north of the Verkhoyan fold-thrust belt, in the Yana segment of the Adycha–Elgin fold-block system [8]. The granitoid massifs of the Ege–Khaysky transverse magmatic rock series are lying on Triassic terrigenous strata crumpled into submeridionally and NW-oriented folds. In the Western Dome of the Arga–Ynnakh–Khaysky Massif, andesine granites are broken through by falcate harpolith of ore-bearing microcline-albite granites with lepidolite, topaz, and amblygonite (Fig. 1). The age of ore-bearing granites dated at 115–129 Ma [18] allows ascribing these to the Albian–Cenomanian magmatic province of Pacific Asia, to which Sn, W, and other metal deposits are linked [20]. During geological surveys and exploration studies in the 1960s–1970s, these granites were related to “alaskites” or “apogranites” [7, 10, 19].

Using a set of geological–petrological and mineralogical–geochemical indicators allowed the identification of microcline–albite granites of the Kester harpolith as high-phosphorous rare-metal granites of the lithium–fluorous geochemical type [2, 9, 15, 18]. Granites are accompanied by ongonite dikes, which formed the Kester intrusive dike complex with granites (Fig. 1) and were described in [2, 7]. Microcline–albite granites of the Kester harpolith (further referred to as rare-metal granites) also contain such accessory minerals as montebrasite (1.9%, on average), tantal-bearing cassiterite (0.2%), the columbite group minerals (further referred to as columbite–tantalite), and other tantal–niobaths (0.4%). Due to the increased content of accessories, rare-metal granites appear to be exhausted tin–rare-metal ores.

The Kester Deposit is an ore-bearing greisen deposit that is located at a hanging endocontact of a harpolith of rare-metal granites at its bend, and submerges westward at 30–75°. The deposit is 1200-m long, up to 130-m wide, and 20–130-m thick. The thickness of the deposit decreases with submergence. Greisens are changed for greisenized granites to the northeast and southeast with distance from harpolith bending. Greisens appear to be grey fine-to-medium-grained and equal-grained lipidgranoblastic quartz–muscovite rocks with massive or veinlet texture, that contain variable amounts of topaz, albite, lepidolite, zinnwaldite, tourmaline, amblygonite, fluorapatite, and other Li, Al, Ca, and Cu phosphates (augelite, francolite, and others). Greisen ore minerals are tantal-bearing cassiterite, columbite–tantalite, wolframite, chalcopyrite, arsenopyrite, loellingite, stannite, kesterite, native bismuth, wolframixiolite, strüverite, ilmenorutile, uranmicrolite, and others. The ore-bearing metasomatites include quartz veinlets of different occurrences, which contain minerals of the greisen association (amblygonite, topaz, cassiterite, wolframite, kesterite, chalcopyrite, arsenopyrite, and others) [10, 13, 18, 19].

In addition to greisens and rare-metal granites, quartz–albite metasomatites composing gently-lying deposits up to 2–8-m thick in greisenized granites are the ore-bearing rocks of the Kester Deposit. The albitite structure is fine-to-medium-grained and granoblastic; the texture is massive. In the time of the formation, albitites preceded quartz–mica greisens and were replaced by the latter. Albitites include quartz, microcline, muscovite, fluorapatite, and Hf-bearing zircon. The ore minerals of albitites are Ta–Nb-bearing cassiterite, columbite–tantalite, strüverite, and uranmicrolite.

Thus, the Kester Deposit includes three types of ore-bearing rocks (according to the order of the formation): rare-metal granites → albitites → greisens. The greisen deposit has been explored down to a depth of 50–60 m, and the mineralization has been traced down to 150–200 m. The greisen ore content

decreases with depth. The ore mineralization is non-uniform, disseminated, nest-shaped, and veinlet. The tin content in the ores attains 0.05–3.0%. The average contents of the components are as follows (%): Sn is 0.28, Ta₂O₅ is 0.0076, Nb₂O₅ is 0.0094, Li₂O is 0.35, Rb₂O is 0.14, and Cs₂O is 0.01. At the deposit, the explored reserves of category C₁₊₂ (t) are as follows: Sn is 17 151, Ta₂O₅ is 468, Nb₂O₅ is 579, Li₂O is 21 600, Rb₂O is 8 616, and Cs₂O is 615 [7]. The forecasted metal resources of category P₁ (thous. t) are the following: Sn is 5.20, Ta₂O₅ is 19.14, Nb₂O₅ is 74.62, Li₂O is 2029.63, Rb₂O is 1036.98, Cs₂O is 39.76, and Ge is 0.09 [8].

Since 1975, the object has been conserved and is now in the State Reserve. In 1991, Technical-Economic Feasibility on a reasonable tentative exploration at the Kester rare-metal deposit (Stocks of the GUP Sakhageoinform) was compiled [7, 8]. In connection with commercial perspectives of the deposit for rare metals, the mineralogical study and the classification of the columbite group minerals appear to be a vital problem.

THE FACTUAL MATERIAL AND METHODS OF STUDY OF MINERALS

In this paper, we demonstrate the results of the study of a collection of granites, metasomatites and ores of the Kester Deposit exhibited at Mining Museum (St. Petersburg Mining University) and the collection of M.A. Romanova, a researcher of the Laboratory of Mathematical Geology, V.A. Steklov Mathematical Institute, acquired during a tentative exploration of the deposit during 1970–1971 (155 samples in total). The stock materials of the GUP Sakhageoinform on the geological mapping and exploration on the scale of 1 : 50000–1 : 1000000, sheet Q-53, and materials of the Kester Deposit exploration (1963; 1971) were used.

