



Research article  
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## Peculiarities of rare-metal mineralization and genetic relationship of mineral associations in the eastern rim of Murzinsko-Aduysky anticlinorium (the Ural Emerald Belt)

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**Abstract.** The paper presents features of the location and composition, as well as a generalization of data on the age of rare-metal mineralization developed at the deposits and occurrences of rare metals and gemstones in the eastern rim of Murzinsko-Aduysky anticlinorium, within the Ural Emerald Belt, which is a classic ore and mineralogical object and has been studied for almost two hundred years. With a significant number and variety of prospecting, research and scientific works devoted mainly to emerald-bearing mica complexes and beryl mineralization, as well as rare-metal pegmatites, scientific literature has so far lacked generalizations on the formation of numerous mineral associations and ore formations that represents a uniform genetic process in this ore district. The aim of the work is a comprehensive geological-mineralogical analysis of mineral associations of the eastern rim of Murzinsko-Aduysky anticlinorium and studying their age, formation conditions and characteristic features to determine the possibility of expanding and using the mineral resource base of the Urals through developing new prognostic and prospecting criteria for rare-metal and gemstone ore formations and creating the new devices for promising objects prospecting.

**Keywords:** Murzinsko-Aduysky anticlinorium; Ural Emerald Belt; rare-metal mineralization; crystal raw materials; beryl mineralization; emerald-beryl deposits

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**Introduction.** During the study of the Ural Emerald Belt (UEB) a lot of prospecting, research, and scientific works were carried out, mainly devoted to emerald-bearing mica complexes, beryl mineralization [1, 2], and rare-metal pegmatites.

Mineralogical analysis of the main mineral associations with rare-metal mineralization within UEB is given, their distinctive features are described and prognostic and estimation complex for the identification of new objects to determine the possibility of expanding and using the mineral resource base of the Urals by developing new prognostic and prospecting criteria for rare-metal and gemstone mineralization is substantiated. The geological and structural features of the area were studied and the main mineral associations in the eastern frame of Murzinsko-Aduysky anticlinorium within UEB were identified, conditions of occurrence and features of the main UEB ore formations were determined, and prognostic and prospecting criteria for rare-metal and gemstone ore formations were developed.

**Methodology.** The microelement composition of minerals of the tantalite-columbite series was studied by ICP-MS method on ELAN 9000 mass spectrometer (D.V.Kiseleva, Zavaritsky Institute of



Geology and Geochemistry, Ural Branch of RAS, Ekaterinburg). The analysis of dark micas was carried out by ICP-MS method on Element2 mass spectrometer by the analytical group of Yu.L.Ronkin (Zavaritsky Institute of Geology and Geochemistry, Ural Branch of RAS, Ekaterinburg). The composition of beryls was studied with electron-probe microanalyzer Cameca SX100 (V.V.Hiller, Zavaritsky Institute of Geology and Geochemistry, Ural Branch of RAS, Ekaterinburg).

**Geological and structural position of the area.** Murzinsko-Aduysky anticlinorium is located on the eastern slope of the Middle Urals and covers a small fragment of the conjugation zone of the East Ural uplift with the advanced structures of the East Ural Trough [3]. Altogether they represent a geological and tectonic structure, part of the East-Ural rare-metal metallogenic province, genetically associated with the formation of Late Permian granite massifs. Nowadays this area occupies 3-5 km wide and about 200 km long, within its limits there are 38 deposits and occurrences of rare-metal, noble-metal, and gemstone raw materials. Territorially the area is located in the eastern frame of Murzinsko-Aduysky anticlinorium, with intensive development of magmatic formations, which differ both in composition and age.

Ordovician formations are represented by dunites, gabbro-norites, and serpentinites of the Bazhenovsky and Alapaevsky complexes, developed in the northeastern and eastern parts of the district. Middle Devonian rocks are represented by diorites of the Lesozavodsky massif, located in the center of the district. Late Permian granitic formations occupy the main part of the UEB area and are represented by granitoids of Murzinsky, Aduysky, and Malyshevsky massifs.

