ISSN 1819-7140, Russian Journal of Pacific Geology, 2016, Vol. 10, No. 3, pp. 155–167. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © E.V. Sklyarov, D.P. Gladkochub, A.B. Kotov, A.E. Starikova, V.V. Sharygin, S.D. Velikoslavinsky, A.M. Larin, A.M. Mazukabzov, E.V. Tolmacheva, E.A. Khromova, 2016, published in Tikhookeanskaya Geologiya, 2016, Vol. 35, No. 3, pp. 9–22.

Genesis of the Katugin Rare-Metal Ore Deposit: Magmatism versus Metasomatism

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Received May 28, 2015

Abstract—Arguments in favor of magmatic or metasomatic genesis of the Katugin rare-metal ore deposit are discussed. The geological and mineralogical features of the deposit confirm its magmatic origin: (1) the shape of the ore-bearing massif and location of various types of granites (biotite, biotite–amphibole, amphibole, and amphibole–aegirine); (2) the geochemical properties of the massif rocks corresponding to A type granite (high alkali content (up to 12.3% $Na_2O + K_2O$), extremely high FeO/MgO ratio ($f = 0.96–1.00$), very high content of the most incoherent elements (Rb, Li, Y, Zr, Hf, Ta, Nb, Th, U, Zn, Ga, and REE) and F, and low concentrations of Ca, Mg, Al, P, Ba, and Sr); (3) Fe–F-rich rock-forming minerals; (4) no previously proposed metasomatic zoning and regular replacement of rock-forming minerals corresponding to infiltration fronts of metasomatism. The similar ages of the barren (2066 ± 6 Ma) and ore-bearing (2055 ± 7 Ma) granites along with the features of the ore mineralization speak in favor of the origin of the ore at the magmatic stage of the massif's evolution. The nature of the ore occurrence and the relationships between the ore minerals support their crystallization from F-rich aluminosilicate melt and also under melt liquation into aluminosilicate and fluoride (and/or aluminofluoride) fractions.

Keywords: magmatism, metasomatism, mineralogy, Katugin rare-metal deposit, and Trans-Baikal Territory

DOI: 10.1134/S1819714016030064

INTRODUCTION

A.P. Smelov is rightfully considered to be one of the most outstanding researchers of Northeast Asia. His numerous papers and monographs [17, 20, 25, 33, 34, etc.] are devoted mainly to key problems of the tectonics, geology, and metamorphism of the Early Precambrian complexes making up the Aldan and Anabar shields. Meanwhile, very often his works clearly emphasize the metallogenic orientation and various aspects of gold, diamond, and platinum mineralization in these regions [6, 14, 18, 19, 27, 28, etc.]. Rare-metal deposits were not among the major interests of Smelov. But knowing his active nature, we are sure that rare-metal deposits located within "his" area of study would eventually fall under the scope of his research. Thus, we thought it would be appropriate to offer a paper about the unique Katugin rare-metal deposit located in the southwest of the Aldan Shield, very close to the Olonde greenstone belt, which was studied by Smelov for many years, for a special issue of the journal *Pacific Geology* dedicated his memory.

The Katugin rare-metal deposit is located in the Kalar district in the north of the Trans-Baikal Territory. This unique deposit is one of the largest Russian Precambrian bodies in its Ta–Nb–Y ore reserves [11]. In addition to Ta, Nb, and Y, the Katugin deposit contains commercial concentrations of Zr, U, REE, and cryolite.

The discovered and explored deposit was attributed to the alkali metamorphic metasomatic rocks confined to deep faults and having no relation to magmatism [1–3, etc.]. Recent reports on the magmatism and metallogeny of Siberia, as well as of Central and East Asia [29, 30], do not question the metasomatic genesis of the ore at this deposit. In fact, the authors of these reports, without any of their own data, simply accepted the opinion of Russian geologists on its origin.

Meanwhile, the last decade was marked by a widely approved alternative point of view on the magmatic genesis of the Katugin deposit related to alkali granites [5, 7–10]. Furthermore, some ideas formally combine alternative viewpoints [11, 15]. According to them, the granites are not related to the mineralization processes, but rather play the same role as metamorphic rocks, i.e., the role of substrate affected by granite-unrelated metasomatic processes responsible for the ore formation.

The adepts of the metasomatic genesis of the Katugin ore deposit [1–3, 11, 15, 16] make various and miscellaneous arguments for their point of view, while the supporters of magmatic genesis [5, 7–10] restrict themselves to stating their position in relation to the nature of the ore-bearing complexes. In this regard, it is advisable to assess the arguments for alternative points of view based on previously published data and recent research results.

The Katugin complex rare-metal deposit is located in the southern margin of the Chara–Olyokma geoblock of the Aldan Shield, in close proximity to the southern boundary of the Stanovoy suture separating this geoblock from the Selenga–Stanovoy Region of the Central Asian fold belt (Fig. 1). This deposit includes two relatively small alkali granite massifs (3 and 18 km^2 in area) enriched in minerals of rare and rare-earth elements, which are localized within the near-latitudinal Kalakan tectonic zone extended along the southern margin of the Early Proterozoic Kodar–Udokan trough composed mainly of metaterrigenous rocks of the Udokan Supergroup (Fig. 2). As is noted above, today Katugin alkali granites are considered either as metasomatic [1–3, 15, 16, etc.], or as igneous [5, 7–10] rocks. Henceforth, we will call them granites, but the schemes and maps borrowed from earlier publications [15] will retain their terminology reflecting the views of the cited authors on the origin of these rocks.

In the course of exploration of the Katugin deposit, the granite massifs to which it is confined were named the Eastern and Western sites [15]. The major explorations were carried out in the Eastern massif (Fig. 2), where over a hundred drillholes were drilled, many trenches were made, and two adits were arranged. Unfortunately, a vast quantity of analytical data, including drillhole sections, rock and mineral analyzes, etc., is provided only in production records and is not accessible to most researchers. 80% of the Western site, a larger granite massif, is covered by moraine deposits and is not studied in detail.

The Eastern granite massif of the Katugin deposit is heart-shaped (Fig. 3). The western block of the massif is composed of massive or slightly foliated biotite and amphibole–biotite granites with amphibole and aegerine–amphibole granites in the northern marginal part of the massif. The eastern block has a more complicated structure with a reverse ratio of the above-mentioned granites. The same part of the massif hosts most ore bodies composed of the same granites, but enriched in ore minerals. The host rocks occur as gneiss, schist, and migmatite of variable compositions.

