ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/349128512

On the Genesis of “White Granite” from the Kester Harpolith, Arga-Ynnakh-Khaya Pluton, East Yakutia

Article *in* Geology of Ore Deposits · December 2020

DOI: 10.1134/S1075701520080024

CITATIONS
3

READS
225

2 authors:

Viktor I. Alekseev
Empress Catherine II Saint Petersburg Mining University
49 PUBLICATIONS **164** CITATIONS

SEE PROFILE

Yu. B. Marin
79 PUBLICATIONS **515** CITATIONS

SEE PROFILE

All content following this page was uploaded by Viktor I. Alekseev on 10 December 2023.

The user has requested enhancement of the downloaded file.

ISSN 1075-7015, Geology of Ore Deposits, 2020, Vol. 62, No. 8, pp. 719–730. © Pleiades Publishing, Ltd., 2020.
Russian Text © The Author(s), 2020, published in Zapiski Rossiiskogo Mineralogicheskogo Obshchestva, 2020, No. 1, pp. 47–63.

On the Genesis of "White Granite" from the Kester Harpolith, Arga–Ynnakh–Khaya Pluton, East Yakutia

V. I. Alekseev[a], * and Yu. B. Marin[a]

[a]*St. Petersburg Mining University, St. Petersburg, 119106 Russia*

**e-mail: alekseev_vi@pers.spmi.ru*

Received November 20, 2019; revised November 21, 2019; accepted December 5, 2019

Abstract—The problem of the origin of "white granite" in the Kester harpolith of the Arga–Ynnakh–Khaya Pluton is discussed. The morphology, occurrence, and nature of the intrusive contacts of the Kester harpolith prove its magmatic origin. The petrographic and petrochemical properties of "white granite" allow its identification as a postorogenic rare-metal high-phosphorus granite of the Li-F geochemical type. The magmatic genesis of the "white granite" texture is supported by statistical methods. The composition, typomorphic properties, ontogenetic features internal structure and relationship of accessory minerals indicate that the major accessories of the granite, that is, cassiterite, columbite, tantalite, "wolframoixiolite," zircon, and ferberite, were formed at the late stage of the low-temperature rare-metal granitic melt. The Kester harpolith within the Arga–Ynnakh–Khaya granite pluton and the eponymous tin–rare-metal deposit genetically related to it are a part of the Far East Superprovince of rare-metal granites.

Keywords: rare-metal high-phosphorus lithium-fluoric granite, accessory minerals, cassiterite, columbite-tantalite, Kestersky harpolith, Yakutia

DOI: 10.1134/S1075701520080024

INTRODUCTION

Demonstration of the magmatic origin of rare-metal Li-F granites (LFGs) was one of the outstanding achievements of Russian geology in the 20th century (Kovalenko, 1977; Beskin et al., 1979, 1999; Yarmolyuk et al., 1987). Owing to this, igneous petrology grew significantly; new types of economic deposits were discovered and rare-metal granite provinces were identified worldwide, including the Central Asia Fold Belt (Yarmolyuk et al., 1987) and Pacific Mobile Belt (Alekseev, 2014). The issue of the relationship between magmatic and metasomatic processes during LFG formation is relevant[1]. This paper is focused on geological, petrographic, petrochemical, and mineralogical features of lepidolite–quartz–microcline–albite rock, "white granites", proving the magmatic origin of the Kester harpolith in East Yakutia.

EXPERIMENTAL

This study is based on the petrography and mineralogy of "white granite", the materials of geological surveying and prospecting at the 1 : 50000–1 : 1000000 scale on map sheet Q-53, and exploration of the Kester deposit. The systematics of rare-metal granites (Beskin et al., 1979, 1999; *Principles* ..., 2007) was used as the basic procedure for division and correlation of granitoids. The terms "rare-metal Li-F granite" and "ongonite" are used for granite of specific compositions and origins to which magmatic and post-magmatic rare-metal deposits are related (Kovalenko, 1977; Yarmolyuk et al., 1987).

"White granite" of the Kester harpolith was studied using the collection of the Arga–Ynnakh–Khaya granitoids of M.A. Romanova, Laboratory of Mathematical Geology at the Steklov Mathematical Institute, Russian Academy of Sciences and the collection of granites and ores of the Mining Museum at the St. Petersburg Mining University; 155 hand specimens were studied. The microstructural and petrographic study was performed on a Leica DM2500 M microscope and an Opton Axioplan Zeiss microscope equipped with the VideoTesT complex for image analysis at the St. Petersburg Mining University; more than 100000 microstructural measurements were made. The results were processed using stochastic structure modeling (Romanova, 1976; Alekseev, 2005). The chemical composition of the reference granite samples of the Agra–Ynnakh–Khaya Pluton was determined using a titrimetric analysis with additional coulometry (F); the data were interpreted with the diagrams of (Maniar and Piccoli, 1989; Maeda, 1990). The composition of the "white granite" minerals was measured on a JSM-6510LA scanning electron

[1] The Kester Complex has been abolished from the Q-53 sheet of the State Geological Map 1000/3 on the ground that rare-metal granites are considered metasomatic (*State* ..., 2016).

microscope equipped with a JED-2200 EDS and a JEOL JXA-8230 electron microprobe at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, St. Petersburg. The operation conditions were a 20 kV acceleration voltage and a 1.5 nA current intensity; the ZAF correction was used for the correction procedure. The concept of mineral ontogeny (Brodskaya and Marin, 2016; Alekseev et al., 2020) was used during investigation of the inner pattern and relationships of the "white granite" minerals.

GEOLOGICAL DESCRIPTION

The Triassic terrigenous sequences of the Yana Plateau in Yakutia are intruded by granitoids of the Ege–Khaya spatial series transverse to the Verkhoyansk folded structures. In 1937, P.P. Epifanov discovered the Kester tin deposit in the Arga–Ynnakh–Khaya Pluton located between the Yana and Borulakh rivers. The deposit is a topaz greisen body in the near contact zone of the eponymous alaskite harpolith. In the 1940s–1970s, the district was prospected and was studied in detail by A.V. Dorofeev and A.A. Martynenko during exploration and operation of the Kester deposit. The rare-metal occurrences were discovered in 1980–1982 as a result of medium- and large-scale surveying and prospecting supervised by V.V. Boyarshinov. Since the 1990s, the Kester deposit has been considered as a source for rare metals, Ta, Nb, Li, Rb, and Cs.

The Arga–Ynnakh–Khaya Pluton is a slightly eroded granitoid body that is divided into the Western and Eastern domes. Their geology, mineralogy, and petrography are described in some publications (Chaikovsky, 1960; Flerov et al., 1971; Koval, 1975; Efremenko, 1976; Romanova, 1976; Nekrasov, 1984; Orlov et al., 1984; Nedosekin, 1988; Trunilina et al., 2019; Alekseev et al., 2020).

The crescent "white granite" outcrop, which is 2300 m long and up to 600 m wide, is exposed by the quarry, trenches, and digging pits in andesine granite on the north slope of Mt. Arga-Turagas in the central part of the Western dome. Tens of 110—170-m-long prospecting boreholes along profiles across the outcrop strike showed that white granite makes up a lenticular westward dipping body curved along striking, the Kester harpolith. The hanging wall of harpolith dips southwest at 30°–40° in the south part and in the north part it dips northwest at 15°–20°. The footwall dips in the west course at 25°–80° (Fig. 1).

The Kester "white granite" are known as "alaskite," "apogranite," "Li-F granite," "Li-F albitophyre," and "metasomatic topaz–albite–quartz rock." The contacts of "white granite" with host andesine granite is sharp and straight (Fig. 2b) with near-contact alteration: the granite is recrystallized and greisenized, while "white granite" contains slab-like granite xenoliths. In the near-contact zone, "white granite" is fine-grained and weakly porphyritic with large quartz phenocrysts. The gentle parts of the harpolith hanging wall are complicated by NNE striking apophyses that intrude andesine granite. In the hanging wall, the "white granite" body contains 0.25–0.5-m-thick stockscheiders, i.e., marginal druse-like pegmatitoids composed of microcline, white mica, and quartz. Thinner stockscheiders were found in the apophysis selvages and along the contact with granite xenoliths. Quartz–microcline pegmatoid schlieren of up to 0.4 m are observed in the contact granite.