Murzinsky massif is located in the north of Murzinsko-Aduysky anticlinorium and composed of granites of three complexes: Yuzhakovsky migmatite-granite, Vatikhinsky adamellite (lower part), and Murzinsky granite (upper part of the massif), the age of the massif is 248-259 Ma [4, 5]. In the Murzinsky massif mirolitic pegmatites with beryl, topaz, and tourmaline of age 230-200 Ma are widespread [6]. Pegmatites formation, according to the authors, should correspond to the regressive stage of Murzinsko-Aduysky anticlinorium formation.

Significant part of UEB is formed by rocks of large polychronic multi-phase Aduysky granite pluton, which is a part of Murzinsko-Aduysky anticlinorium (Fig.1). Pluton belongs to the anatectic adamellite granitoid series of continental-collisional type [7], formed in abyssal facies (4-6 km). In [8] four stages of Murzinsko-Aduysky granite complex formation based on Rb-Sr and Sm-Nd-datings are discussed: Early Permian stage (~260 Ma) with the formation of the main mass of the complex, Late Permian stage (~250 Ma) with the introduction of leucocratic granites in the eastern part of the Murzinsky and northern part of the Aduysky massifs, Middle-Late Triassic stage (~230 Ma) with the formation of pegmatitic leucogranites and pegmatites in the northern part of the Aduysky massif and, finally, Early Jurassic stage (~200 Ma) with the intrusion of rare-metal pegmatites in the eastern part of the Aduysky massif.

Malyshevsky leucogranite massif is represented by three separate small bodies ( $6-7 \times 1.5-2.5$  km), deposited in hypabyssal facies and located in a chain in the Susansky fault zone along the eastern contact of the Aduysky granite massif. The massif is composed of post-collision leucocratic reddish-pink medium- and coarse-grained porphyritic granites. Malyshevsky granites differ from Aduysky granites by higher ferruginicity and radioactivity, the content of accessory thorite, etc. Malyshevsky granite massif has an age of 240-220 Ma [5].

Early works [9, 10] clearly distinguish the Triassic-Early Jurassic stage in the geodynamic history of the Ural folded Belt in the Southern and Middle Urals, which began with post-orogenic stretching and rifting and ended with locally manifested ancient Cimmerian folded-slip-thrust dislocations. The maximum of this stretching occurs at the Triassic-Permian boundary. This age stage (255-240 Ma) is very widely manifested and often found in metamorphic and intrusive complexes of the Urals.



At that time intensive block tectonics, crustal granitoid magmatism, and alternating in space and time processes of crustal stretching and compression due to different reasons of both global and regional nature take place in the area of the eastern rim of Murzinsko-Aduysky anticlinorium [9, 11]. All these processes have led to the formation of major post-collisional mineral associations and ore concentrations in the form of rare-metal (Ta-Nb-Be), gemstone (chrysoberyl, emerald, phenakite) mineralization in the eastern framing of Murzinsko-Aduysky anticlinorium.

**Types of rare-metal mineralization.** The main geological-genetic types of rare-metal mineralization are distinguished within the UEB ore district: vein, metasomatic ores, and hydrothermalites [12, 13]. Albite-microcline pegmatites with Be-Nb-Ta mineralization (Lipovy Log, Kvartalny deposits, and a number of smaller ones) are confined to the conjugation zones of NW and NE structures in the areas of lateral uplift of the granite massif roof (Fig.2). The largest pegmatite bodies are localized in gentle cracks of NE strike-slip. Chemical Th-U-Pb dating of uraninite and monazite from rare-metal pegmatites of the Kvartalny deposit established the age of these vein rocks – 268-262 Ma [14].

In some cases, deposits of rare-metal granites are formed jointly (in the same ore field) with emerald-beryl ores, such as Krasnoarmeysky deposit. In pegmatites and granites, the most widespread process is albitization of two stages: the first stage is the formation of perthitic structures in potassium feldspars. Then albitization develops through cracks in pegmatites and mica complexes. This albitization is represented by veins composed of medium-grained albite and sometimes by a lamellar aggregate of cleavelandite. This process is associated with the formation of industrial rare-metal (Ta-Nb-Be) mineralization at UEB deposits and occurrences.