The major ore minerals of the Katugin deposit include pyrochlore, columbite (Ta, Nb, and REE), fluocerite, gagarinite, yttrofluorite, tveitite, bastnaesite (REE, Y), zircon (Zr), and cryolite. A more complete list of the rock-forming and ore minerals is given in the table. It should be noted that cryolite occurs as vein–disseminated and pockety segregations in the granites and also makes up a large separate body in the southern part of the eastern block of the Eastern massif. This body is up to 10 m in thickness. It is traced for 200 m along the strike.

ORIGIN OF THE KATUGIN DEPOSIT

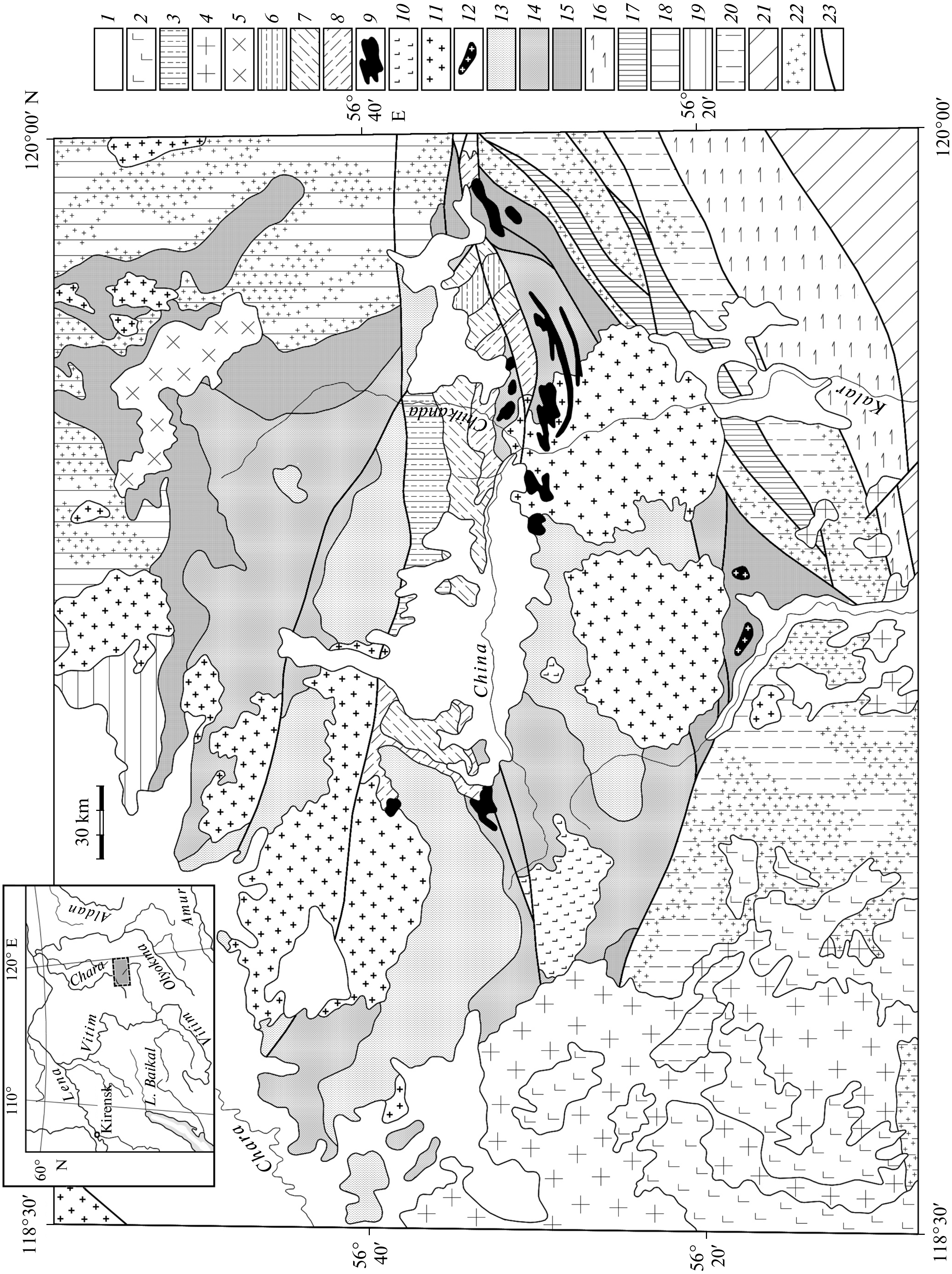
The major arguments in favor of the metasomatic genesis of the ore-bearing granites at the Katugin deposit are most clearly formulated in the recent publication of V.V. Arkhangelskaya et al. [2, p. 153]:

(1) The zonal structure of the ore deposit with the replacement of the rock-forming minerals of its outer zones by rock-forming minerals of its inner zones, and in the same direction, the replacement of earlier generations of ore-forming and ore minerals by later generations.

→

Fig. 1. Schematic geological map of Udokan subzone of the Kodar–Udokan trough [13].