In the western near-contact zone of the "white granite" harpolith close to its bend, a body of topaz-mica-quartz greisen with cassiterite that forms the Kester tin deposit is localized. The greisen body is concordant to the harpolith roof; gradual transition from "white granite" to alteration determines the specific structural and morphological type of the deposit as an intermediate between the mineralized dome and mineralized dike. The greisenisation grade substantially decreases in the harpolith footwall and with distance from the bend toward the NE and SE on the surface. A pipe-like fluid-explosive body consisting of early magmatic breccia composed of large fragments of andesine granite and granodiorite cemented by "white granite" and late granitoid breccia cemented by greisen–tourmalinite body is observed in the host granite close to the harpolith bend (Fig. 1).

Along with the described harpolith, tens of NW and NE trending 0.2 to 10-m-thick "white granite" dikes that form a belt 6 km in length are observed in the Western dome and its eastern outer contact zone. Ongonite dikes that are 0.7– to 2-m thick are localized close to harpolith (Fig. 1). The white granite dikes have intrusive contacts with granodiorite and andesine granite and are frequently accompanied by stockscheiders and magmatic breccias composed of fragments of host granodiorite, granite, and hornfels cemented by "white granite".

In addition to the Kester deposit, many points of rare-metal and tin mineralization as quartz veins, metasomatic zones, and cassiterite placers along the channels of the Turagas River and Ilin-Salaya and Agatovy Creeks are present. Dikes and stock-like intrusions of albite granite, to which the Tumannoe and Ytyr-Khalan occurrences are related, are found at the outer contact (Fig. 1).

THE PETROGRAPHY AND PETROCHEMISTRY OF "WHITE GRANITES"

"White granite" is a saccharoidal massive or schliere rock (Fig. 2a). The mineral composition is, vol %: 28–41 albite (An_{2-7}), 13–29 microcline, 23–41 quartz, 7–13 white mica, 0.5–3 topaz, and 0.1–3 montebrasite. On the basis of exploration drilling, lep-

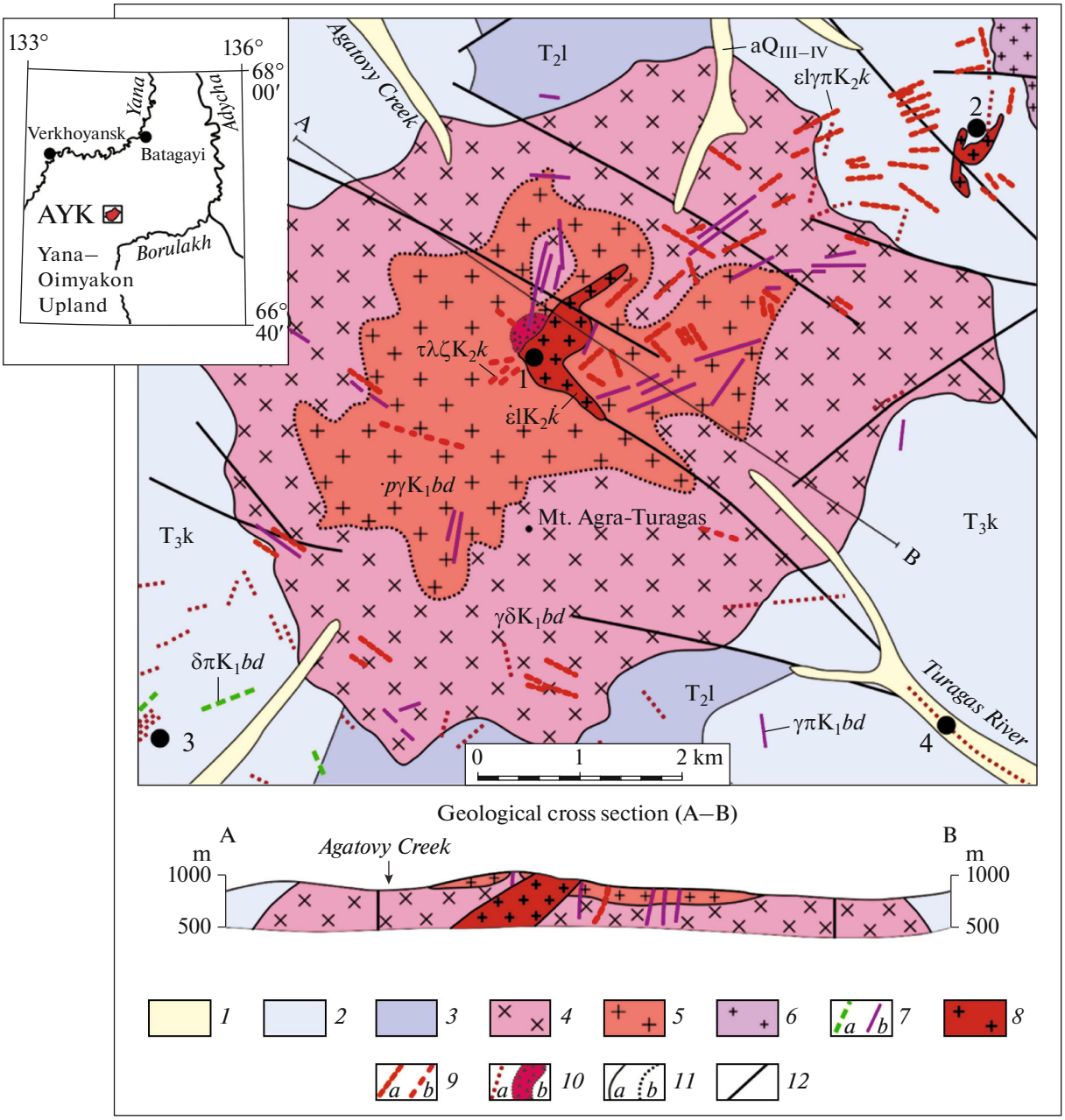

Fig. 1. A schematic geological map of the Western dome of the Agra–Ynnakh–Khaya Pluton, after Dorofeev and Martynenko (1963) and Boyrashinov et al. (1980, 1988). (*1*) alluvial and talus–solifluction boulder–pebble sediments, debris, sand, and sandy clay ($aQ_{III–IV}$); (*2*) Carnian sandstone and siltstone (T_3k); (*3*) Ladinian siltstone and sandstone (T_2l); (*4–7*) Baky–Derbeke Complex: (*4*) main phase granodiorite ($\gamma\delta K_1bd$), (*5*) main phase andesine granite ($p\gamma K_1bd$), (*6*) additional phase biotite and two-mica granites (γK_1bd), (*7*) dikes of (*a*) porphyry diorite ($\delta\pi K_1bd$) and (*b*) porphyry granite, porphyry leucogranite, and vein aplite ($\gamma\pi K_1bd$); (*8, 9*) Kester Complex: (*8*) main phase fine- to coarse-grained ovoid "white granite" ($\varepsilon l\gamma K_2k$), (*9*) dikes of (*a*) fine-grained "white granite" and (*b*) vein ongonite ($\tau\lambda\zeta K_2k$]; (*10*) undivided mineralized zones (*a*) and fluid explosive breccias (*b*); (*11*) geological boundaries between (a) rock of different age and (b) facial varieties; (*12*) faults. Numerals in circles are rare-metal and tin deposits and prospects: (1) Kester; (2) Tumannoe; (3) Ulakhan-Egelyakh; (4) Turagas placer. Geographical location of the Agra–Ynnakh–Khaya Pluton (AYK) is shown in the insertion.

idolite–montebrasite–albite "white granite" dominates in the apical part (0–60 m), which transits to the muscovite–topaz–albite variety with depth (60–150 m).