The formation of rare-metal pegmatites, according to the results of early studies [15], occurred at 550-600 °C. Under the influence of

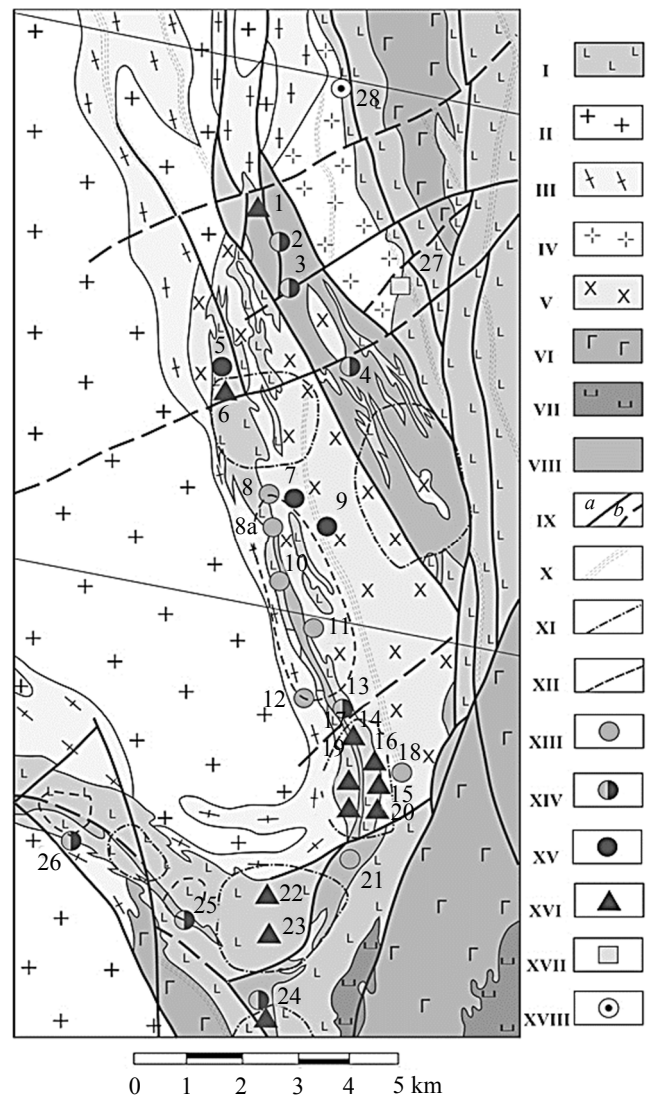


Fig.1. Schematic location of deposits and occurrences of the UEB ore district [13]:

- I – siliceous-basalt and rhyolite-basalt strata  $S_1$  (andesites, carbonaceous-siliceous schists, amphibolites, quartzites); II – granites;
- III – granite-gneiss with xenoliths of the host rocks; IV – alaskite granites; V – diorites, quartz diorites, gabbro-diorites; VI – gabbro and apogabbro amphibolites; VII – dunites, peridotites, serpentinites;
- VIII – calcified serpentinites, talc-carbonate, chlorite-talc rocks;
- IX – faults (*a* – established, *b* – supposed); X – crushing, schistose and mylonitization zones; XI – roof uplift areas; XII – roof dip areas;
- XIII – emerald deposits; XIV – emerald-beryllium deposits;
- XV – beryl deposits; XVI – rare-metal deposits; XVII – molybdenum deposits; XVIII – gold deposits; 1 – Poludensky deposit; 2 – Aulsky deposit; 3 – Malyshevky (Mariinsky) deposit; 4 – Starkovsky ore occurrence; 5 – Malinovy Klyuch ore occurrence; 6 – plot N 7; 7 – Zagrebayev point ore occurrence; 8 – Pervomaisky (Troitsky) deposit; 8a – Artem (Makarievsky) deposit; 9 – Diorite plot ore occurrence; 10 – Krupskay (Lublinsky) deposit; 11 – Sverdlovsky (Sretensky) deposit; 12 – plot N 616 ore occurrence; 13 – ore occurrence Berezovaya Roshcha; 14 – Kvartalny deposit; 15 – Lipovy Log deposit; 16 – ore occurrence Zhyla N 40; 17 – Plot N 2 deposit; 18 – ore occurrence Teply Kluch; 19 – Solnechnaya Gorka deposit; 20 – plot N 115 deposit; 21 – Cheremshansky deposit; 22 – Plot N 5 deposit; 23 – Plot N 293 deposit; 24 – Krasnoarmeysky deposit; 25 – Krasnobolotsky deposit; 26 – Ostrovnoy deposit; 27 – Yuzhno-Shammeyky deposit; 28 – Rudnichny deposit