(*1*) Quaternary sediments; (*2*) plateau basalts (N_2–Q); (*3*) Jurassic coal-bearing terrigenous sediments; (*4*) granite, granodiorite, granosyenite, and monzonite of Ingamakit Complex (PZ_3); (*5*) nepheline syenite, granosyenite, and monzonite of Khanino Complex (PZ_3); (*6*) variegated Ordovician sediments; (*7*) variegated Cambrian sediments; (*8*) variegated Vendian sediments; (*9*) gabbro–dolerite, gabbro, and dolerite porphyrite of Doros Complex; (*10*) layered plutons of Chiney Complex; (*11*) granites of Kodar Complex; (*12*) rare-metal granites of Katugin Complex; (*13–15*) carbonate–terrigenous sediments of Udokan Supergroup: (*13*) Kemen Subgroup, (*14*) Chiney Subgroup, (*15*) Kodar Group; (*16*) anorthosite of Kalar Complex; (*17*) slightly metamorphosed sedimentary–volcanic strata of Subgan Complex; (*18*) tonalite–trondhjemite orthogneisses of Olyokma Complex; (*19*) Chara sequence (garnet–biotite and garnet–hypersthene–biotite (±sillimanite, ±cordierite) plagiogneiss, mafic granulite, quartzite, and magnetite quartzite); (20) Kalar sequence (garnet–biotite (±sillimanite, ±hypersthene) plagiogneiss with interlayers and lenses of two-pyroxene granulite, calc–silicate rocks, quartzite, and magnetite quartzite; (*21*) metamorphic and magmatic complexes of Selenga–Stanovoy Superterrain of Central Asian mobile belt; (*22*) areas enriched in Precambrian granitoids; (*23*) faults.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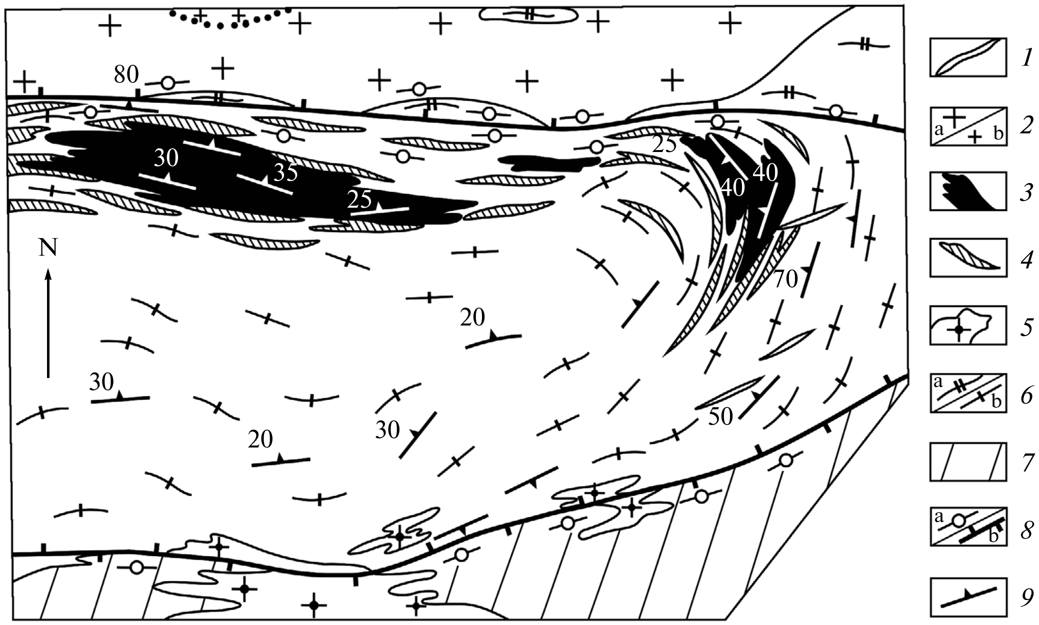

Fig. 2. Location of high-temperature sodium metasomatic rocks in the trough complex [15]. Name of figure and legend are taken from the work cited.

(*1*) Diorite porphyry dikes; (*2*) rapakivi-like granite of Early Proterozoic epiplatform massif ((a) coarse- and medium-grained, (b) fine-grained); (*3*) high-temperature sodium metasomatic rocks; (*4*) fine-grained porphyroblastic gneiss, migmatite; (*5*) Lower Proterozoic synmetamorphic plagiogranite; (*6*) Lower Proterozoic metasedimentary rocks ((a) protoplatform trough, (b) trough complex); (*7*) Archean basement; (*8*) disjunctive structures ((a) foliation of fault rocks, (b) tectonic sutures limiting trough); (*9*) foliation dip.

(2) The transitions between the mineral types of metasomatic rocks correspond to replacement fronts of infiltration metasomatic zoning: each transition is characterized by the complete replacement of one rock-forming mineral by another (biotite by amphibole and amphibole by aegirine); the composition of all of the metasomatic zones is more or less stable and does not depend on the zone thickness.

(3) The occurrence of xenoliths of the embedding rocks—biotite metapelite and diabase porphyry—inside the ore body.

(4) Zircons containing relic cores with the age corresponding to that of the host rocks or the age of the clastic zircons occurring in these rocks.

(5) Low (150–300°C) hydrothermal formation temperatures of the ore minerals at the deposit (quartz, fluorite, gagarinite, and cryolite) and low homogenization temperatures of the inclusions in them (max 450–500°C).

(6) Preservation of the metapelite layering replaced by metasomatic rocks and wave-cut marks on the planes in the deposit rock.

Below we consider these arguments one by one.

(1–2) It is obvious that the first two arguments are the most important and, with reasonable substantiation, would be quite sufficient to prove the metasomatic nature of the deposit. Meanwhile, it is substantiation of the metasomatic zoning accompanied by regular replacement of rock-forming mineral assemblages that is questionable. First of all it should be noted that the configuration of the most thoroughly studied Eastern granite massif (Fig. 3) is more consistent with a magmatic body, rather than a near-fault metasomatic zone. In addition, the "thickness" of this massif (over a kilometer) is also hard to explain from the standpoint of infiltration formation. All publications justifying the metasomatic nature of the Katugin granites [1–3, 15, 16, etc.] contain no detailed sections that would reveal the metasomatic zoning with a successive replacement of mineral parageneses. The given maps (Fig. 3) demonstrate a well-defined complicated structure of the massif, and the authors of the publication [15] can rightfully discuss the ore columns and ore bodies rather than classical zoning related to the infiltration metasomatism.

The margin of the western block of the Eastern massif was studied through old main trench well-washed for many years and thus well-exposed (Fig. 4). Most of the section is composed largely of fine- and medium-grained gneissic arfvedsonite granites including sporadic aegirine–arfvedsonite granites. The contacts between these granite varieties are gradual. The southwestern part of the section is dominated by aegerine–arfvedsonite granites contacted to the host fine-grained biotite gneisses. A xenolith of mafic biotite gneiss and a green diabase dike were identified in the profile to the north, in the arfvedsonite granites.