"White granite" is equigranular from coarse- to fine-grained. Albite of two generations is predominant. Relatively coarse thick-tabular albite 1 that is 1 : 3 to 1 : 6 in elongation forms the rock framework; fine-blade albite 2 (1 : 5–1 : 12) fills interstices between grains of albite 2 or is embedded as poikilitic crystals in microcline and quartz. Inclusions of glass, topaz, and

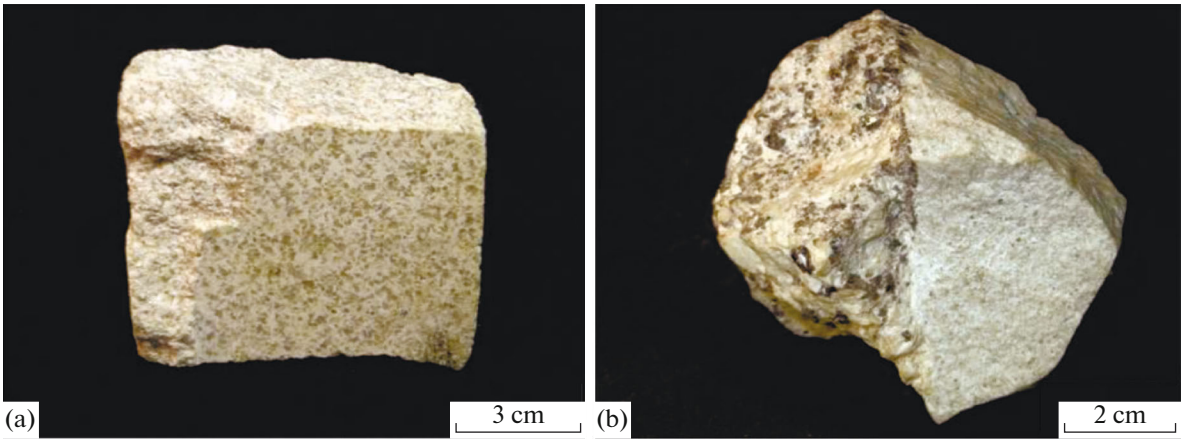

Fig. 2. White granite of the Kester harpolith. (a) medium-grained white granite from the east side of the Kester open pit; (b) the sharp straight contact of fine-grained lepidolite white granite and coarse-grained biotite granite, the watershed between the Turagas River and Ilin-Salaa Creek.

fine cassiterite are observed in albite phenocrysts in ongonite (Nekrasov, 1984). Microcline-perthite in white granite is anhedral, whereas quartz is equant : bipyramidal and rounded to pea-like in course- and fine-grained varieties, respectively. Zones with oriented albite, lepidolite, and montebrasite inclusions forming a snowball-like structure are observed in quartz. White mica occurred as poorly shaped lamellar crystals of ferrous lepidolite with inclusions and rims of later phengite.

According to the published data (Nedosekin, 1988; Trunilina et al., 2019), "white granite" is moderate felsic (67.11–79.95 wt % SiO_2), subalkali (7.27–8.84 wt % K_2O + Na_2O wt %), and rich in Al (14.61–17.84 wt % Al_2O_3) rocks. It belongs to the high-phosphorous type, is enriched in F (0.8–2.2 wt %) and rare elements, Li, Rb, Cs, Ta, Nb, and Sn. The chemical analysis of the reference samples supports such a composition. Low MgO (0.01–0.07 wt %) and Fe_2O_3 + FeO (0.28–0.51 wt %) concentrations, the high FeO/(FeO + MgO) ratio (0.86–0.96), and high Li_2O (up to 1.33 wt %), P_2O_5 (up to 2.04 wt %), and F (up to 2.08 wt %) were measured (Table 1).

Granites of the Arga–Ynnakh–Khaya Pluton are plumasitic. On the A/CNK versus A/NK diagram (Maniar and Piccoli, 1989; Maeda, 1990), country andesine granite falls into the S-type granite field and has affinity to the collisional geodynamic type. "White granite" differs from it in its higher Al content: the ASI and agpaitic coefficients are 1.29–1.30 and 0.71–0.73, respectively. The agpaitic coefficient increases with depth and in time (in the transition to ongonite). On the discriminatory diagram (Fig. 3), "white granite" is intermediate between collisional *S*-type granites and post-orogenic *A*-type granites. Trunilina et al. (2019) referred "white granite" and ongonite to plumasitic rare-metal granites, noting such features of intraplate granites as their high Rb/Sr ratio and Nb content. The FeO/(FeO + MgO) value (0.86–0.96) of "white granite" is also close to that of intraplate granites.

Using the VideoTest computer image analyzer, a correlation analysis of the "white granite" mineralogy and texture was performed. It was established that the sizes of microcline, albite, quartz, mica, topaz and montebrasite grains are positively correlated: the grains increase or decrease in coarse- and fine-grained white granite, respectively. The modes of major rock-forming minerals, quartz, microcline, albite, and lepidolite, are negatively correlated. The content of accessory minerals is inversely proportional to that of alkali feldspars and is directly correlated with the quartz content. The topaz and montebrasite modes are closely coupled (Table 2).

MINERALOGY OF "WHITE GRANITE"

The concentration of rare and volatile elements typical of the Kester "white granite" is reflected in the assemblage of accessory minerals. Topaz, montebrasite, cassiterite, columbite-(Fe), and tantalite-(Mn) are the major accessories (0.1–0.5%); fluorapatite, zircon, "wolframoixiolite," ferberite, strüverite, ilmenorutile, ilmenite, monazite-(Ce), and uraninite are minor (<0.1%). Accessory minerals are attracted to lepidolite grains and are associated with topaz and montebrasite (Fig. 4). Blue fine-grained montebrasite is uniformly scattered within the feldspar–quartz groundmass. Topaz occurs as barrel-like and rounded crystals forming subaggregates with quartz, albite, and montebrasite. Topaz inclusions are present in relatively large montebrasite and quartz grains. The assemblage of accessory minerals in "white granite" is markedly different from that in granodiorite, andesine granite, and leucogranite of the Arga–Ynnakh–Khaya Pluton. Titanite, allanite, fluorite, anatase, and pyrrhotite are absent in "white granite"; zircon, rutile,

Table 1. The chemical composition (wt %) of granites from the Arga–Ynnakh–Khaya Pluton

Component		"White granite"			Granite	
	13	208	15	138	146	19
SiO_2	70.09	70.55	70.16	67.23	71.17	67.96
TiO_2	0.05	0.07	0.04	0.09	0.35	0.38
Al_2O_3	16.53	16.15	16.50	16.97	15.48	15.63
Fe_2O_3	0.10	0.30	0.10	0.34	0.48	1.08
FeO	0.18	0.21	0.23	0.13	1.32	1.51
MnO	0.07	0.07	0.08	0.08	0.03	0.04
MgO	0.01	0.01	0.01	0.07	0.57	0.14
CaO	0.37	0.48	0.43	0.37	1.22	2.12
Na_2O	4.39	4.49	4.72	5.59	3.60	3.30
K_2O	4.18	3.98	3.96	2.94	4.69	5.02
Li_2O	0.62	0.57	0.60	1.33	0.02	0.07
P_2O_5	1.89	1.51	1.77	2.04	0.25	0.38
H_2O^-	0.20	0.21	0.21	0.24	0.29	0.56
F	0.44	0.60	0.58	1.08	0.07	0.10
LOI	1.20	1.42	1.08	2.36	0.98	2.07
—O=F	0.19	0.25	0.24	0.45	0.03	0.04
Total	100.13	100.37	100.23	100.41	100.49	100.32

(13, 208, 15) "White granites" of the Kester harpolith at the depths of 0, 15, and 80 m, respectively; (138) ongonite; (146, 19) andesine granite and porphyry granite from the western harpolith contact, respectively.