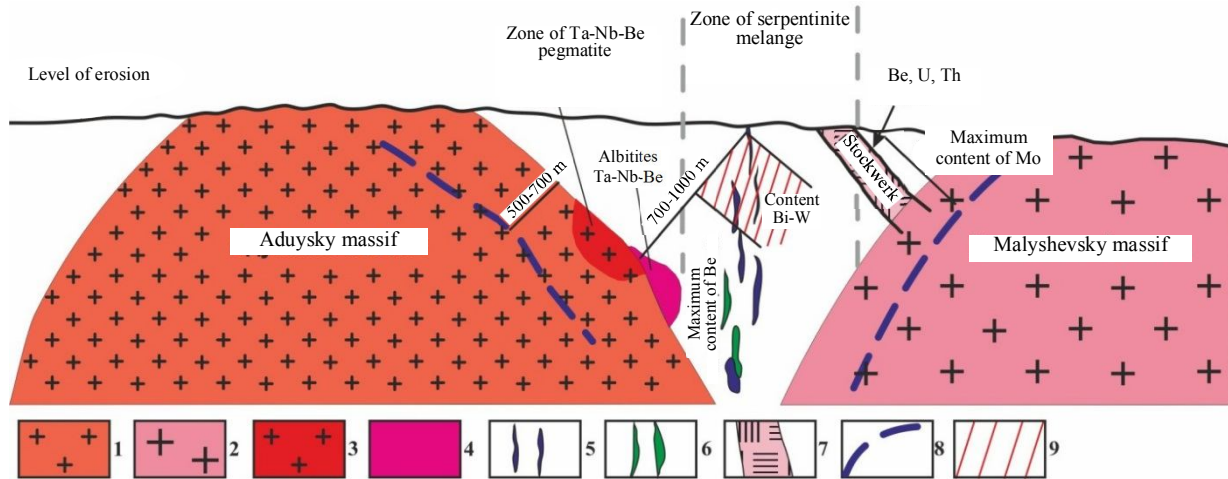


Fig.2. Scheme of mineral associations formation in the eastern exocontact of the Aduysky massif

1 – granites of the Aduysky massif; 2 – granites of the Malyshevsky massif; 3 – rare-metal pegmatites; 4 – rare-metal albitites; 5 – mica complexes; 6 – quartz-plagioclase veins; 7 – greisens; 8 – endocontact zone; 9 – Bi-W ore formation zone

high-temperature pneumatolite-hydrothermal solutions, there was the formation of vein-like bodies of albite with amphibole, which are analogs of albitite and occur in Mariinsky emerald-beryl deposit. Based on the data of mineral geothermometers [16-18] we can speak about rather high (500-550 °C) temperatures of formation of the studied vein-like bodies.

The main ore tantalum-niobium mineralization forms commercial deposits and is mainly represented by minerals of the tantalite (Fe,Mn)Ta<sub>2</sub>O<sub>6</sub> – columbite (Fe,Mn)Nb<sub>2</sub>O<sub>6</sub> series: columbite-Fe, columbite-Mn, tantalite-Fe. The minerals occur in deposits and occurrences of rare-metal pegmatites and separate small pegmatoid bodies and quartz-plagioclase veins at emerald-beryl deposits. Crystals and grains of the tantalite-columbite group of minerals are often 0.1-3 mm in size, but sometimes larger precipitates (up to 6-7 cm) occur. The size of short prismatic crystals is usually 0.1-0.3 mm, whereas flattened prismatic crystals are 0.2-0.4 mm. The development of late uranium-bearing hydroxycalcite-microlite [19], where UO<sub>2</sub> content varies from 10.61 to 13.74 %, has been established for minerals of the tantalite-columbite group. Microanalysis (sample 2) showed that columbites are enriched in Y, Zr, Hf, Th, U, and lanthanides (La, Nd, Gd, Dy, Er, and Yb) (Table 1). At first, there is a decrease of light lanthanides with europium minimum, then quite sharp increase of heavy lanthanides (Fig.3).