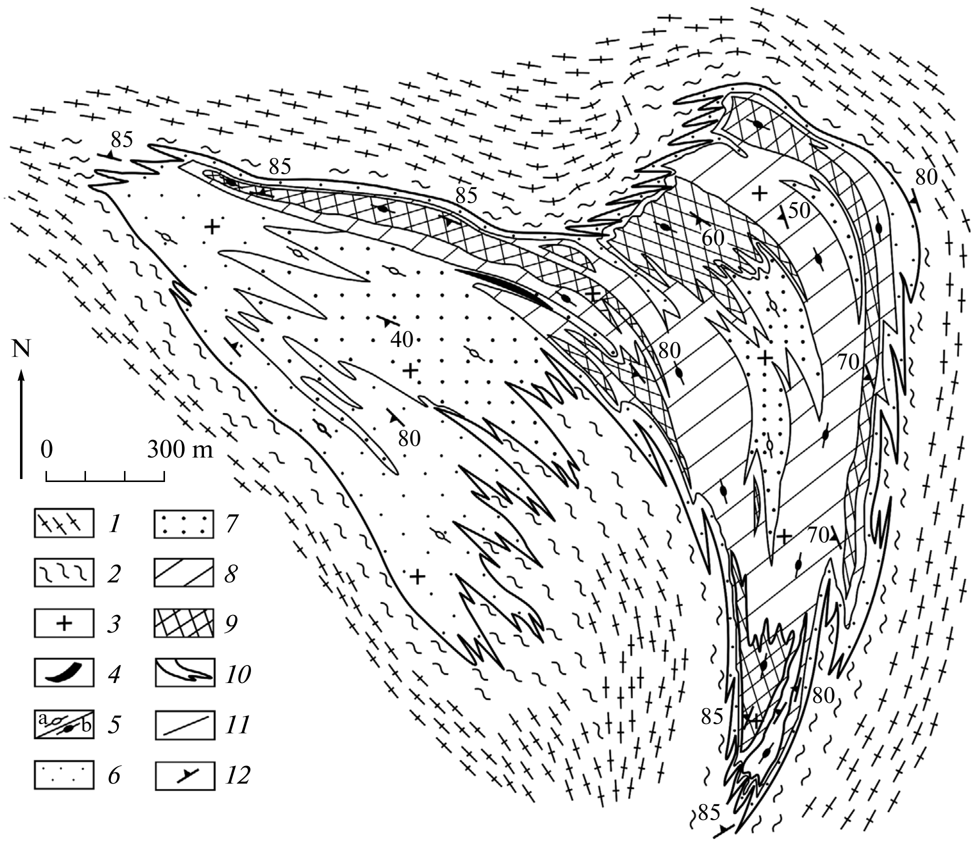

Fig. 3. Structure of eastern metasomatic body ([15], slightly simplified. Name of figure and legend are taken from the work cited). (*1–4*) Main metamorphic and igneous rocks and tectonite: (*1*) largely biotite, rarer biotite–amphibole gneiss and crystalline schist; (*2*) migmatite, granitized gneiss, and crystalline schist; (*3*) granite; (*4*) pegmatite and aplite veins; (*5*) tectonite ((a) relatively low-foliated rocks (augen–gneiss granite); (b) blastomylonite, blastocataclasite); (*6–9*) metasomatic rocks: (*6*) biotite, (*7*) biotite–amphibole, (*8*) amphibole, (*9*) aegerine–amphibole; (*10*) granite body contour; (*11*) boundaries of metasomatic zones (of different granite types, in our opinion); (*12*) foliation dip.

In addition, the granites contain individual discordant pegmatite veins (up to 3 m in thickness), coarse grained arfvedsonite granite (up to 2 m in thickness), and medium-grained aegirine granite with astrophyllite (up to 10 cm in thickness). The contact of the granites with biotite gneisses (completely exposed) is not gradual and not tectonized. The gneisses are hornfels-like in the contact zone. Biotite and biotite–amphibole granites were not identified in the profile; however, according to the data on drill cores, their contact with the arfvedsonite granites is fairly abrupt. Therefore, considering the relationships between the above-mentioned major granite varieties of the Eastern massif and the presence of intersecting aegirine and arfvedsonite granite veins, it is possible to assume different intrusion phases rather than metasomatic zoning.

According to petrographic study of the massif rock, the replacement of biotite by amphibole and amphibole by aegirine described in [2] is not confirmed. The relationships between the mafic minerals in the case of their joint occurrence (biotite–amphibole and amphibole–aegerine) are indicative either of their simultaneous growth, or of their formation in the corresponding order of the magma crystallization.

(3) The inclusions of metamorphic rocks in the granites can equally be interpreted as relics of primary rocks in the metasomatic rocks and as common xenoliths in the granites.

(4) The presence of ancient cores in the zircons of the Katugin granites, whose age corresponds to the age of "metasomatized rocks," is highly controversial, because this assumption was confirmed only by the results of thermoisochronic Pb–Pb isotopic studies [2]. The systematic U–Pb (ID TIMS) geochronology of the accessory zircons from the "barren" and "ore" granites at the Katugin deposit are indicative of the fact that they are similar in age (2066 ± 6 and 2055 ± 7 Ma, respectively) [5, 7]. Meanwhile, the morphological features of the studied zircons, the occurrence of melt and crystalline inclusions in them, and, finally, the specifics of the distribution of trace elements, clearly testify to their magmatic origin [5, 7, 10].

(5) The low temperature of mineralization recorded by cryometric data and of homogenization of

Minerals identified in alkali granites, cryolite rocks (+ fluoroaluminate segregations in the granite) and as crystalline inclusions in zircon, Katugin Massif, Trans-Baikal Region

Mineral	Formula	Alkali granites	Inclusions in zircon	Cryolite rocks
Quartz	SiO_2	+	+	+
K-feldspar	$KAlSi_3O_8$	+	+	+
Albite	$NaAlSi_3O_8$	+	+	+
Zircon	$ZrSiO_4$	+		+
Thorite	$ThSiO_4$	+	+	+
Annite–fluorannite	$KFe_3AlSi_3O_{10}(OH,F)_2$–$KFe_3AlSi_3O_{10}(F,OH)_2$	+	+	+
Polylithionite	$KLi_2AlSi_4O_{10}(F,OH)_{2f}$	+		+
Hydrotetraferriannite	$(H_2O,K)Fe_3FeSi_3O_{10}(OH)_2$	+		
Aegirine	$NaFeSi_2O_6$	+	+	+
Na–Fe-amphibole (subgroup)	$(Na,K)Na_2Fe^{2+}_4Fe^{3+}Si_8O_{22}(F, OH)_2$	+		+
Astrophyllite	$(K,Na)_3(Fe,Mn,Zn)_7(Ti,Nb,Sn)_2Si_8O_{24}(O,OH)_7$	+		+
Bafertisite	$Ba_2(Ti,Sn)_2(Fe,Mn)_4(Si_2O_7)_2O_2(OH)_2(F,OH)_2$	+		+
Fe-chlorite		+	+	
Pyrochlore (supergroup)	$(Ca,Na,REE,Y,Pb)_2Nb_2O_6(OH,F)$	+	+	+
Columbite-(Fe)	$(Fe,Mn)Nb_2O_6$	+		+
Fergusonite-(Y)	$YNbO_4$	+	+	
Samarskite-(Y)	$(Y,Ce,U,Fe)_3(Nb,Ta,Ti)_5O_{16}$	+	+	
Euxenite-(Y)	$(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$	+		
Ferberite	$(Fe,Mn)WO_4$	+		+
Pseudobrookite	Fe_2TiO_5	+		
Pseudorutile	$Fe_2Ti_3O_9$	+		
Ilmenite	$(Fe,Mn)TiO_3$	+		+
Magnetite	$FeFe_2O_4$	+		+
Rutile	TiO_2	+		+
Cassiterite	SnO_2	+	+	+
Cerianite-(Ce)	$(Ce,Th)O_2$			+
Goethite	$(Fe,Mn)O(OH)$	+	+	+
Siderite	$(Fe,Mn)CO_3$	+	+	+
Rhodochrosite	$(Mn,Fe)CO_3$			+
Calcite	$CaCO_3$	+		+
Bastnaesite-(Ce)	$(Ce,La,Nd)(CO_3)F$	+	+	+
Parisite-(Ce)	$Ca(Ce,La,Nd)_2(CO_3)_3F_2$	+		
Synchysite-(Ce)	$Ca(Ce,La,Nd)(CO_3)_2F$		+	
Fluorapatite	$Ca_5(PO_4)_3F$	+		
Monazite-(Ce)	$(Ce,La,Nd)PO_4$	+	+	
Xenotime-(Y)	YPO_4	+	+	
Xenotime-(Yb)	$(Yb,Y)PO_4$		+	
Cheralite-(Ce)	$(Ce,Th,Ca)(P,Si)O_4$	+		
Barite	$(Ba,Sr)SO_4$	+		+
Galena	PbS	+	+	
Sphalerite	ZnS	+		+
Molybdenite	MoS_2	+		

Table (Contd.)