The mineralogical–petrographic studies (rock diagnostics, determining of parageneses, interrelationships and successions in the mineral formation) were carried out using a Leica DM2500 M microscope and a LAS hardware–software complex for the image analysis. Minerals were diagnosed and examined employing a JEOL JSM-6510LA scanning electron microscope (JEOL Ltd, Japan) with a JED-2200 energy dispersion equipment (JEOL Ltd, Japan) at the Institute of Precambrian Geology and Geochronology of the Russian Academy of Sciences, IPGG (IGGD) RAS (St. Petersburg, the analyst was O.L. Galankina). The analysis mode required an accelerating stress of 20 kV; a current of 1.5 nA; the size of a spot was 2–3 μm; the time of spectrum accumulation was 50 s; the ZAF-method of matrix effect correction was also used. The mineral composition was identified using a JEOL JXA-8230 electron probe X-ray spectral microanalyzer (JEOL Ltd, Japan) in

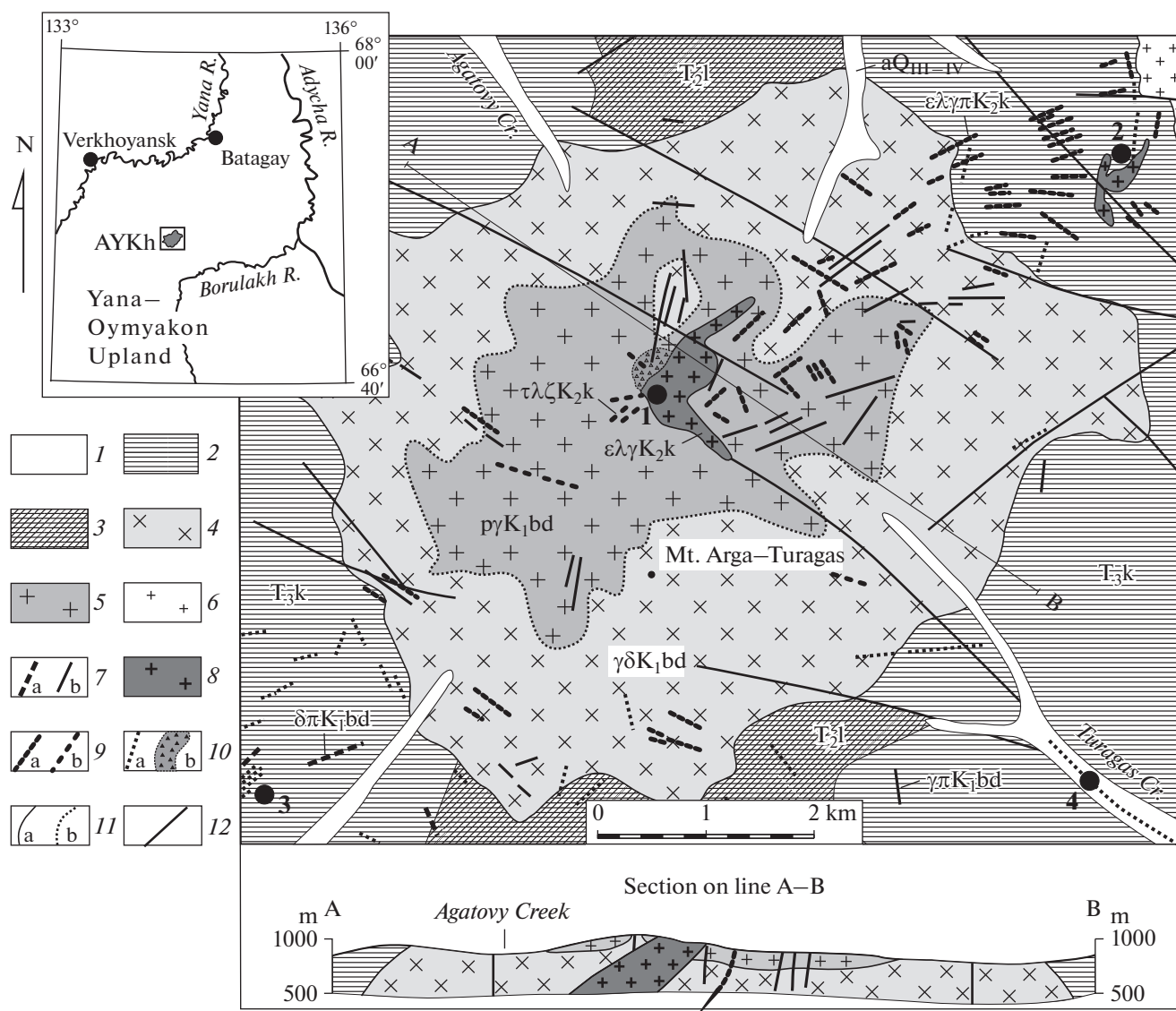


Fig. 1. A geological map of the Western Dome of the Arga–Ynnakh–Khaysky Massif (after Dorofeev and Martynenko, 1963; data are borrowed from Boyarshynov et al., 1980; 1998). (1), Fluvial and talus–solifluction boulder–pebble deposits, grusses, sands, and loamy sands (aQ_{III-IV}); (2), the Carnian sandstones and siltstones (T_3k); (3), the Ladinian siltstones and sandstones (T_2l); (4)–(7), the Baky–Derbekinsky Complex: (4), granodiorites of the main phase ($\gamma\delta K_1bd$), (5), andesine granites of the main phase (γK_1bd), (6), biotite and two-mica granites, and leucogranites of the additional phase (γK_1bd), (7), diorite–porphyrite dikes ($\delta\pi K_1bd$) (a), granite–porphyry dikes, leucogranite–porphyry, and aplite dikes of the vein phase ($\gamma\pi K_1bd$) (b), (8)–(9), the Kester Complex: (8), fine-to-coarse-grained ovoidophy apogranites of the main phase ($\epsilon\lambda\gamma K_2k$), (9), fine-grained apogranite dikes ($\epsilon\lambda\pi K_2k$) (a), ongonite dikes of the vein phase ($\tau\lambda\zeta K_2k$) (b); (10), undivided mineralized zones (a), fluid–explosive breccias (b); (11), geological boundaries between formations of different ages (a) and facial varieties (b); (12) faults. Circles show the rare-metal and tin–ore occurrences: (1), Kester, (2), Tumannoye, (3) Ulakhan–Egelyakh, (4), Turagas placer). The inset shows the geographical location of Arga–Ynnakh–Khaysky Massif (AYKh).

the Shared Facilities Center of St. Petersburg Mining University (the analyst was E.V. Pigova). The microprobe analysis mode required an accelerating stress of 20 kV and a probe current of 100 nA. Natural minerals, pure oxides, and metals were used as the reference samples. The concept of mineral ontogeny was applied to study the anatomy and interrelationships between minerals [1, 5].