Large emerald-beryl deposits (Mariinsky, Sverdlovsky, Krupskaya, etc.) are located above the troughs of granite massif roofs (Fig.2). Ore complex is represented by mica complexes (micaites) and

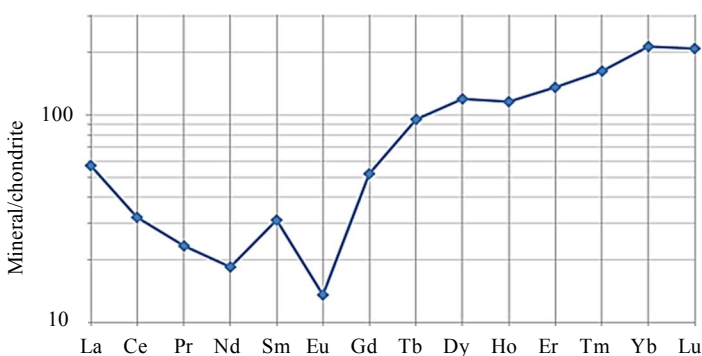


Fig.3. Distribution of rare earth elements in columbites (average of three samples, normalized on chondrite composition), Kwartalny deposit

beryl-quartz-plagioclase veins [20]. The most significant distribution of mica complexes with ore mineralization (rare-metal Be and gemstone) is in the eastern contact of Murzinsko-Aduysky anticlinorium, where the world-famous emerald deposits (Mariinsky, Sverdlovsky, Krasnobolotny) have been studied and explored. Mineral paragenesis of mica (phlogopite, fluorite, apatite, beryllium minerals, plagioclase, tourmaline, quartz, muscovite) and geochemical features (increased content



of beryllium, lithium, rubidium, cesium, fluorine, boron and carbonic acid) allow referring mica complexes to greisen facies by ultrabasite of Bazhenov and Alapaev complexes (Table 2).

Table 1

Trace element composition of columbite group mineral (sample 2), ppm, Kvartalny deposit

Element	Content	Element	Content	Element	Content
Li	3.48	Zr	4579	Gd	14.4
Be	1.18	Nb	69612	Tb	4.76
Sc	23.2	Mo	1.78	Dy	41.0
Ti	846	Ag	832	Ho	8.92
V	3.32	Cd	9.11	Er	30.6
Cr	2.63	Sn	64.4	Tm	5.70
Mn	61764	Sb	0.13	Yb	47.1
Co	0.43	Te	0.45	Lu	7.08
Ni	0.95	Cs	0.38	Hf	307
Cu	13.2	Ba	33.7	Ta	86486
Zn	89.5	La	18.7	W	202
Ga	3.75	Ce	27.8	Tl	0.20
Ge	0.20	Pr	3.03	Pb	86.9
Rb	6.84	Nd	11.7	Bi	158
Sr	14.4	Sm	6.30	Th	176
Y	249	Eu	1.04	U	3460

Table 2

Composition of dark mica from mica deposits, ppm, the Ural Emerald Belt [13]

Sampling point	Mariinsky deposit (emerald-beryl), 4 analyses	Krasnobolotny deposit (alexandrite-chrysoberyl) 3 analyses	Kvartalny deposit (rare-metal pegmatites) 4 analyses	Sverdlovsky deposit (emerald-beryl) 4 analyses
Li	3762	3974	5850	1350
Be	201	24.8	40.5	16.4
Rb	3310	2855	4580	2497
Sr	104	261	17.7	10.9
Y	bdl	13.8	26.8	bdl
Zr	bdl	58.2	97.3	bdl
Nb	21.8	113	67.7	41.0
Mo	bdl	bdl	33.3	bdl
Ag	bdl	0.09	0.70	bdl
Sn	20.3	1045	18.1	10.3
Cs	457	464	249	314
Ba	251	573	267	671
La	0.33	17.1	15.2	0.06
Ce	0.81	37.5	37.6	0.17
Pr	0.03	4.54	5.01	bdl
Nd	0.24	18.1	21.4	bdl
Sm	0.04	3.54	5.34	0.00