Mineral	Formula	Alkali granites	Inclusions in zircon	Cryolite rocks
Pyrrhotite	$Fe_{1-x}S$	+		
Pyrite	FeS_2	+		+
Chalcopyrite	$CuFeS_2$	+		+
Bornite	Cu_5FeS_4	+		
Bismuthine	Bi_2S_3	+	+	
Lead	Pb	+		
Bismuth	Bi	+	+	
Fluorite + Y-fluorite	$(Ca,Y)F_2$	+	+	+
Cryolite	Na_3AlF_6	+	+	+
Elpasolite	K_2NaAlF_6			+
Simmonsite	Na_2LiAlF_6			+
Tveitite-(Y)	$Ca_{1-x}Y_xF_{2+x}$, $x \approx 0.3$	+	+	+
"Ba–Sr-Tveitite"	$(Ba,Sr,Ca)_{1-x}Y_xF_{2+x}$, $x \approx 0.3$			+
Gagarinite-(Y)	$NaCaYF_6$	+	+	+
Fluocerite-(Ce)	$(Ce,La,Nd)F_3$	+	+	+
Chiolite	$Na_5Al_3F_{14}$		+	+
Neighborite	$NaMgF_3$			+
Weberite	Na_2MgAlF_7			+
Usovite	$Ba_2CaMgAl_2F_{14}$			+
Ba-fluoroaluminate	$BaAlF_4(OH)$, $BaCa_2AlF_9$, $BaCa_4AlF_{13}$			+
H_2O–OH-fluoroaluminate	Prosopite, thomsenolite, pachnolite, etc.	+		+

Table is based on new data of the authors (petrographic thin sections and scanning microscopy results) and scientific literature [1–3, 10, 21, 31, 32, 35]. The subgroup of Na–Fe-amphiboles includes fluoride members of leakeite, nyboite, arfvedsonite, and riebeckite ([22, 31, 32]).

the fluid inclusions in the quartz, fluorite, gagarinite, and cryolite in the Katugin granites [2] is a significant, but clearly insufficient, argument to justify the hydrothermal–metasomatic nature of these minerals, because such inclusions often fix different stages of the cooling of the system, rather than early crystallization. In our opinion, it is of major importance that the conducted investigation identified the prevalence of NaF and NaCl fluid inclusions in the salt phase NaCl, which may be due to the evolution of both the alkali granitic melt and an autonomous hydrothermal–metasomatic system.

(6) Preservation of wave-cut marks and other signs of sedimentary origin [2] in the "sedimentary rock relics" among the granites which are assumed to have a metasomatic origin, in our opinion, needs no comments, because the host metamorphic rocks are characterized by a well-defined crystallization foliation and metamorphic banding, and their metamorphism conditions correspond to high-temperature amphibolite facies. Preservation of the primary sedimentary structures in these rocks is simply impossible.

Thus, the arguments in favor of the metasomatic genesis of the alkali granites at the Katugin deposit either do not withstand a critical analysis, or are ambiguous, with alternate interpretations favoring their magmatic origin. In addition to mentioned above arguments in favor of magmatic origin of the deposit we can supplement the following information:

(1) The Katugin granites are characterized by elevated and high alkalinity (up to 12.3% Na_2O and K_2O), extremely high iron content ($f = 0.96–1.00$), and very high contents of most incoherent elements (Rb, Li, Y, Zr, Hf, Ta, Nb, Th, U, Zn, Ga, REE, except for Eu) and F, as well as low concentrations of Ca, Mg, Al, P, Ba, and Sr [8, 9]. The high iron content is also typical of rock-forming mafic minerals of these granites. In particular, mica occurs as essentially pure annite with the MgO content from not higher than 2 wt %, while the biotite of the host metamorphic rocks contains 6–10 wt % MgO [2]. Meanwhile, no signs of voluminous subtraction of MgO from the rocks were established. Alongside with that, the high iron content of the rock-forming mafic minerals is

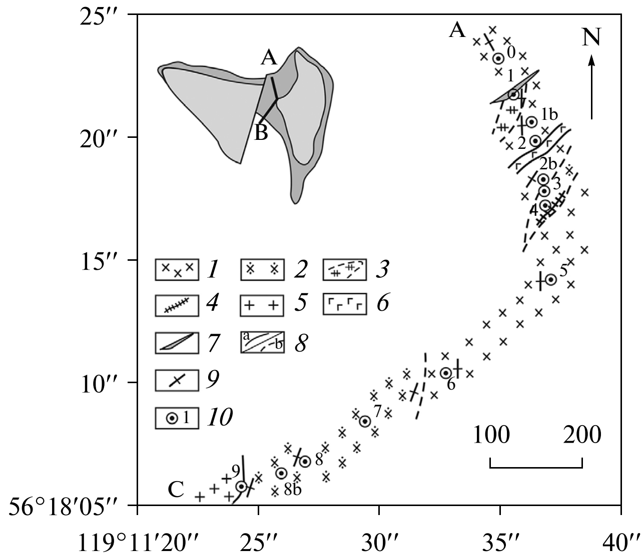

Fig. 4. Section of western marginal part of eastern segment of the Eastern massif.

(*1*) Arfvedsonite medium- and coarse-grained granite; (*2*) aegerine–arfvedsonite medium- and coarse-grained granite; (*3*) mafic biotite gneiss; (*4*) vein of aegirine granite with astrophyllite (out of scale); (*5*) biotite medium-grained gneiss; (*6*) diabase; (*7*) quartz vein; (*8*) geological boundaries: (a) mapped and (b) gradual or assumed; (*9*) foliation strike in granite; (*10*) observation points.

Inset ([15]) shows the section position in the massif. Grey shades indicate alkali granite (light), including ore granite (dark).

fully consistent with the typical characteristics of the intraplate alkali A-type granites [4, etc.].