COLUMBITE–TANTALITE AT THE KESTER DEPOSIT

At the Kester Deposit, a diversity of the columbite group minerals is determined by variations in Ta/Nb and Mn/Fe ratios and concentrations of Ti^{4+} , W^{6+} , and Sn^{4+} non-formula isomorphous impurities. According to the adopted classification [11], three mineral types have been distinguished, including

Table 1. Chemical composition (mass%) of the columbite group minerals in rare-metal granites and ongonites of the Kester Deposit

Component	Columbite-(Fe)-o (8)			Columbite-(Fe)-g (26)			Columbite-(Mn) (80)			Tantalite-(Mn) (34)		
	1-1	1-2	Av.	1-3	1-4	Av.	1-5	1-6	Av.	1-7	1-8	Av.
TiO ₂	3.43	2.27	2.39	1.01	1.70	1.38	0.67	0.47	0.69	0.74	1.26	0.77
MnO	4.56	3.00	4.44	6.76	5.88	6.94	13.41	12.11	12.13	10.14	10.25	10.94
FeO*	12.55	16.54	13.62	12.62	13.06	12.26	3.71	5.68	5.86	5.46	5.42	4.40
Nb ₂ O ₅	47.06	58.70	50.61	65.34	64.24	63.40	44.32	51.27	54.87	26.01	25.33	23.91
SnO ₂	—	—	—	—	—	—	—	—	0.03	1.68	0.79	0.29
Ta ₂ O ₅	27.76	12.81	23.43	12.02	9.66	11.51	36.50	27.77	24.37	54.83	54.01	58.45
WO ₃	4.01	6.80	5.29	1.50	5.29	4.15	0.23	2.68	1.63	0.75	1.80	0.78
Total	99.37	100.12	99.78	99.25	99.82	99.64	98.83	99.98	99.58	99.61	98.86	99.55
The formula coefficients of cations												
Ti	0.16	0.10	0.11	0.05	0.08	0.06	0.03	0.02	0.03	0.04	0.07	0.04
Mn	0.24	0.15	0.24	0.34	0.29	0.35	0.75	0.62	0.64	0.68	0.63	0.62
Fe	0.66	0.83	0.71	0.63	0.64	0.61	0.21	0.30	0.31	0.26	0.33	0.33
Nb	1.35	1.59	1.43	1.76	1.71	1.70	1.33	1.47	1.55	0.85	0.83	0.85
Sn	—	—	—	—	—	—	—	—	—	0.01	0.02	0.05
Ta	0.48	0.21	0.40	0.19	0.15	0.19	0.66	0.48	0.41	1.11	1.07	1.08
W	0.07	0.11	0.09	0.02	0.08	0.06	0.00	0.04	0.03	0.02	0.03	0.01

The representative (1-1–1-8) micro X-ray spectral analyses and the average composition (Av.) of minerals are shown. Columbite-(Fe)-o denotes columbite-(Fe) in ongonites (The number of analysis is given in the brackets). Columbite-(Fe)-g stands for columbite-(Fe) in rare-metal granites. Columbite-(Mn) and tantalite-(Mn) label those in rare-metal granites. The blank means that the element is not detected. FeO* is the sum of FeO + Fe₂O₃. The formula coefficients are calculated for six oxygen atoms.

columbite-(Fe), columbite-(Mn) and tantalite-(Mn) (Table 1). A subsequent crystallization and overgrowing of early tantal–niobaths by the later ones is a genetic feature of the studied minerals [2]. Due to this, columbite–tantalite is commonly presented by concentric-zonal polymineral individuals (Figs. 2c, 2d, and 2e). The results of a micromineralogical study of columbite–tantalite from the Kester Deposit and its evolution in a rock series: rare-metal granites → albites → greisens are shown below.

Columbite–tantalite in rare-metal granites and ongonites. Columbite–tantalite is found in rare-metal granites in the form of hypidiomorphic extended-tabular crystals of 15–150 μm by the [001] axis, while in ongonites their size is 2–50 μm ; more rarely, up to 680 μm ; the thickness is 2–20 μm . The columbite–tantalite crystals are not transparent or weakly translucent in the transmitting light, and are reddish-brown. The paragenesis of tabular crystals of columbite-(Mn) with albite is the most typical; less faceted columbite-(Fe) grains in muscovite, lepidolite, and cassiterite are much more rarely found (Figs. 2a, 2c, and 2d). The columbite-(Fe) intergrowths with cyrtolite, wolframoixiolite, and ferberite are found [2]. The inclusions of lath-shaped columbite-(Fe) of 20–50 μm length (rarely up to 100 μm) and a width of 2–10 μm in topaz are the “visiting card” of the Kester rare-

metal granites (Fig. 2b). Columbite-(Fe) is found in ongonites as lath-shaped crystals of 5–20 μm (up to 80 μm) length in the albite, muscovite, tourmaline, fluorapatite, and cyrtolite grains. Wolframoixiolite fringes and intergrowths with wolframite are typical for the columbite-(Fe) grains [2] (Fig. 2f). Tantalite-(Fe) forms the outer fringes of columbite–tantalite of 1–10 μm width, rarely up to 15–18 μm (Figs. 2c and 2e). In some cases, xenomorphic tantalite precipitates in the form of microinclusions of up to 8 μm in topaz and tantal-bearing cassiterite are found.

In rare-metal granites, the columbite group minerals are most widely developed and diversified in terms of types (Table 1). Columbite-(Fe), which forms the cores of polymineral individuals of columbite–tantalite (Fig. 2c and 2f) fringed by broken columbite-(Mn) and tantalite-(Mn) zones, is only found in granites and ongonites. The typical concentric zonality of columbite–tantalite in granites (from the core to the rim) is columbite-(Fe) → columbite-(Mn) → tantalite-(Mn) + uranmicrolite → columbite-(Mn). In turn, the mineral types of each zone have inner oscillatory zonality (Figs. 2c, 2d, and 2e).