Table 2. Correlation grain sizes and modes in "white granites" from the Kester harpolith

	Grain size							Mineral mode						
	Mc	Ab	Qtz	Lpd	Tp	Mnb	Acc	Mc	Ab	Qtz	Lpd	Tp	Mnb	Acc
Mc		0.52	0.47	0.39	0.16	0.10	–0.17		0.01	–0.52	–0.14	–0.19	–0.03	–0.14
Ab	*0*		0.66	0.57	0.21	0.11	–0.39	*0.99*		–0.70	–0.43	–0.04	0.05	–0.41
Qtz	*0*	*0*		0.49	0.10	0.03	–0.34	*0*	*0*		0.13	–0.16	–0.29	0.33
Lpd	*0*	*0*	*0*		0.42	0.45	–0.12	*0.19*	*0*	*0.22*		–0.25	–0.05	–0.02
Tp	*0.20*	*0.09*	*0.42*	*0*		0.41	0.02	*0.07*	*0.68*	*0.14*	*0.02*		0.67	0.14
Mnb	*0.41*	*0.39*	*0.82*	*0*	*0*		–0.11	*0.79*	*0.65*	*0*	*0.67*	*0*		–0.07
Acc	*0.17*	*0*	*0*	*0.34*	*0.88*	*0.36*		*0.20*	*0*	*0*	*0.89*	*0.20*	*0.51*	

Correlation coefficients are upright (significant values are underlined); confidence levels are italicized ("0" < 0.05). The number of the analyses is 101 088; the number of granite samples is 109. Ab, albite; Acc, accessories; Lpd, lepidolite; Mc, microcline; Mnb, montebrasite; Qtz, quartz; Tp, topaz.

and apatite are negligible. We emphasize the rare-metal nature of the "white granite" mineralization; Li, Ta, Nb, Sn, W, and Hf-bearing minerals are predominant (Flerov et al., 1971; Orlov et al., 1984; Kokunin, 2011; Trunuilina et al., 2019).

The typomorphic properties of cassiterite are a dark brown or black color, bipyramidal grains of 30–770 μm, and high Ta_2O_5 and Nb_2O_5 contents, average 5.33 and 1.21 wt %, respectively (Table 3). Tantalum-bearing cassiterite is associated with Nb–Ta-bearing rutile as strüverite (average Ta_2O_5 and N_2O_5 is 12.38 and 1.39 wt %, respectively), and ilmenorutile (9.57 wt % Nb_2O_5, 7.80 wt % Ta_2O_5) (Figs. 4a, 4b). Zircon from white granite contains substantial HfO_2 5.69 wt % and UO_2 2.94 wt %; the Zr/Hf ratio is 3.5–26.6.

The columbite group minerals form euhedral thin-tabular crystals with characteristic zoning due to columbite-(Fe) surrounded by the wide rims of tantalite-(Mn) and a Ta/(Na + Nb) ratio increases from the core (average 0.20) to the rim (0.69) (Fig. 4d). Inter-

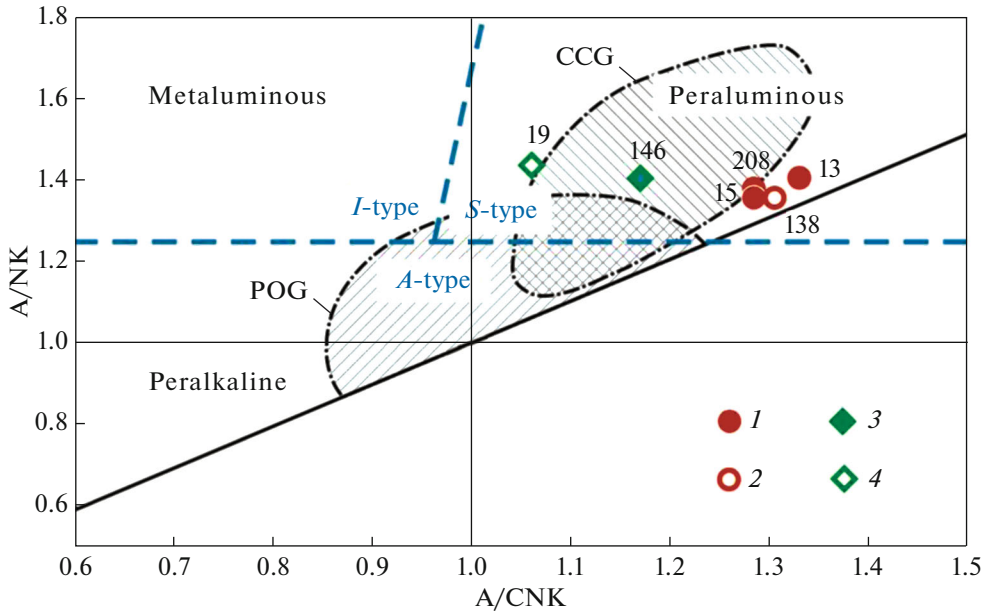

Fig. 3. The alkalinity index versus the aluminous index diagram for granites of the Arga–Ynnakh–Khaysky Pluton [A/NK = $Al_2O_3/(Na_2O + K_2O)$, A/CNK = $Al_2O_3/(CaO + Na_2O + K_2O)$]. The solid lines bound fields of granitoid petrochemical varieties; the dotted-dashed lines show boundaries of continental–collisional granites (CCG) and post-orogenic granites (POG) (Maniar and Piccoli, 1989), dotted lines show I-, S-, and A-type granites (Maeda, 1990). Points (1, 2) Kester complex: (*1*) "white granite"; (*2*) ongonite; Baky-Derbeke Complex: (*3*) main phase andesine granite, (*4*) vein phase porphyry granite. The points correspond to the numbers in Table 1.

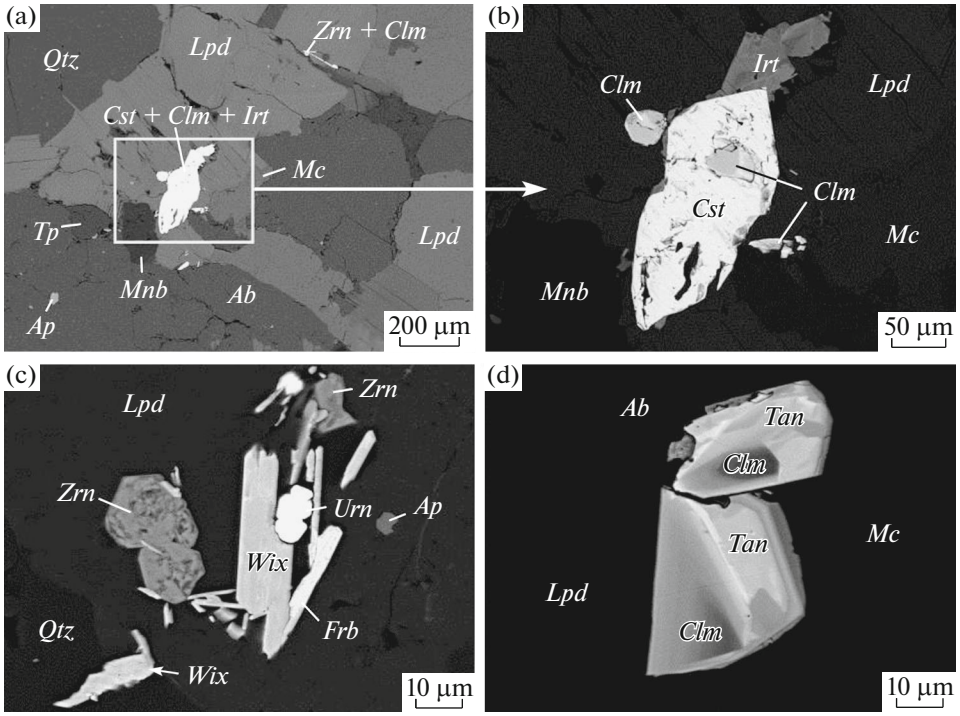

Fig. 4. Back-scattered electron images of accessory minerals from "white granites" of the Kester harpolith. (a) medium-grained lepidolite–microcline–albite granite containing topaz, montebrasite, fluorapatite, tantalian cassiterite, W-bearing columbite-(Fe), ilmenorutile–strüvite, and Hf-bearing zircon; (b) inclusions of columbite–tantalite in cassiterite rimmed by ilmenorutile–strüvite, magnified fragment of a; (c) intergrowth of wolframoixiolite, Nb–Ta-bearing ferberite, U–Hf-bearing zircon, and uraninite in ongonite; (d) W-bearing cassiterite columbite-(Fe) rimmed by tantalite-(Mn) in coarse-grained lepidolite–microcline–albite granite. Ab, albite; Ap, fluorapatite; Clm, columbite-(Fe); Frb, ferberite; Irt, ilmenorutile–strüvite; Lpd, lepidolite; Mc, microcline; Mnb, montebrasite; Qtz, quart; Tan, tantalite-(Mn); Tp, topaz; Wix, wolframoixiolite; Urn, uraninite; Zrn, U–Hf-bearing zircon.