(2) The F content in these granites varies from 0.16 to 2.80 wt % [8, 9]. Such a high F content in the granites is hard to explain by the imposition of later ore mineralization, because their silicate minerals, including rock-forming fluorannite, polylithionite, arfvedsonite, and bafertisite, are also characterized by a high F content, which is again typical of intraplate alkali A-type granites.

(3) No signs are found of recrystallization of mafic minerals in granites. They have similar compositions and show no crystallization traces in either the massive or foliated granite varieties. If the arfvedsonite or aegerine were recrystallized in the course of later superimposed metamorphic processes, then the composition of the pyroxene and amphibole would be different, taking into account the different composition of the fluids under granite crystallization and metamorphism.

(4) The frequent occurrence of microperthites in all granite types, which are logically interpreted as the result of high-temperature breakdown of magmatic K–Na feldspar during the cooling of the system, is hard to explain from the standpoint of metasomatism.

RELATIONSHIP BETWEEN MAGMATISM AND ORE FORMATION PROCESSES

Based on the magmatic nature of the alkali rocks and associated mineralization, it is essential to consider the manifestation time and possible stages of ore genesis. In this regard, it is advisable to consider separately three types of mineralization at the Katugin massif such as Zr, Ta–Nb–REE, and F–Al.

Zircon Mineralization

Zircon is observed in all granite varieties at the Katugin deposit, but its content varies; in particular, it forms both rare individual fine crystals and fairly large "pockety" segregations of up to 1.5 cm in size [2]. In the latter case, the zircon content occasionally reaches 20% and the zircon appears to be a rock-forming mineral. In some cases, the zircons are free from inclusions of other minerals (except for quartz and albite), but, as a rule, they are enriched in fine (2–15 μm) inclusions of bastnaesite, fluocerite, gagarinite, tveitite, yttrofluorite, fluorite, thorite, and cryolite (Fig. 5, table). Inclusions of fluoride minerals are evidently predominant. Zircons of this type are described at the Paleoproterozoic Sn–Ta–Nb (REE, cryolite) Madeira deposit [23], which is similar to the Katugin deposit in many parameters, but is younger in age (1822 ± 22 Ma). The authors note that inclusion-bearing zircons are not suitable for dating due to the high lead content and believe that the appearance of inclusions in the zircon is caused by later hydrothermal processes. Alongside with that, there are no signs of hydrothermal processing of the zircon-bearing granite matrix, so such a selective effect of late hydrothermal processes on zircon alone is extremely unlikely. The capture of inclusions under growing of zircon crystals is more probable.

Ta–Nb–REE Mineralization

The minerals of this type listed in the table are concentrated mainly in the granites in the marginal part of the Eastern massif. They occur as (a) individual grains, their segregations, and ore intergrowths in the granite; (b) inclusions in zircon (see above); and (c) interstitial segregations among silicate minerals.

Individual crystals and their clusters are most characteristic of pyrochlore (Figs. 6a, 6b), which often contains inclusions or is overgrown by a rim of opaque minerals. According to the investigation results, most pyrochlore crystals and grains are heterogeneous in structure due to both variations in the pyrochlore composition and inclusions of other minerals (Figs. 6c, 6d). The rim contains bastnaesite, columbite, fluocerite, and pyrochlore hydration products.

The ore intergrowths contain various minerals, of which pyrochlore, columbite, fluocerite, ilmenite, and occasional sulfides (sphalerite, galena, pyrrhotite,

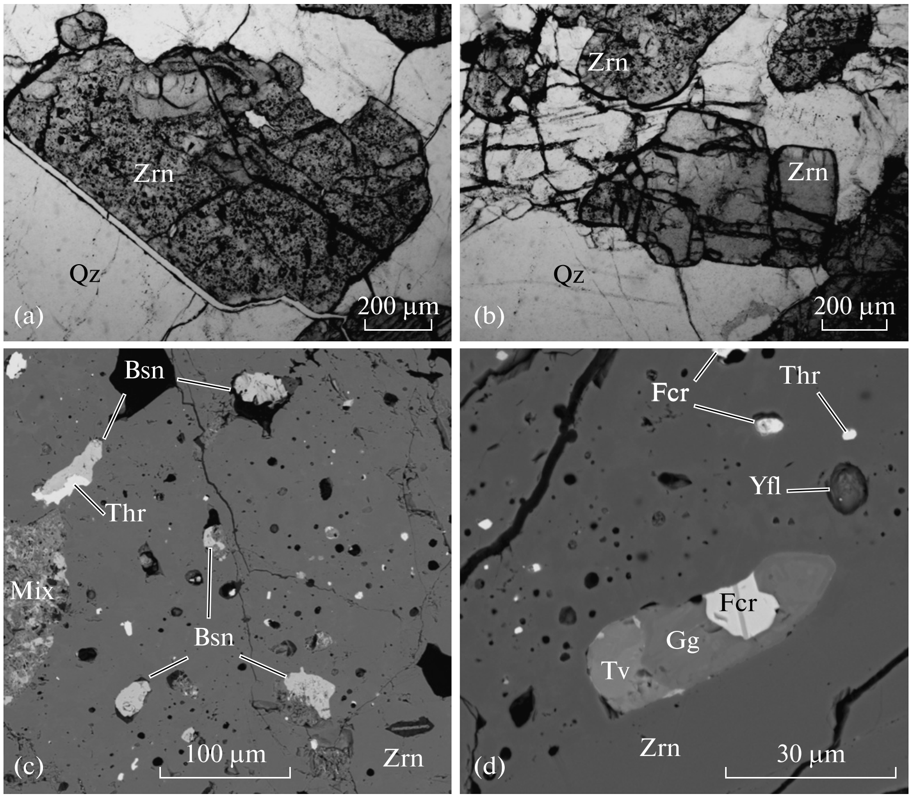

Fig. 5. (a, b) Microphotographs and (c, d) BSE images of zircons with and without inclusions.

(a) Zircon with ore mineral inclusions; (b) simultaneous occurrence of zircons with (top) and without (bottom) inclusions; (c, d) zircons with fluoride and fluorcarbonate inclusions. Thorite, quartz, and cryolite are also observed. (Bsn) bastnaesite, (Gg) gagarinite, (Fcr) fluocerite, (Qz) quartz, (Thr) thorite, (Tv) tveitite, (Zrn) zircon, (Yfl) yttrofluorite, (Mix) fine-grained aggregate of gagarinite, tveitite, and bastnaesite. These and the following images were obtained with scanning electron microscopes with EDS: LEO1430VP with INCAEnergy 350 (Geological Institute, Siberian Branch, Russian Academy of Sciences, Ulan-Ude) and TESCAN with INCAEnergy 350 (Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences, Novosibirsk).

and pyrite) are the most frequent (Fig. 7). The distribution of such intergrowths in the rock is extremely irregular.