Columbite-(Fe) in ongonites and columbite-(Fe) in rare-metal granites are different in their ratios of the main components: Mn/(Mn + Fe) is 0.22–0.49 and 0.16–0.37; Ta/(Ta + Nb) is 0.07–0.17 and 0.12–0.31,

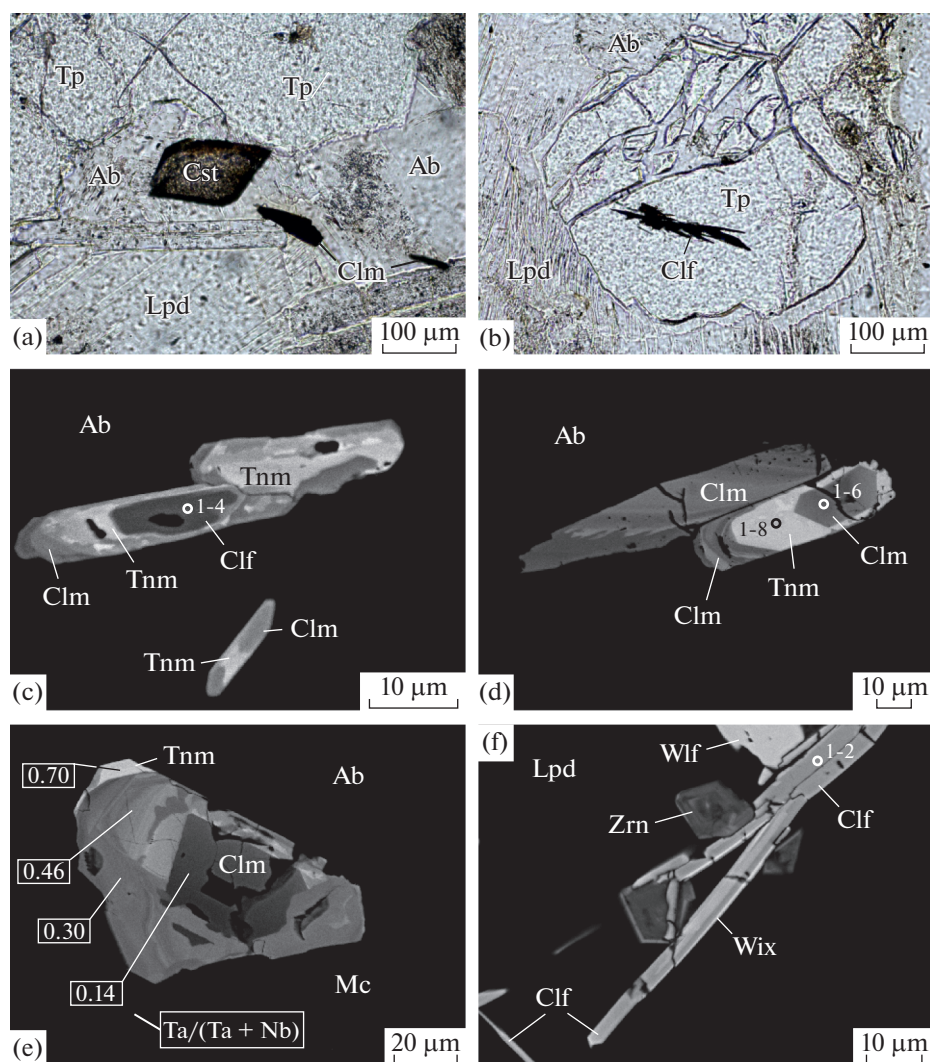


Fig. 2. Columbite group minerals in rare-metal granites (a–e) and in ongonites (f) of the Kester Deposit. Photographs of thin sections without analyzer (a and b), and BSE (Back Scattered Electrons) imaging (c–f). The point numbers correspond to the numbers of analyses in Table 1. (a), Tabular columbite-(Mn) and dipyramidal tantal-bearing cassiterite in intergrowth with albite and lepidolite; (b), the intergrowth of lath-shaped columbite-(Fe) crystals in topaz; (c), tabular columbite-(Fe) with tantalite-(Mn) and columbite-(Mn) fringes in albite; (d), tabular columbite-(Mn) with tantalite-(Mn) and columbite-(Mn) fringes in albite; (e), a twin of columbite-(Mn) with the Ta and Nb zonal distribution; (f), lath-shaped columbite-(Fe) with wolframixiolite fringe in intergrowth with uranium–hafnium-bearing zircon and wolframite from ongonite. Ab, albite; Clf, columbite-(Fe); Clm, columbite-(Mn); Cst, tantal-bearing cassiterite; Lpd, lepidolite; Mc, microcline; Ms, muscovite; Tp, topaz; Wlf, wolframite; Wix, wolframixiolite; and Zrn, zircon.

respectively (Fig. 3). The differences are also observed in the content of TiO_2 : 2.39% (1.56–3.45) and 1.38% (0.55–2.33), accordingly. Here and below the average content of the component is indicated and the content variation is shown in brackets. The typical features of columbite-(Fe) are the absence of a tin impurity and the highest concentration of WO_3 , 5.29% (4.04–6.79) and 4.15% (1.51–7.12), respectively (see Table 1).

Columbite-(Mn) is the main tantal–niobate of the Kester Deposit. It is presented by zonal crystals with a tantalite-(Mn) fringe (Fig. 2e). In rare-metal granites, columbite-(Mn) is notable for a relatively high ferruginosity, $\text{Mn}/(\text{Mn} + \text{Fe})$ is 0.50–0.88, and 0.68, on

average (Fig. 3). The lowest content of TiO_2 is 0.69% (0–2.83), SnO_2 is 0.03% (0–1.13), and the increased content of WO_3 accounting for 1.63% (0–6.07) are observed in it (Table 1). In rare cases, a sufficient impurity of $\text{SnO}_2 > 1.0\%$ (apfu > 0.03) is found in columbite-(Mn), which forms intergrowth with cassiterite.