End of Table 2

Sampling point	Mariinsky deposit (emerald-beryl), 4 analyses	Krasnobolotny deposit (alexandrite-chrysoberyl) 3 analyses	Kvartalny deposit (rare-metal pegmatites) 4 analyses	Sverdlovsky deposit (emerald-beryl) 4 analyses
Eu	0.14	0.94	0.95	0.09
Gd	0.03	3.45	5.59	bdl
Tb	bdl	0.53	1.04	bdl
Dy	0.04	3.14	5.98	bdl
Ho	bdl	0.56	1.13	bdl
Er	0.02	1.71	3.29	bdl
Tm	bdl	0.22	1.37	bdl
Yb	0.02	1.47	2.66	0.00
Lu	bdl	0.20	0.37	bdl
Ta	16.9	302	30.8	9.01
W	1.20	24.8	1.35	0.19
Tl	21.4	18.7	26.8	17.0
Pb	6.01	8.58	5.36	1.27
Th	0.04	3.52	4.34	bdl
U	0.08	3.07	3.54	0.04
Sc	16.7	10.4	12.2	8.42
V	94.9	70.9	87.3	57.8
Cr	1008	1257	34.6	738
Co	46.8	3.68	57.6	55.3
Ni	525	32.6	1206	878
Cu	73.9	4.02	2.25	2.02
Zn	608	252	664	555
Ga	51.2	97.9	49.1	28.0

Note: bdl is below detection limit.

While the main part of granite massifs of Murzinsko-Aduysky anticlinorium is formed in the Permian period, mica complexes located in their exocontacts are of later Triassic and Jurassic ages. According to the dating data (by Rb-Sr method using the Triton thermal ionization 9-collector mass-spectrometer of VSEGEI, B.V.Belyatsky) we may distinguish three stages [21] of emerald-beryl mica formation on the UEB area: ~230 Ma (Glinsky deposit), ~205 Ma (Mariinsky deposit and Zarechny beryl occurrence) and ~190 Ma (71 km occurrence). These studies confirm the early age determinations [22], where the Rb-Sr method (Triton mass spectrometer, Central Research Institute VSEGEI, B.V.Belyatsky) determined the age  $206.6 \pm 1.4$  Ma, which within an error agrees with the Sm-Nd age of  $212 \pm 22$  Ma. Based on these studies, we can conclude that the formation of mica complexes is closely related to the fluid that separated from deep melts during the Triassic-Early Jurassic stage of development (stretching and riftingogenesis) of the Southern and Middle Urals.

Based on extensive factual material it has been established, that the emerald raw material is confined to the phlogopite zone and its contact with plagioclase lenses, i.e. to the central part (swells) of mica veins [23]. Mica veins over 1.2 m thick are the richest in emerald raw material, comprising 62.5 % of the total raw material mass with a relatively low (30.1 %) frequency of occurrence. The 0.4-1.2 m thick veins are classified as moderately productive, and those less than 0.4 m thick are practically unproductive. The overwhelming (more than 95 %) amount of emerald raw material is



concentrated in the mica veins; they also have the highest (13.4 ppm) content of beryl. For the main host rocks and ore complex (emerald-bearing mica and quartz-plagioclase veins with beryl) from the Mariinsky deposit new data on the magnetic susceptibility and electrical resistivity were obtained. The results of the research allowed the creation of a new express methodology for the identification of productive mica veins in boreholes and faces by simultaneous measurement of magnetic susceptibility and electrical resistivity of rocks during mining operations in the underground mine [24].

Table 3 shows the prognostic and prospecting criteria developed for mica veins for emeralds.