Table 3. The chemical composition (wt %) of cassiterite, columbite, and tantalite from "white granites" of the Kester harpolith

Component	Cassiterite			Columbite-(Fe)			Tantalite-(Mn)		
	1	2	Av. (144)	3	4	Av. (25)	5	6	Av. (43)
TiO_2	0.28	0.26	0.07	1.83	0.85	1.40	0.73	1.26	0.81
MnO	0.11	1.50	0.04	5.28	8.13	6.93	12.31	10.25	11.00
FeO*	0.67	1.43	0.85	13.83	10.62	12.26	2.55	5.42	4.29
Nb_2O_5	1.88	1.43	1.21	63.18	64.57	63.48	17.03	25.33	25.32
SnO_2	92.93	89.42	92.47	–	–	–	–	0.79	0.55
Ta_2O_5	2.36	7.56	5.33	9.42	12.85	11.35	67.21	54.01	56.39
WO_3	–	–	–	6.13	2.15	4.21	0.30	1.80	0.88
Total	98.22	100.24	99.97	99.67	99.18	99.64	100.13	98.86	99.23
	Formula coefficients [O = 2 (cassiterite), O = 6 (columbite, tantalite)]								
Ti	0.01	0.01	0.00	0.08	0.04	0.06	0.04	0.07	0.04
Mn	0.00	0.00	0.00	0.26	0.41	0.35	0.79	0.63	0.68
Fe	0.01	0.03	0.02	0.68	0.53	0.61	0.16	0.33	0.26
Nb	0.02	0.02	0.01	1.69	1.74	1.71	0.59	0.83	0.84
Sn	0.94	0.89	0.93					0.02	0.02
Ta	0.02	0.05	0.04	0.15	0.21	0.18	1.39	1.07	1.12
W				0.09	0.03	0.06	0.01	0.03	0.02

Representative (1–6) and average (Av., number of samples in parentheses) electron microprobe data for minerals are given. A dash denotes that the element was not detected; FeO* is FeO + Fe_2O_3.

growths of columbite-(Fe) with Hf-bearing zircon, wolframoixiolite, and ferberite are characteristic. Columbite–tantalite is the most frequently observed as inclusions in topaz and lepidolite and is less frequent in quartz, apatite, montebrasite, and cassiterite (Fig. 4b). Columbite-(Fe) contains on average, wt %: 11.35 Ta_2O_5, 4.21 WO_3, and 1.40 TiO_2; tantaline-(Mn) contains, wt % 25.32 Nb_2O_5, 0.88 WO_3, 0.55 SnO_2, 0.81 TiO_2 0.81 (Table 3). Minor SnO_2 is characteristic of ilmenorutile (0.74 wt %) and strüverite (0.55 wt %). We found wolframoixiolite for the first time in "white granites"; its average composition is wt %: 60.70 Nb_2O_5, 7.71 Ta_2O_5, 10.44 WO_3, 12.17 FeO, 7.10 MnO, 1.41 TiO_2 (Fig. 4c). The mineral replaces columbite and predates Nb–Ta-bearing ferberite (2.25 wt % Nb_2O_5, 3.03 wt % Ta_2O_5) forming stable association with the latter (Alekseev et al., 2020).

DISCUSSION

In a similar manner to that for other rare-metal granite intrusions in Eurasia, the discussion about the origin of the Kester harpolith has evolved together with ideas of rare-metal granite petrology (Beus et al., 1962; Kovalenko, 1977; Beskin et al., 1979, 1999; Yarmolyuk et al., 1987; Rub A.K. and Rub M.G., 2006; *Petragraphic* ..., 2009). Most researchers considered the harpolith as an individual intrusion and referred characteristic of to alaskite of the late intrusion phase. The mineralized dome in the apical part of the harpolith and the gradual transition from greisen to characteristic of have led to the popular hypothesis that the formation of the Kester white granite is a result of metasomatic transformation of alaskite. Followers of this idea named characteristic of as "apogranite" and only microcline, quartz 1, zircon, and apatite were considered as magmatic minerals. All other constituents of apogranite were referred to post-magmatic ones, including albite, lepidolite, quartz 2, topaz, amblygonite, and cassiterite (Chaikovsky, 1960; Flerov et al., 1971; Koval, 1975). Over time, the idea of the magmatic origin of white granite was established and the Kester Complex of rare-metal granites (small intrusions) was identified (Ivanov, 1969; Efremenko, 1976; Nekrasov, 1984; Orlov et al., 1984; Nedosekin, 1988; Alekseev, 2014; Trunilina et al., 2019).

Geological indications of "white granite" genesis. The authors of the Q-53 sheet of the State Geological Map 1000/3 described the Kester white granite harpolith as a manto-like greisen body (*State* ..., 2016). However, the hypothesis of the metasomatic origin of "white granite" contradicts such facts as the absence of metasomatic zoning of "albitized" and "gresenized" rocks; the distribution of "greisenisation" down to 170 m below the surface, i.e., through the depth of the studied harpolith; the absence of parental "alaskite" at the low level of the Kester deposit; and

extremely weak alteration of andesine granite adjacent to the white granite.

We will provide the geological indications of the magmatic origin of "white granite".

(1) The Kester harpolith has structural and morphological features of an intrusion cutting the main phase granite and granodiorite of the Agra–Ynnakh–Khaya Pluton (Fig. 1). The sharp intrusion contacts of "white granite" with andesine granite (Fig. 2), along which stockscheiders and numerous granite xenoliths in "white granite" are observed, are the most informative indications. Contacts with country granites were described many times on the surface, in the open pit, and in numerous boreholes (Chaikovsky, 1960; Flerov et al., 1971; Efremenko, 1976; Romanova, 1976; Orlov et al., 1984; Nedosekin, 1988; Trunilina et al., 2019).

(2) The "white granite" harpolith is accompanied by a series of small "white granite" and ongonite intrusions forming an intrusion–dike complex typical of rare-metal granites (Beskin et al., 1979; Yarmolyuk et al., 1987; Alekseev, 2014).

(3) The explosive pipe composed of fluid-explosive breccia with fragments of the main phase granites cemented by "white granite" (Fig. 1) in the outer contact zone of the Kester zone is the major evidence for the magmatic genesis of the latter. Porphyry granites of the final vein phase of the Baky–Derbeke diorite–granodiorite–granite complex are present among breccia fragments cemented by "white granite"; this indicate the formation of the "white granite" at the late stage of magmatic evolution and its belonging to a different igneous complex. It should be noted that fluid-explosive breccias similar to Kester are described from other LFG plutons: Alakha in Altai (Kudrin et al., 1994), Asakan–Shumilovo and Etyka in Transbaikal Region, Odinokoe in Yakutia, and Tigriny in Primorsky Krai (Alekseev, 2014).