In rare-metal granites, the outer columbite–tantalite fringes are enriched with tantal: $\text{Ta}/(\text{Ta} + \text{Nb})$ is 0.50–0.74, and 0.60, on average (Fig. 2e). Tantalite is presented by a manganese type with a relatively low ratio of $\text{Mn}/(\text{Mn} + \text{Fe})$, which is 0.61–0.96 (0.72, on

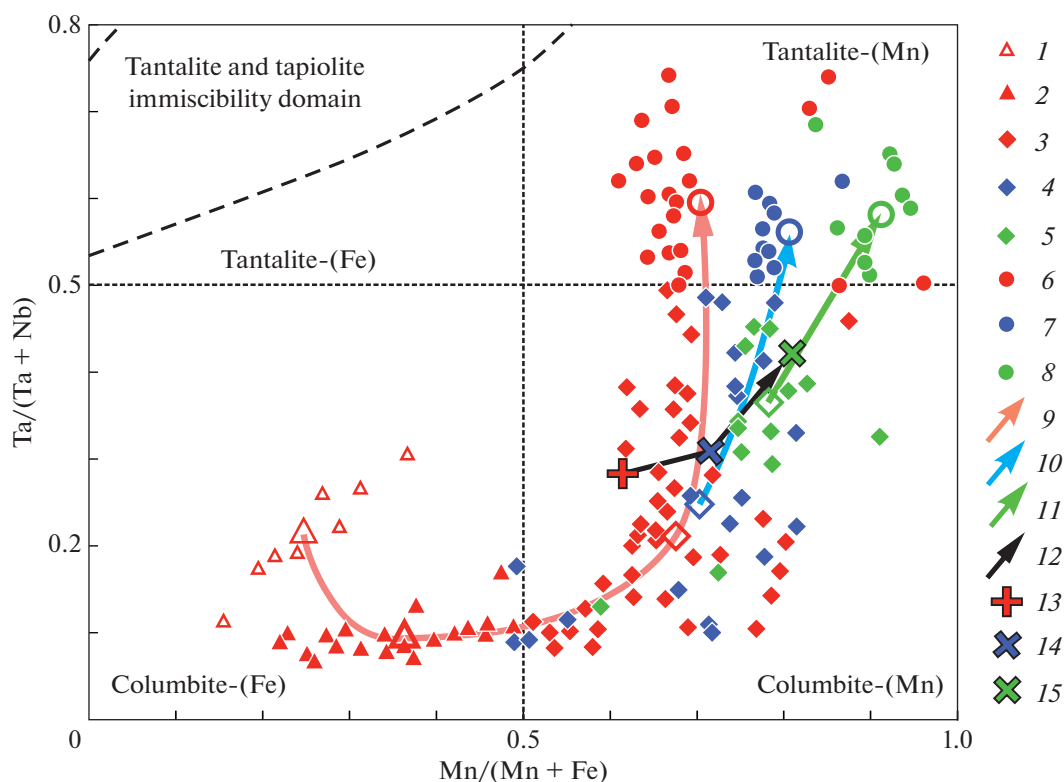


Fig. 3. The composition and evolutionary trends of the columbite group minerals at the Kester Deposit shown on the columbite rectangular diagram [22]. The ratios of atomic quantity of the main cations in columbite-(Fe) in ongonites (1) and rare-metal granites (2); in columbite-(Mn) in rare-metal granites (3), albitites (4), and greisens (5); in tantalite-(Mn) in rare-metal granites (6), albitites (7), and greisens (8). Large-size non-filled denominations show average compositions of the corresponding mineral types. The arrows indicate the evolutionary trends for the columbite–tantalite composition during growth in rare-metal granites (9), albitites (10), and greisens (11); the evolution of the columbite–tantalite composition (12) in a rock series rare-metal granites (13) → albitites (14) → greisens (15).

average) (Fig. 3). As well as columbite-(Mn), tantalite-(Mn) in granites is notable for a decreased share of SnO_2 at 0.29% (0–1.69) and an increased content of WO_3 , 0.78% (0–4.72) (Table 1).

Columbite-(Fe) in ongonites is different from columbite-(Fe) in rare-metal granites in higher ferruginosity ($\text{Mn}/(\text{Mn} + \text{Fe})$ is 0.25 and 0.36, respectively) and an increased content of Ta_2O_5 (23.43% and 11.51%, accordingly) (Fig. 3). The level of cations of W in columbite-(Fe) in ongonites is at its maximum: the apfu is 0.09 (see Table 1).

In columbite–tantalite crystals, lens-shaped uranmicrolite inclusions of 1–15 μm are found that are extended along the tantalite fringes of the crystals. In one case, a continuous uranmicrolite fringe of 25 μm thickness, which covers a tantalite-(Mn) zone, is observed. It should be noted that in some grains, the columbite–tantalite zones are surrounded by the columbite-(Mn) fringes (Figs. 2c and 2d).

Columbite–tantalite in albitites. Columbite–tantalite in albitites is emplaced in albite, quartz, and muscovite interstitions as single crystals or intergrowths with cassiterite, strüverite, cyrtolite, and fluorapatite.

Hypidiomorphic thin tabular crystals of columbite-(Mn)-II of 20–120 μm are predominant (Figs. 4a and 4b). Columbite and tantalite in albitites are assigned the index II, while columbite and tantalite in greisens—index III. A subordinate amount of weakly ferruginous columbite-(Fe)-II is observable. Small xenomorphic inclusions of columbite-(Mn)-II and tantalite-(Mn)-II of 1–25 μm are found in the grains of tantalite-bearing cassiterite.

Columbite-(Mn)-II is similar to columbite in granites in terms of its structure: from the core to the rim, an increase of the Ta/Nb ratio takes place up to the transition to tantalite-(Mn)-II (Fig. 4a). The inverse zonation of columbite is more rarely observed with increasing Ta/Nb ratio from the margins to the center of the core of the grain, and tantalite-(Mn)-II forms lens-shaped precipitates in the columbite core (Fig. 4b).

Columbite-(Mn)-II in albitites has low ferruginosity, $\text{Mn}/(\text{Mn} + \text{Fe})$ is 0.69, on average (Fig. 3); it persistently contains a moderate amount of WO_3 , 1.47% (0–4.49). The impurity of SnO_2 is small and is episodically found, 0.13% (0–0.87) (see Table 2). Tantalite-