The interstitial segregations are composed of fluorides and fluorcarbonates, often with a small amount of chlorite, and have a very complicated structure (Figs. 8a, 8b). Tveitite with numerous fine oriented inclusions of fluocerite or early bastnaesite is predominant (Fig. 8b). Bastnaesite, which developed after the fluorides, forms veinlets and individual segregations and occasionally symplectites with chlorite (Fig 8a).

F–Al Mineralization

Despite the great diversity of fluoroaluminates in the granites at the Katugin deposit (table), they are clearly dominated by cryolite. As is mentioned above, cryolite makes up a fairly large body in the marginal part of the Easter massif. The cryolite of this body and other relatively large cryolite segregations contain crystals and intergrowths of F-bearing arfvedsonite, ftuorannite, bafertisite, lepidolite, K-feldspar, quartz, pyrochlore, gagarinite, tveitite, ilmenite, pyrite, sphalerite, magnetite, and barite. The most remarkable fine (from a few millimeters to a few centimeters) interstitial or rounded segregations are composed of Na–Ca–Mg fluoroaluminates (cryolite, weberite, ralstonite, prosopite, gearksutite, and pachnolite–thomsenolite) and Ba fluoroaluminates (usovite and Ba-jacobssonite), including previously unknown Ba phases [21]. Silicate minerals (except for bafertisite) are almost absent in such segregations (Figs. 8c, 8d).

The available data make it possible to suggest that the major portion of the Katugin mineralization is related to the magmatic stage of evolution of the alkali granite melt. The formation of the ore minerals was due to two interrelated processes:

(1) Crystallization of ore minerals directly from the melt. This applies to zircon, pyrochlore, gagarinite, and yttrofluorite, which are commonly observed as individual crystals, occasionally forming segregations, and as their monomineral intergrowths, and also to tantalite, fergusonite, pyrochlore, fluocerite, ilmenite, and sulfides forming polymineral intergrowths.

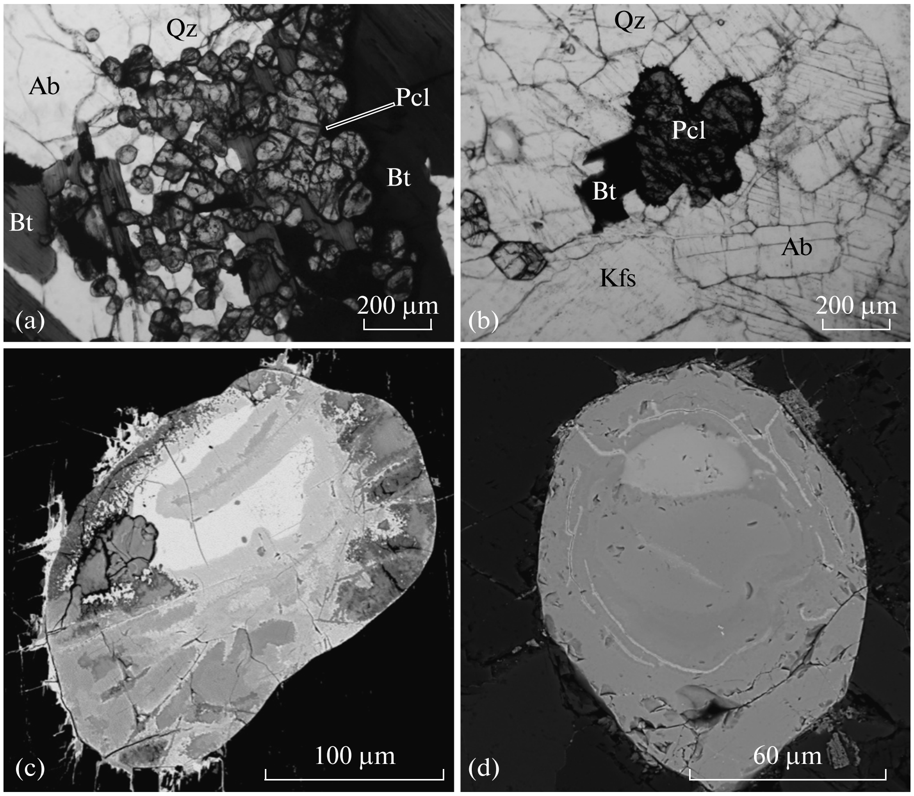

Fig. 6. Microphotographs and BSE images of pyrochlore.

(a, b) Microimages of (a) pyrochlore segregations and (b) individual grains, in the latter case with bastnaesite and columbite overgrowth rim. (c, d) complex structure of pyrochlore crystals. (Ab) Albite, (Bt) biotite, (Kfs) K-feldspar, (Qz) quartz, and (Pcl) pyrochlore.

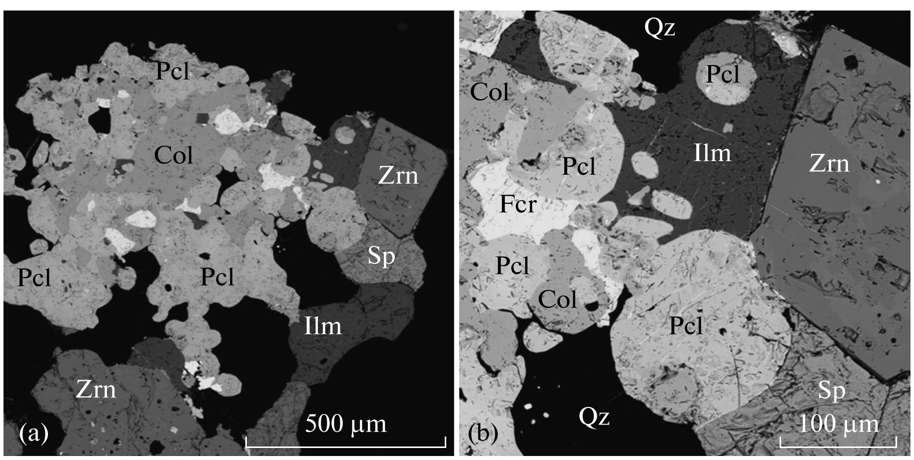

Fig. 7. BSE images of ore mineral intergrowths in granite.

(a) General view of intergrowth dominated by pyrochlore and columbite segregations. Rare ilmenite, fluocerite, sphalerite, and galena on margins of zircon grains with ore inclusions. (b) Intergrowth fragment: (Col) columbite, (Fcr) fluocerite, (Ilm) ilmenite, (Qz) quartz, (Pcl) pyrochlore, (Sp) sphalerite, and (Zrn) zircon.