In rare-metal granitic melts, which reached a shallow depth (0.5–3 km), the fluid pressure could be substantially increased in regard to the lithostatic load [up to 7.5 MPa (Alekseev, 2014)]. This overpressure was reached at the final stage of the Kester white granite harpolith in its hanging wall. The explosion pipe composed of the early magmatic breccia of andesine granite cemented by "white granite" and the late breccia of various granitic rocks in the greisen–tourmaline cement was formed as a result of deep erosion at the intersection of northwest and northeast trending faults that govern magma inflow. The near contact mineralized greisen forming the Kester rare-metal–tin deposit was formed in the hanging wall of the "white granite" harpolith under these conditions.

Petrological indications of the genesis of "white granite." The petrographic features are the reliable indications of the magmatic origin of the Kester "white granite" harpolith. The "white granite" mineralogy and texture are consistent with the LFG characteristics described from numerous rare-metal-granite complexes in the Transbaikal Region, Primorsky Krai, Mongolia, France, Czechia, Germany, Egypt, and China (Kovalenko, 1977; Beskin et al., 1979, 1999; Yarmolyuk et al., 1987; Cuney et al., 1992; Huang et al., 2002; Rub and Rub, 2006; Alekseev, 2014; Breiter et al., 2017; Emam et al., 2018; Xie et al., 2018; René, 2019). The ovoid-like porphyry texture of rare-metal plumasitic granites with the snowball-like structure in quartz is typical of "white granite". The glass inclusions in albite from ongonite, which forms a unified igneous complex with "white granite", indirectly testify to the magmatic origin of them (Nelrasov, 1984).

In accordance with valid petrochemical and geochemical classifications, "white granite" and ongonite of the Arga–Ynnakh–Khaya Pluton are post-orogenic moderately alkaline plutonic rocks, plumasitic rare-metal granites of the Li-F geochemical type (Kovalenko, 1977; Beskin et al., 1979, 1999; Yarmolyuk et al., 1987; Maniar and Piccoli, 1989; Maeda, 1990; *Petrograhic* ..., 2009; Trunilina et al., 2019) (Fig. 3).

The absence of protolith relics, i.e., minerals of country granodiorite or granite (biotite, oligoclase–andesine, orthoclase, titanite, rutile and others) in "white granite" contradicts the their metasomatic origin. The post-magmatic genesis of white granite is not consistent with the uniformly distributed accessory minerals (cassiterite, montebrasite, topaz, and tantaloniobates) and the absence of monomineralic segregations and chain aggregates of accessories.

M.A. Romanova modeled the "white granite" texture on the basis of the Vistelius conception of "ideal granite." According to the working hypothesis, the sequence of intergranular contacts of microcline, quartz, and albite in primary igneous granites is not different from a simple Markov chain. As a result of the Markov chain calculations, it was established that "white granite" crystallized in a homogeneous medium throughout the space of the harpolith. It was concluded the igneous nature of the "white granite" texture was disturbed in the roof part of the harpolith due to superimposed albitization and greisenization (Romanova, 1976; Vestelius, 1980).

The magmatic origin of "white granite" is supported by a correlation analysis of its texture and composition. The strong correlation between grain size of obviously magmatic minerals (microcline and quartz) on the one hand and albite, mica, and accessories on the other hand indicates an absence of substantial secondary alteration in "white granite" with a probability exceeding 0.95. Microcline, quartz, albite, white mica, topaz, montebrasite, and cassiterite grains simultaneously increase or decrease in size in individual aggregates and therefore are formed during one-stage mineral-forming process of magma crystallization. The negative correlation between the modes of major minerals, quartz and alkali feldspars, and a positive relationship of the accessory and quartz modes

were established in "white granite". These features were described as typical of magmatic aggregates (Alekseev, 2005). The topaz and montebrasite modes strongly correlate, which reflects the high Al and F concentrations typical of granite magma (Table 2).

As was previously revealed by the method of mathematical geology (Vistelius, 1980; Romanova, 1980; Alekseev, 2005), albitized and greisenized granites are distinguished by a strong direct correlation between the modes and size of topaz, mica, and accessory minerals, as well as those of newly formed quartz and albite. On this basis, the following petrographic facts contradict the assumption of the alteration of "white granite": (1) the absence of a correlation between the quartz, topaz, and mica modes; (2) a strong negative correlation between the mode and grain size of quartz and the modes of topaz (correlation coefficient (–0.31), cassiterite (–0.24), columbite-tantalite (–0.29), and other accssories (–0.34); (3) a negative correlation between the sizes of quartz and accessory grains (–0.34) and albite and accessory grains (–0.39); and (4) a negative correlation between the size of albite grains and the topaz mode (–0.30) (Table 2).

Mineralogical indications of "white granite" genesis. "White granite" mineral assemblage is typical of the Li–F-type microcline–albite granites; however, this assemblage is frequently divided into primary magmatic and secondary pneumatolytic minerals within the frameworks of the "apogranite" hypothesis. Therefore, the accessory assemblage is more stable during post-magmatic transformation, which is of particular importance to establish the genesis of the "white granite". Accessory minerals are considered in modern petrology as one of the concentrators of rare elements in the magmatic process, which makes them useful in the study of granitoid petrogenesis.

The assemblage of accessories in "white granites" consists minerals that are characteristic of subalkali granites: topaz, montebrasite, columbite–tantalite, zircon, wolframoixiolite, ferberite, strüverite, ilmenorutile, ilmenite, monazite-(Ce), and others. The "white granite" accessories have the typochemical features of LFG minerals: Nb- and Ta-bearing cassiterite, rutile, and ferberite; U–Hf-bearing zircon; Sn-bearing tantalite and strüverite (Koval, 1975; Kovalenko, 1977; Meskin et al., 1979; Yarmolyuk et al., 1987; Cuney, 1992; Johan and Johan, 1994; Belkasmi et al., 2000; Rub and Rub, 2006; Alekseev, 2014; Breiter et al., 2017; Alfonso et al., 2018; Emam et al., 2018; René, 2019).

Tantalum, which is an minor element and an economic rare metal of LFGs, is permanently present in compositions of "white granite" accessories (cassiterite, columbite, ferberite, and rutile). Tantalum-bearing ferberite, which is untypical in post-magmatic rocks, was observed (Alekseev et al., 2020). Cassiterite from "white granite" with anomalously high Ta_2O_5 5.33 wt %, which is not observed in greisen and is typical of rare-metal granites and pegmatites (Maksimyuk and Voronina, 1989; Tindle and Breaks, 1998), is indicative. Columbite in "white granite" shows core-to-rim increase in Ta/Nb ratio, which is typical of rare-metal granites. (Belkasmi et al., 2000; Breiter et al., 2017; Alfonso et al., 2018; René, 2019).

For the first time, we found tungsten as an isomorphic impurity in the columbite group minerals from "white granite", which is characteristic of the accessory assemblages in the Far East LFGs (Alekseev, 2014).

The paragenesis of Nb–Ta-bearing ferberite and wolframoixiolite that resulted from polymorphic transformation of columbite-(Fe), is an important evidence of the origin of the "white granite". Wolframoixiolite of a similar composition is common in the Eurasian LFGs as intergrowths with wolframite, columbite, or Nb-bearing rutile and is an indicator mineral of rare-metal granites and pegmatites (Johan and Johan, 1994; Breiter et al., 2017; Xie et al., 2018; Alekseev et al., 2020; René, 2019).

The accessory tantaloniobates were formed at the late crystallization stage of rare-metal granite magma. The columbite–tantalite group minerals precipitate from a differentiated low-temperature melt at them saturation in Ta and Nb (Chevychelov et al., 2010). Metasomatic columbite is formed under the effect of a fluid equilibrated with microcline–albite granite (Alekseev, 2014). Further redistribution of Ta and Nb determines the overprinting of columbite by tantalite and transformation of the columbite structure to the wolframite one to form wolframoixiolite (Voloshin and Pakhomovsky, 1988; Alekseev et al., 2019).