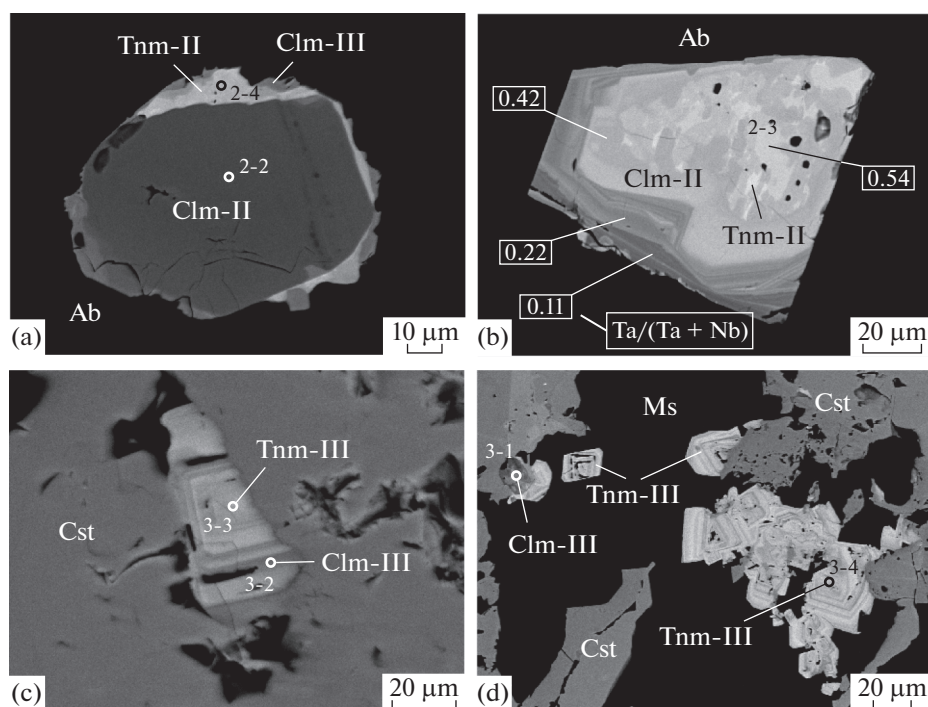


Fig. 4. Columbite group minerals in albitites (a and b) and greisens (c and d) of the Kester Deposit. The BSE (Back Scattered Electrons) images are shown. The point numbers correspond to the numbers of analyses in Table 2. (a), tabular columbite-(Mn)-II with tantalite-(Mn)-II and columbite-(Mn)-III fringes in albite; (b), zonal columbite-(Mn)-II with tantalite-(Mn)-II inclusions in albite; (c), rhythmically-zonal tantalite-(Mn)-III inclusion with columbite-(Mn)-III zones in Nb-Ta-bearing cassiterite; (d), rhythmically-zonal tantalite-(Mn)-III with the core and zones of columbite-(Mn)-III in intergrowth with tantal-bearing cassiterite in muscovite. For explanations for minerals see Fig. 2.

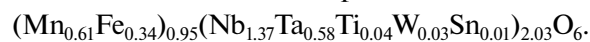
(Mn)-II is still less ferruginous than columbite, $Mn/(Mn + Fe)$ is 0.77–0.87; it is different in the lowest share of Ta among tantalites of the deposits, $Ta/(Ta + Nb)$ is 0.54–0.62, and 0.58, on average (Fig. 3). Tantalite-(Mn) in albitites contains the minimum amounts of TiO_2 , 0.69% (0.11–1.45), and WO_3 , 0.45% (0–0.87). A very small impurity of SnO_2 , 0.74%, on average, (Table 2) is typically observed. In some cases, tantalite-(Mn)-II in albitites is surrounded by a fringe of late, likely greisen columbite-(Mn)-III. (Fig. 4a).

Columbite-(Mn)-III in greisens. Columbite-(Mn)-III in greisens is presented by xenomorphic inclusions of 5–50 μm in Nb-Ta-bearing cassiterite (Fig. 4c). Inclusions in topaz of lath-shaped columbite–tantalite of 20–40 μm in length are described. Columbite–tantalite in greisens is presented by columbite-(Mn)-III and tantalite-(Mn)-III. Tantalite-(Mn)-III makes up the outer zones or inner domains in columbite-(Mn)-III and is often rhythmically interlayered with the former (Figs. 4c and 4d). Columbite and tantalite in greisens exhibit minimum ferruginosity, $Mn/(Mn + Fe)$ is 0.75 (0.59–0.91) and 0.90 (0.76–0.94), respectively (Fig. 3), and the lowest content of WO_3 at 0.79% (0–2.83) and 0.86% (0–2.51). Among columbite–tantalites of the deposit, columbite-(Mn)-III and tantalite-(Mn)-III are appreciably notable for

high tin content: SnO_2 accounting for 0.50% (0–1.16) and 2.01% (0.78–3.74), respectively; the highest concentration of TiO_2 at 2.15% (1.19–2.84) is detected in tantalite-(Mn)-III (Table 2).

DISCUSSION OF THE RESULTS

Columbite–tantalite of the Kester Deposit. Columbite–tantalite is revealed in rare-metal granites, ongonites, albitites, and greisens of the Kester Deposit. It is characterized by wide compositional variations and is presented by three mineral types, including columbite-(Fe), columbite-(Mn), and tantalite-(Mn). Columbite-(Mn) is predominant: the average parameters at the deposit are $Ta/(Ta + Nb) = 0.30$ and $Mn/(Mn + Fe) = 0.64$. In columbite–tantalite, the share of tantal $Ta/(Ta+Nb)$ does not exceed 0.74 (Fig. 3), the formula coefficients of Ta and Nb vary within 0.12–1.48 and 0.50–1.84, respectively. The variation limits of the $Mn/(Mn + Fe)$ ratio are 0.16–0.96. The generalized empirical formula of columbite–tantalite of the Kester Deposit is



At the Kester Deposit, columbite–tantalite is presented by polymineral individuals with concentric growth zonality (from the core to the rim): columbite-(Fe) → columbite-(Mn) → tantalite-(Mn) + uranmi-

Table 2. The chemical composition (mass%) of the columbite group minerals in rare-metal albitites and greisens of the Kester Deposit