Table 3

Prognostic and prospecting criteria of mica veins for emeralds

Criteria and indicators	Emerald (productive) veins	Weakly mineralized and unproductive veins
Host rocks and contacts	Talc shales, contacts of talc shales with diorite porphyrites	Talc shale contacts with quartzites, amphibolites and carbonaceous-siliceous shales
Strike	Northwest	North East
Dip	Northeastern, southwest	Northwest, southeast
Dip angle, deg.	> 30	< 30
Thickness, m	0.4-1.8	0.1-0.4
Mineral composition	Phlogopite, plagioclase, light green beryl, smoky quartz	Phlogopite, actinolite, chlorite
Beryllium oxide content, %	> 0.01	< 0.01
Fluorine content, %	> 2.0	< 2.0
Cr/Ti ratio	> 0.3	< 0.3
Refractive index of phlogopite	< 1.580	> 1.580
Magnetic susceptibility, SI unit	< $2.4 \times 10^{-4}$	> $2.0 \times 10^{-4}$

Beryl and emerald crystals are green or bluish-green. Some crystals, along with the green coloring (inclusions of  $\text{Cr}^{3+}$ ), have a yellowish-green coloring due to impurities  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$ . The distribution of coloring in crystals is uniform, zonal and spotty. The zoning is usually color – colorless green color, by light to dark green by tone, dull to bright by saturation. It is noted that the coarse zoning corresponds to different generations of emerald formation, while the fine zoning corresponds to the rhythmic fluctuations in the composition of the emerald-forming solution.

Variations in the composition of beryls, especially the Na, Li, Cs, Fe, and Mg contents, can serve as an indicator of the fractionation and evolution of the mineral and host rock [25, 26]. Magnesium is the main replacement cation for emeralds of almost all deposits. Emeralds from Russian (Urals), Brazilian, and Zambian deposits are referred to the so-called shale type, associated with mica and pegmatites. They are characterized by high magnesium (0.70-3.10 %) and sodium (0.20-2.80 %) concentrations. In contrast, the Colombian emeralds have low contents (0.00-0.76 % Na and 0.00-0.94 % Mg) [27]. According to sources [26, 28], part of the iron in emerald can be present in trivalent form  $\text{Fe}^{3+}$ ; lithium can replace beryllium, with the charge balance being compensated by the addition of a single-valent cation in the channel. For chromium and vanadium, which determine the coloring of emerald, the following regularities are revealed – the content of  $\text{Cr}_2\text{O}_3$  is usually much higher than  $\text{V}_2\text{O}_3$ , except for emeralds from the deposits of Muzo (Colombia) [26, 29] and Diakou (China) [30, 31].

The microprobe analysis of beryl samples from Colombia, Ural, and Brazil has shown that the main diagnostic signs of the deposit when using this method can be the following: the degree of

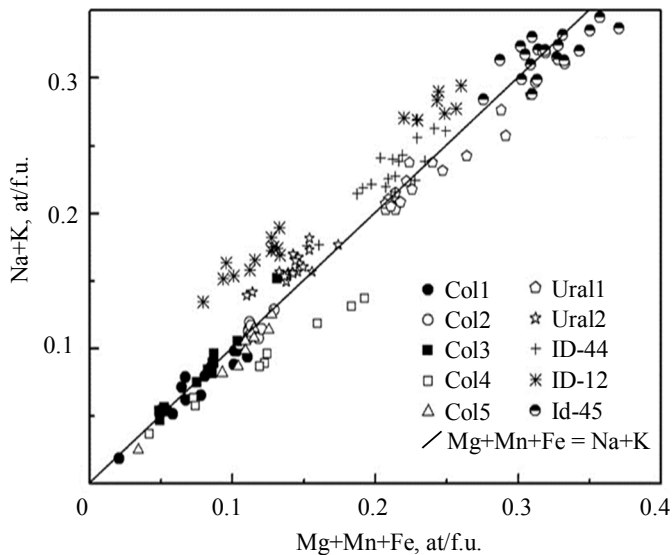


Fig.4. Ratio of total concentration of Mg+Mn+Fe and Na+K alkaline cations in investigated beryl samples

Col – Colombia; Ural – Ural (Ural1 – Mariinsky, Ural2 – Sverdlovsky deposit); ID – Brazil

substitution of aluminum position with impurity cations, the degree of ferruginicity and magnesianity, the content of alkaline cations. Fig.4 shows the ratio of total concentration (Mg + Mn + Fe) and alkaline cations (Na+K) in emeralds from Colombia, Brazil, and the Urals. According to the results of studies [32] it was proved that the main chromophore in the Ural emeralds is  $\text{Cr}^{3+}$  (content 0.5-1.5 wt %).