The crystallization of the columbite group minerals and their replacement by wolframoixiolite is considered as an imprint of the transition from the magmatic to the pneumatolytic stage of the rare-metal granite formation associated with the appearence of the evolutionary mineral sequence: columbite → tantalite → wolframoixiolite → Nb-bearing ferberite (Breiter et al., 2017; Xie et al., 2018; Alekseev et al., 2019). Zircon with high Hf and U concentrations as well as with the Zr/Hf ratio reaching 3.8 in "white granite" is a clear indication of the late magmatic crystallization of a highly differentiated granitic melt (Huang et al., 2002; Kempe et al., 2004; Xie et al., 2018).

Analogues of "white granite". The comprehensive similarity to the rare-metal granite plutons in Eurasia is one of the arguments for the magmatic origin of the Yakutia "white granite". As can be seen from geological, petrological, and mineralogical data, "white granite" is similar to LFGs of the Etyka (Transbaikal Region), Voznesenka (Primorsky Krai), Zinnwald

(Czechia), Nuweibi (Egypt), and many other plutons (Beskin et al., 1997, 1999; Yarmolyuk et al., 1987; Rub and Rub, 2006; Breiter et al., 2017; Emam et al., 2018). The Yakutia "white granite" is distinguished by a substantial role of phosphate minerals, fluorapatite, montebrasite, and others; this is explained by the regional geochemical specialization of the crustal protolith in the source area for the rare-metal granitic magma (Trunilina et al., 2019). Taking the high phosphorous content into account, granites of the Alakha pluton in Mountain Altay (Kudrin et al., 1994), Echassieres Pluton in French Massif Central (Koval, 1975; Cuney et al., 1992), and Yichun Pluton in Jiangxi Province, China (Belkasmi et al., 2000; Huang et al., 2002) are the most similar to "white granite".

Small LFG intrusions that make up dike areas of ongonite magmatism have been identified in East Russia since the 1980s. Similar areas form the long Far East belt and control large W–Sn and rare-metal deposits of the Pacific Belt (Alekseev, 2014). The Kester harpolith and accompanying LFG dike complex is one of the elements of the Far East magmatic superprovince of rare-metal granite; the Kester tin–rare-metal deposit is genetically related to this harpolith. The listed genetic indications conclude that the Western dome of the Arga–Ynnakh–Khaya granitoid pluton was injected by fluid-saturated high-alkali granitic magma, which formed the Kester harpolith of rare-metal microcline–albite granite of the lithium–fluorine type.

CONCLUSIONS

(1) The morphology, occurrence, and evidence of intrusive contacts of the Kester "white granite" harpolith are reliable signs of its magmatic origin. The harpolith and the accompanied series of small "white granite" and ongonite intrusions form a rare-metal intrusion–dike complex. An explosive pipe composed of breccia with fragments of country granitoids cemented by "white granite" is found in the outer harpolith contact.

(2) Petrography and petrochemistry of the "white granite" indicate its formation as a result of crystallization of moderately alkali fluid-saturated magma and allows identification of the studied rock as post-orogenic rare-metal high-phosphorous granite of the Li-F geochemical type. The magmatic genesis of the "white granite" texture and its partial alteration are supported by statistical methods.

(3) Assemblage and chemistry of the accessory minerals of "white granite" correspond those of minerals of subalkali rare-metal gran. Ontogenic analysis of the inner structure of minerals and relationshops between them conclude that the major accessories, cassiterite, columbite, tantalite, wolframoixiolite, zircon, and ferberite, were formed at the late low-temperature stage of the rare-metal granite melt.

(4) White granite is analogue of the Li-F granites of some rare-metal intrusive complexes in Eurasia. The Kester harpolith of the Arga–Ynnakh–Khaya deposit and the eponymous tin–rare-metal deposit that is genetically related to it are members of the Far East magmatic superprovince of rare-metal granites.

ACKNOWLEDGMENTS

We are deeply grateful to V.N. Podkorytov, principal researcher of the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences for the chance to use materials from the personal files of M.A. Romanova, scientific researcher of the Laboratory of Mathematical Institute, Mathematical Institute, Russian Academy of Sciences. We thank O.L. Galankina, senior scientific researcher of the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences for her assistance in the study of granite minerals.

REFERENCES

Alekseev, V.I., About an origin of lithium-fluoric granite in the Northern massif (Chukotka), *Zap. Ross. Mineral. O-va*, 2005, no., pp. 19–30.

Alekseev, V.I., *Litii-ftoristye granity Dal'nego Vostoka* (Lithium-Fluoric Granites of the Far East), St Petersburg: Saint-Petersburg Mining University, 2014.

Alekseev, V.I., Marin, Yu.B., and Galankina, O.L., Wolframoixiolite in lithium-fluoric granites of the Arga–Ynnakh–Khaysky massif, Yakutia, *Zap. Ross. Mineral. O-va*, 2019, no. 3, pp. 44–58.

Alfonso, P., Hamid, S.A., Garcia-Valles, M., Llorens, T., Moro, F.J.L., Tomasa, O., Calvo, D., Guasch, E., Anticoi, H., Oliva, J., Parcerisa, D., and Polonio, F.G., Textural and mineral-chemistry constraints on columbite-group minerals in the Penouta deposit: evidence from magmatic and fluid-related processes, *Mineral. Mag.,* 2018, vol. 82, pp. 199–S222.

Belkasmi, M., Cuney, M., Pollard, P.J., and Bastoul, A., Chemistry of the Ta–Nb–Sn–W oxide minerals from the Yichun rare metal granite (SE China): genetic implications and comparison with Moroccan and French Hercynian examples, *Mineral. Mag*, 2000, vol. 64, no. 3, pp. 507–523.

Beskin, S.M., Larin, V.N., and Marin, Yu.B., *Redkometal'nye granitovye formatsii*, (Rare-Metal Granite Formations), Leningrad: Nedra, 1979.

Beskin, S.M., Marin, Yu.B., Matias, V.V., and Gavrilova, S.P., What does it really mean: "rare-metal granite"? *Zap. Ross. Mineral. O-va*, 1999, no. 6, pp. 28–40.

Beus, A.A., Severov, E.A., Sitnin, A.A., and Subbotin, K.D., *Al'bitizirovannyie i greizenizirovannye granite (apogranity),* (Albitized and Greisenized Granites (Apogranite)), Moscow: Acad. Nauk USSR, 1962.

Breiter, K., Korbelova, Z., Chladek, S., Uher, P., Knesl, I., Rambousek, P., Honig, S., and Sesulka, V., Diversity of

Ti–Sn–W–Nb–Ta oxide minerals in the classic granite related magmatic–hydrothermal Cinovec/Zinnwald Sn–W–Li deposit (Czech Republic). *Europ. J. Mineral.*, 2017, vol. 29, pp. 727–738.

Brodskaya, R.L. and Marin, Yu.B., Ontogenetic analysis of mineral individuals and aggregates at microand nanolevel for the restoration of ore-forming conditions and assessment of mineral raw technological properties, *Zap. Gorn. Inst.*, 2016, vol. 219, pp. 369–376.

Chaikovsky, V.K., *Geologiya olovonosnykh mestorozhdenii Severo-Vostoka SSSR* (Geology of Tin-Bearing Deposits of Soviet Nortehast) Moscow: Gosgeoltekhizdat, 1960.

Chevychelov, V.Yu., Borodulin, G.P., and Zaraiskiy, G.P., Solubility of columbite (Mn, Fe)(Nb,Ta)2O6 in granitoid and alkaline melts at 650–850°C and 30-400 MPa: an experimental investigation, *Geochem. Int.*, 2010, vol. 48, no. 5, pp. 456–464.

Cuney, M., Marignac, C., and Weisbrod, A., The Beauvoir topaz–lepidolite albite granite (Massif Central, France): the disseminated magmatic Sn–Li–Ta–Nb–Be mineralization, *Econ. Geol.*, 1992, vol. 87, pp. 1766–1794.

Efremenko, E.A., High-aluminous granitoid formation in the Yana–Borulakh ore district of Yakutia, *Geol. Geofiz.*, 1976, no. 3, pp. 33–44.