Component	Albitites						Greisens					
	Columbite-(Mn)-II (33)			Tantalite-(Mn)-II (14)			Columbite-(Mn)-III (21)			Tantalite-(Mn)-III (12)		
	2-1	2-2	Av.	2-3	2-4	Av.	3-1	3-2	Av.	3-3	3-4	Av.
TiO ₂	0.92	1.06	0.96	1.07	0.16	0.69	1.68	0.60	0.84	2.84	1.72	2.15
MnO	14.50	14.37	12.12	12.46	12.15	12.30	11.55	13.08	12.61	13.99	13.88	13.31
FeO*	4.19	2.79	5.43	3.64	3.26	3.23	3.57	5.02	4.33	1.59	0.94	1.51
Nb ₂ O ₅	56.42	52.25	52.57	27.67	24.99	24.69	34.05	59.78	46.53	27.80	23.12	22.88
SnO ₂	—	0.42	0.13	0.81	0.57	0.74	0.97	0.28	0.50	2.78	1.12	2.01
Ta ₂ O ₅	21.60	28.01	27.05	54.51	57.93	57.74	46.64	20.20	34.17	48.45	58.42	57.19
WO ₃	2.36	0.54	1.47	0.07	0.56	0.45	1.71	0.45	0.79	2.51	0.03	0.86
Total	99.99	99.43	99.73	100.23	99.62	99.83	100.18	99.41	99.78	99.95	99.23	99.90
The formula coefficients of cations												
Ti	0.04	0.05	0.05	0.06	0.02	0.04	0.09	0.03	0.04	0.15	0.09	0.12
Mn	0.76	0.76	0.64	0.75	0.68	0.76	0.66	0.68	0.69	0.83	0.85	0.82
Fe	0.22	0.15	0.29	0.22	0.25	0.20	0.20	0.26	0.23	0.09	0.06	0.09
Nb	1.57	1.48	1.49	0.89	1.03	0.81	1.04	1.65	1.36	0.88	0.75	0.75
Sn	—	0.02	0.01	0.02	0.00	0.02	0.05	0.01	0.03	0.08	0.06	0.06
Ta	0.36	0.48	0.46	1.06	0.96	1.15	0.86	0.34	0.60	0.92	1.15	1.13
W	0.04	0.01	0.02	0.00	0.02	0.01	0.03	0.01	0.01	0.05	0.00	0.02

The representative micro X-ray spectral analyses (2-1–2-4, 3-1–3-4) and the average composition (Av.) of minerals are shown. The number of analyses is given in the brackets. The blank means that the element is not detected, FeO* is the sum of FeO + Fe₂O₃. The formula coefficients are calculated for six oxygen atoms.

crolite → columbite-(Mn) (Figs. 2c, 2d, 2e, and 4a). In each zone, the mineral types have oscillatory zonality, specifically typical for columbite–tantalite in albitites and greisens (Figs. 4b, 4c, and 4d). The compositional variations of columbite–tantalite are frequently displayed in the appearance of individuals with close contents of Ta, Nb, Fe, and Mn, which causes disordering of the columbite layered structure and the formation of wolframioxiolite fringes around columbite–tantalite (Fig. 2f) [2]. The columbite–tantalite paragenesis includes albite, topaz, lepidolite, Nb-Ta-bearing cassiterite, wolframioxiolite, wolframite, U-Hf-bearing zircon, and strüverite.

In the examined columbite–tantalites, the impurity components are Ti⁴⁺, W⁶⁺, and Sn⁴⁺. Wolfram is a typomorphic impurity in columbite–tantalite of the Kester Deposit, WO₃ is 1.77%, on average (apfu is 0.03). In tantalite-(Mn), WO₃ is 0.70%, while in columbite-(Fe), WO₃ is 2.67%, reaching 7.12%. The wolfram impurity is more typical for columbite, whereas the tin impurity is typomorphic for tantalite: the average content of SnO₂ in columbite–tantalite is 0.19%, the content of SnO₂ in tantalite is 1.01%, on average (apfu is 0.03) (Tables 1 and 2). At the deposit, the impurity of TiO₂ in columbite–tantalite is 0.92%, on average, and plays the role of a compensator of het-

erogenic isomorphism (Nb, Ta)⁵⁺ ↔ W⁶⁺. The data show the inverse dependence between the atomic quantity of Ta and Nb and the concentrations of W and Ti impurities (Fig. 5). This allows us to assume the isomorphic replacement of cations in the *B* position according to the following scheme: 2 (Nb, Ta)⁵⁺ ↔ W⁶⁺ + Ti⁴⁺.

The atomic share of wolfram W/(W + Ta + Nb + Ti + Sn) in the *B* position of the columbite–tantalite structure of the Kester Deposit is 1%, on average. Columbite-(Fe) in ongonites and rare-metal granites is mostly enriched with wolfram, 4% and 3%, accordingly. We note that, as mentioned, the wolfram impurity is a typomorphic feature of tantal–niobaths at the rare-metal tin deposits of the Far East [1, 2].

The evolution of columbite–tantalite. Based on the occurrence frequency of columbite–tantalite in various rocks of the Kester Deposit, its most intense crystallization occurred in rare-metal granites, while at the postmagmatic stage of the formation of tantal–niobaths it was gradually reduced from albitites to greisens. The zonality and evolution of columbite–tantalite in successively formed rocks indicates the changes in the bedrock composition during the formation of specific rocks and an entire deposit formation process.

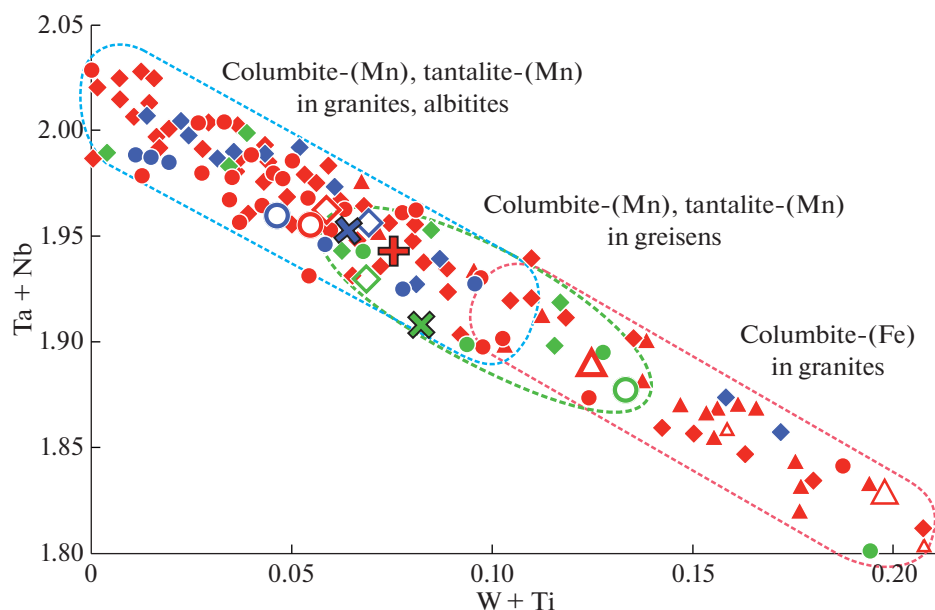


Fig. 5. The dependence of the quantity of Ta and Nb cations on W and Ti cations in the columbite group minerals at the Kester Deposit. For explanations see Fig. 2. The colored dotted line shows the fields of the highest point clustering showing the composition of columbite–tantalite mineral types in various rocks.