(2) Liquation of high-F granite melt into aluminosilicate and fluoride or aluminofluoride melts. The immiscibility of the aluminosilicate and aluminofluoride melts was previously substantiated for the Ary–Bulak ongonites (East Trans-Baikal Region) [12]. The earliest stages of melt liquation are recorded by numerous fine inclusions of fluoride and fluorcarbonate minerals in the zircon. In the course of further evolution, the fluoride melts enriched in rare earth elements were crystallized in the interstitial spaces and

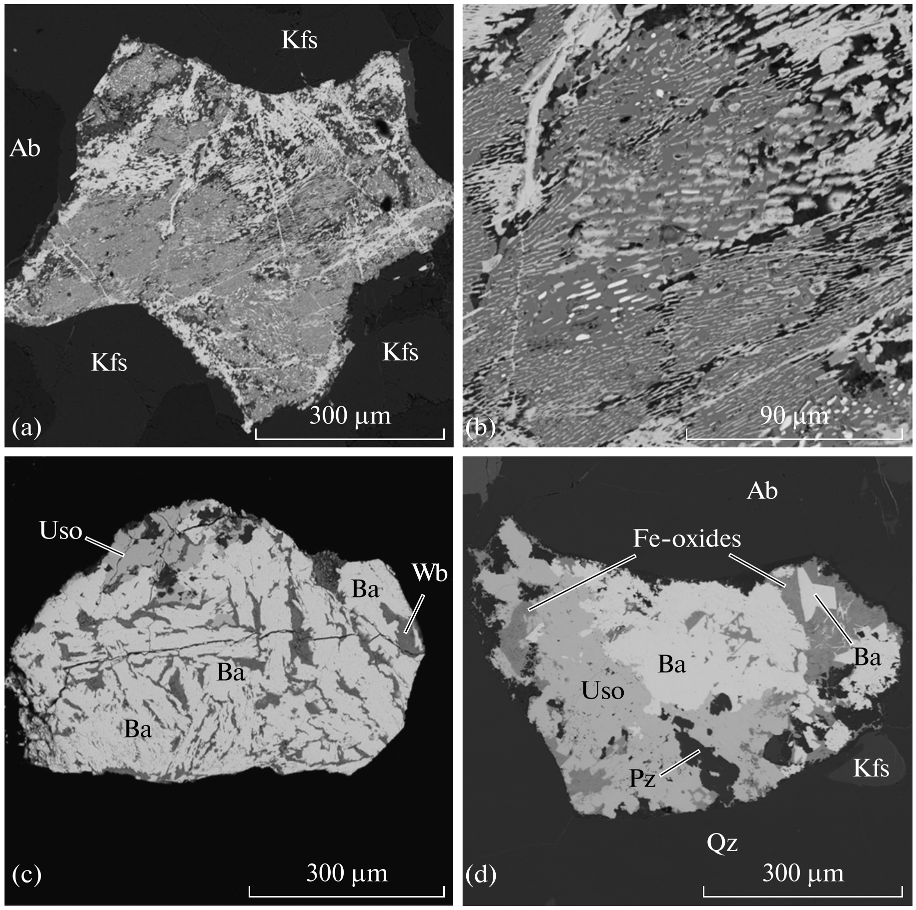

Fig. 8. BSE images of interstitial segregations in granite of fluorides and fluorcarbonates (a, b) and (c, d) Ba, Na, and Ca fluoroaluminates.

(a) Fluoride and fluorcarbonate segregation and (b) its fragment. The segregation is dominated by tveitite (gray) enriched in oriented inclusions of fluocerite (white) and early bastnaesite. Late bastnaesite (light gray) forms regular intergrowths with chlorite (dark gray) and develops along fractures. (c, d) Fluoroaluminate aggregates are mainly composed of Ba-phases. (Ab) Albite, (Ba) $BaAlF_4(OH)$ fluoroaluminate, (Kfs) K-feldspar, (Qz) quartz, (Pz) prosopite, (Uso) usovite, (Wb) weberite, (Fe-oxides) iron oxides and hydroxides.

formed complex breakdown structures involving tveitite, fluocerite, gagarinite, and bastnaesite. The later stages of melt evolution during crystallization of the massif led to the formation of globules and interstitial segregations of fluoroaluminates with a variable composition up to "squeezing" of the aluminofluoride melt with further development of a relatively large cryolite body.

CONCLUSIONS

In our view, the data submitted in this paper are indicative of the magmatic genesis of the Katugin rare-metal deposit. This conclusion is confirmed by the following arguments: (1) the configuration of the ore-bearing granite massifs and the specifics of their localization within various types of alkali granites (biotite, amphibole, and amphibole–aegerine); (2) the geochemical features of the ore-bearing granites corresponding to intraplate A type granites (high alkalinity (12.3% $Na_2O + K_2O$); extremely high iron content ($f = 0.96–1.00$); very high contents of most incoherent elements (Rb, Li, Y, Zr, Hf, Ta, Nb, Th, U, Zn, Ga, and REE) and F; as well as low concentrations of Ca, Mg, Al, P, Ba, and Sr; (3) the specific composition of the rock-forming minerals of the ore-bearing granites (high Fe and elevated F contents); (4) no evidence of metasomatic zoning and successive replacement of rock-forming minerals (biotite → arfvedsonite → riebeckite) corresponding to replacement fronts of infiltration metasomatic zoning.

The similar age of the barren (2066 ± 6 Ma) and ore (2055 ± 7 Ma) granites at the Katugin deposit and the specifics of the ore mineralization are indicative of the fact that the ore was generated largely at the magmatic stage of their evolution. The nature of the ore occurrence and the specific relationships between the ore minerals suggest their crystallization directly from the F-rich aluminosilicate melt and also under melt liquation into aluminosilicate, fluoride, or aluminofluoride.

The rare-metal deposits of the Slave Province (Canada), confined to the alkali granite massifs of Blatchford Lake with an age of 2094 ± 10 Ma, can be considered as an age and genetic analogue of the Katugin deposit [7]. According to the paleomagnetic data [24, 26], the northern part of Laurentia, which hosts these deposits was located at that time near the southern flank of the Siberian craton (recent coordinates). These data are indicative of a large igneous province (LIP) in the range of 2000–2100 Myr, which was located on the area of these two ancient cratons.

ACKNOWLEDGMENTS

The work was supported by the Russian Science Foundation (project no. 14-17-00325). We are grateful to an anonymous reviewer, whose professional remarks made an invaluable contribution to improvement of this paper.

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Recommended for publishing by A.N. Didenko

Translated by E. Maslennikova