Emam, A., Zoheir, B., Radwan, A.M., Lehmann, B., Zhang, R.Q., Fawzy, S., and Nolte, N., Petrogenesis and evolution of the Nuweibi rare-metal granite, Central Eastern Desert, Egypt, *Arabian J. Geosci.,* 2018, vol. 11, no. 23, paper 736.

Flerov, B.L., Indolev, L.N., Yakovlev, Ya.V., and Bichus, B.Ya., *Geologiya I genesis oovorudnykh mestorozhdenii Yakutii* (Geology and Genesis of Tin-Bearing Deposits of Yakutia), Moscow: Nauka, 1971.

Huang, X.L., Wang, R.Ch., Chen, X.M., Hu, H., and Liu, C.S., Vertical variations in the mineralogy of the Yichun topaz–lepidolite granite, Jiangxi Province, southern China, Can. Mineral., 2002, vol. 40, pp. 1047–1068.

Ivanov O.P. Formations analysis of tin-bearing deposits in the Yano-Borulakh district, *Rudoobrazovanie i ego svyaz' s magmatizmom* (Ore Formation and its Relation with Magmatism), Yakutsk: Yakut book publishing house, 1969, pp. 67–70.

Johan, V. and Johan, Z., Accessory minerals of the Cinovec (Zinnwald) granite cupola, Czech Republic. Part 1. Nb-, Ta- and Ti-bearing oxides, *Mineral. Petrol.*, 1994, vol. 51, pp. 323–343.

Kempe, U., Gruner, T., Renno, A.D., Wolf, D., and Rene, M., *Discussion on Wang et al. (2000): Chemistry of Hf-rich zircons from the Laoshan I- and A-type granites, Eastern China, Mineral. Mag.,* 2004. Vol. 68, no. 4, pp. 669–675.

Kokunin, M.V., Rare minerals of the forgotten deposit, *Otechestvennaya Geol.,* 2011, no. 1, pp. 72–82.

Koval', P.V., *Petrologiya i geokhimiya al'bitizirovannykh granitov* (Petrology and Geochemistry of Albitized Granites), Novosibirsk: Nauka, 1975.

Kovalenko, V.I., *Petrologiya i geokhimiya redkometal'nykh granitov* (Petrology and Geochemistry of Rare-Metal Granitoids), Novosibirsk: Nauka, 1977.

Kudrin, V.S., Stavrov, O.D., and Shuriga, T.N., New spodumene type of tantalum-bearing rare-metal granite, *Petrologiya,* 1994, vol. 2, no. 1, pp. 88–95.

Maeda, J., *Opening of the Kuril Basin deduced from the magmatic history of Central Hokkaido*, North Japan, *Tectonophysics,* 1990, vol. 174, pp. 235–255.

Maksimyuk, I.E. and Voronina, L.B., *Cassiterite, Tipomorfism mineralov* (Typomorphism of Minerals: A Reference Book), Moscow: Nedra, 1989, pp. 204–218.

Maniar, P.D. and Piccoli, P.M., Tectonic discrimination of granitoids, *Geol. Soc. Am. Bull.,* 1989, vol. 101, pp. 635–643.

Nedosekin, Yu.D., *Redkometal'nye granity Severo-Vostoka SSSR,* (Rare-Metal Granites in Soviet Northeast), Moscow: Nauka, 1988.

Nekrasov, I.Ya., *Olovo v magmaticheskom i postmmagmaticheskom protsesse* (Tin in Magmatic and Postmagmatic Processes), Moscow: Nauka, 1984.

Orlov, Y.S., Filimonov, Y.A., and Boyarshinov, V.V., Revisited on genesis of alaskaite in Arga–Ynnakh–Khaisky massif (East Yakutia), *Geologiya i poleznye iskopaemye Verkhoyano-Kolymskoi skladchatoi sistemy* (Geology and Mineral Resources of the Verkhoyansk-Kolyma Fold System), Yakutsk: Yakut book publishing house, 1984, pp. 74–81.

Petrograficheskii kodeks. Magmaticheskie, metamorficheskie, metasomaticheskie, impaktnye obrazovaniya (Petrographic Code. Magmatic, Metamorphic, Metasomatic, and Impact Rocks), 3rd Ed. St. Petersburg: VSEGEI, 2009.

Printsipy raschleneniya i kartirovaniya granitoidnykh intruzii i vydeleniya petrologo-metallogenicheskikh variantov granitoidnykh serii (Principles of Subdivision and Mapping of Granitoid Intrusions and Recognition of Petrological–Metallogenical variants of Granitoid Series), St. Petersburg: VSEGEI, 2007.

René, M., Nb–Ta-Ti Oxides in topaz granites of the Geyer Granite Stock (Erzgebirge Mts., Germany), *Minerals*, 2019, vol. 9, no. 3, p. 155.

Romanova, M.A., Markovsky properties of grains sequences in rare-metal granite, their use in prospecting works and petrological researches, *Geologicheskaya informatsiya I matematicheskaya geologiya* (Geological Information and Mathematical Geology), Int. Geol. Congr. 25th Session, Moscow: Nedra, 1976, pp. 53–65.

Romanova, M.A., Problems of mathematical geology at research of granitoid in Yakutia. In: *Osnovnye metody matematicheskoi geologii I rezul'taty issledovanii* (Fundamental Methods of Mathematical Geology and Results of Studies),Yakutsk: YaF Sib. Otd. Akad. Nauk SSSR, 1980, pp. 18–31.

Rub, A.K. and Rub, M.G., *Redkometal'nye granity Primor'ya* (Rare-Metal Granites of Primorye), Moscow: VIMS, 2006.

Gosudarstvennaya geologicheskaya karta Rossiiskoi Federatsii. Masshtab 1 : 1000000 (tret'e pokolenie). Seriya Verkhoy-

ano–Kolymskaya. List Q-53—Verkhoyansk. Ob'yasnitel'naya zapiska (State geological map of Russian Federation. Scale 1 : 1000000 (the third generation). A series Verkhoyansk-Kolyma. Sheet Q-53—Verkhoyansk. Explanatory note.)) Ed. V.V. Kalashnikov, Saint Petersburg: VSEGEI, 2016.

Tindle, A.G. and Breaks, F.W., Oxide minerals of the Separation Rapids rare-element granitic pegmatite group, northwestern Ontario, *Can. Mineral.,* 1998, vol. 36, pp. 609–635.

Trunilina, V.A., Orlov, Yu.S., Zaitsev, A.I., and Roev, S.P., High-phosphorous lithium-fluorine granites of eastern Yakutia (Verkhoyansk-Kolyma orogenic region), *Russ. J. Pac. Geol.*, 2019, vol. 38, no. 1, pp. 64–79.

Vistelius, A.B., *Osnovy matematicheskoi geologii (opredelenie predmetal, izlozhenie apparata* (Principles of Mathematical Geology (Definition and Algorithm)), Leningrad: Nauka, 1980.

Voloshin, A.V. and Pakhomovskiy, Y.A., *Mineralogiya tantala i niobiya v redkometal'nykh pegmatitakh* (Tantalum and Niobium Mineralogy in Rare-Metal Pegmatites), Leningrad: Nauka, 1986.

Xie, L., Wang, Z.J., Wang, R.C., Zhu, J.C., Che, X.D., Gao, J.F., and Zhao, X., Mineralogical constraints on the genesis of W–Nb–Ta mineralization in the Laiziling granite (Xianghualing district, south China). *Ore Geol. Rev.,* 2018, vol. 95, pp. 695–712.

Yarmolyuk, V.V., Kovalenko, V.I., and Pavlov, V.A., *Acid and intermediate magmatic rocks of the conjugate activation zones, Magmaticheskie gornye porody, Kislye I srednie porody* (Magmatic Rocks. Acidic and Intermediate Magmatic Rocks), Moscow: Nauka, 1987, vol. 4, pp. 234–259.

Translated by I. Baksheev

View publication stats