The columbite–tantalite compositional evolution is governed by the geochemical trends that cause changes in the rare-metal magma and postmagmatic fluid composition, particularly, an increase of the Ta/Nb and Mn/Fe ratios [12, 17, 21]. A full evolutionary cycle is manifested in rare-metal granites: the crystallization of columbite-(Fe) is replaced by the formation of columbite-(Mn) and the process is terminated by the formation of the tantalite-(Mn) fringes. A reduced evolution of columbite-(Mn) → tantalite-(Mn) is typical of metasomatites. In the history of the deposit, columbite-(Mn) is replaced by tantalite-(Mn) with increasing Ta/Nb and Mn/Fe ratios by three times, precisely, in the process of the formation of rare-metal granites, albitites, and greisens. The turning point of the evolution observed in rare-metal granites and albitites, and manifested in the overgrowing of tantalite-(Mn) by the later generation of columbite-(Mn) likely occurs due to fluids of the latest stages of albitization and greisenization.

In the rock series: rare-metal granites → albitites → greisens the Ta/Nb and Mn/Fe ratios increase in columbite–tantalite (Fig. 3). A trend of the Sn/W ratio increase in columbite–tantalite is consistent with the above tendencies. The content of WO_3 in the rock series granites → albitites → greisens decreases, as seen from 1.97 → 1.24 → 0.77%. The maximum concentration of WO_3 is 7.12%, which is observed in the early magmatic columbite-(Fe) (Fig. 5). At the same time, in this rock series the concentration of SnO_2 increases, from 0.09 → 0.27 → 1.09%. The maxi-

um concentration of SnO_2 is 3.74% in the late greisen tantalite-(Mn) (Table 2).

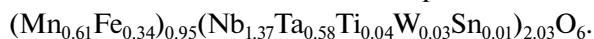
The genesis of columbite–tantalite and the prospects of rare-metal mineralization at the Kester Deposit. The diversity and evolution of the columbite group minerals at the Kester Deposit from columbite-(Fe) to tantalite-(Mn) indicates a deep differentiation of the bedrock granitic magma typical of the rare-metal ore-magmatic systems. Similar systems include columbite–tantalite mineralization of rare-metal lithium-fluoric granites and the attendant albitites and greisens [3, 9, 12, 14, 17, 21]. The remoteness of the compositional field of columbite–tantalite of the Kester Deposit from the tapiolite-tantalite immiscibility domain on the columbite rectangular diagram (see Fig. 3) indicates the high activity of volatiles (P , F , and B), and decreased temperature and pressure of the mineral-forming medium [23], whereas similar features of typomorphism and the evolution of columbite–tantalite in rare-metal granites, albitites, and greisens are evidence of their genetic relationship and belonging to a single ore-magmatic system.

At the Kester Deposit, the commercial rare-metal mineral formation was manifested at the magmatic and early magmatic stages, at the transition from the early alkali-stage to the acidic stage of metasomatism [3, 14, 17]. According to mineralogical–geochemical and petrological features, the object is similar to the Beauvoir and Montebret (Montebrer) (Montebrè) deposits on the Massif Central, France [15, 24]. The presence of small intrusions of rare-metal granites and ongonites in the deposit region [7, 8] allows the fore-

casting of new objects of magmatic and metasomatic tantalite–columbite mineralization [3, 17]. The prospects for columbite in tin placers of the Turagas, Ilin-Salaa, and Agatovy creeks should also be positively estimated.

CONCLUSIONS

(1) Three mineral types have been distinguished at the Kester Deposit, columbite-(Fe), columbite-(Mn), and tantalite-(Mn), which are part of rare-metal granites, ongonites, albitites, and greisens. Columbite-(Mn) is predominant: $Ta/(Ta + Nb) = 0.30$, and $Mn/(Mn + Fe) = 0.64$. The generalized formula of columbite–tantalite of the Kester Deposit is



(2) Columbite–tantalite forms polymineral individuals with concentric growth zonality (from the core to the rim): columbite-(Fe) → columbite-(Mn) → tantalite-(Mn) + uranmicrolite → columbite-(Mn). The paragenesis of columbite–tantalite includes albite, topaz, lepidolite, Nb-Ta-bearing cassiterite, wolframioxiolite, wolframite, U-Hf-bearing zircon, and strüverite.

(3) In columbite–tantalite of the Kester Deposit, WO_3 is a typomorphic impurity, at 2.67%, on average (apfu is 0.04); the maximum value is 7.12% (apfu is 0.11). This indicates the isomorphic replacement of cations in the *B* position according to the following scheme: $2(Nb, Ta)^{5+} \leftrightarrow W^{6+} + Ti^{4+}$. In tantalite-(Mn), SnO_2 is a typomorphic impurity, at 1.01%, on average (apfu is 0.03); the maximum value is 3.74% (apfu is 0.21).

(4) At the Kester Deposit, the columbite–tantalite evolution is accompanied by an increase in Ta/Nb, Mn/Fe, and Sn/W ratios manifested in the change of columbite by tantalite both in the process of the formation of ore-bearing rocks and in this rock series: rare-metal granites → albitites → greisens. The variation limits of $Ta/(Ta + Nb)$ and $Mn/(Mn + Fe)$ ratios are 0.07–0.74 and 0.16–0.96, respectively.

(5) The diversity and evolution of the columbite group minerals of the Kester Deposit indicate their belonging to the rare-metal ore–magmatic system, which includes ore-bearing rare-metal granites, albitites, and greisens. The presence of small intrusions of rare-metal granites and ongonites in the deposit area allows the forecasting of new objects with bedrock and placer columbite–tantalite mineralization.

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