The coloring of medium and pale green beryls (emeralds) is also associated with high  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  content (0.5-0.7 wt %). Iron atoms are isomorphic in the beryl structure, replacing aluminum in the octahedral position. The main source of chromium for coloring of emeralds of the Mariinsky deposit was chromspinellides of the Bazhenov ophiolitic complex. A change in the composition of

chromspinellides from high-alumina to low-alumina is observed, which occurred during the metasomatic processing of primary chromites under the influence of high-temperature fluorine-saturated hydrothermal solutions [32]. A similar situation with chromophores is described in emeralds from some Brazilian deposits [33, 34].

Currently, there are no identified deposits on the UEB territory, which would contain only alexandrite-chrysoberyl mineralization in commercial concentration. Alexandrites are extracted as by-product during the extraction of emerald-beryllium middlings [1, 35]. The analysis of earlier exploration for beryls and emeralds in the UEB revealed that alexandrite-chrysoberyl mineralization usually crystallizes in a different geological and structural position in relation to emerald-bearing mica and has its own characteristics:

- Alexandrite-chrysoberyl mica shales with phenakite are located in the contour and often outside the contours of emerald-bearing zones, in structures of sublatitudinal direction. This is particularly clear in the Sverdlovsky, Krasnobolotny, and Cheremshansky deposits.

- The localization of emerald and alexandrite mineralization varies across the deposits. Emerald-bearing mica shales bodies in blocks of commercial reserves have submeridional (strike azimuth 340-355°, dip angle 80-85°) or northwestern (strike azimuth 290-315°, dip azimuth NE, dip angle 50-80°) directions. The veins with chrysoberyl-alexandrite mineralization outside the contours of emerald-bearing blocks have a sublatitudinal (strike azimuth 50-80°, dip azimuth NW, dip angle 50-75°) direction.

- The composition of ore bodies with alexandrite-chrysoberyl mineralization differs from emerald-bearing veins with mineral diversity and forms phlogopite-chlorite veins. The chlorite content varies from 10-30 to 60-70 %.

- Chrysoberyl-alexandrite mica shales with phenakite differs from emerald-bearing mica shales in higher BeO content, according to geochemical and gamma-neutron well logging (0.05-2.00 %).

Four main mineral associations with alexandrite and chrysoberyl are observed on the UEB territory: mica shale complexes; plagioclase veins in mica shales; chlorite zones with phenakite and intermediate margarite rim from mica shale complexes; muscovite-fluorite lenses from mica shales. In 2021, we have described a fifth, rare and unusual mineral association: alexandrite + phlogopite + emerald + allanite + Cr-spinel + fluorite.



The highest content of chrysoberyl and alexandrite crystals is recorded in mica veins, the mineral composition of which includes, in addition to phlogopite, veins, and nodules of berylliferous margarite and elongated tourmaline crystals. The frequency of occurrence of mica veins of this paragenesis is 25.6 %, they include 37.6 % of chrysoberyl from the total volumes. Mica shale veins with phlogopite, plagioclase, beryl, and fluorite have the highest (60.1 %) specific chrysoberyl by mass [13] (Table 4).

Table 4

Prognostic and prospecting criteria of mica veins for chrysoberyl

Criteria and indicators	Productive veins	Weakly mineralized and unproductive veins
Host rocks and contacts	Talc shales, contacts of talc shales with diorite porphyrites	Talc shale contacts with quartzites, amphibolites and carbonaceous-siliceous shales
Strike	North East	Northwest
Dip	North-east, south-east	Northwest
Dip angle, deg.	> 30	< 30
Thickness, m	0.4-1.5	0.1-0.4
Mineral composition	Phlogopite, Be-margarit, tourmaline, plagioclase	Phlogopite, actinolite

Quartz-plagioclase veins were formed later than pegmatites and mica shales complexes. They are remote from the massif and confined to blocks of harder rocks (amphibolites, diorites), where they fill sublatitudinal fractures (more often gentle, less often steep) of 290-350° direction with a dip angle of 40-45°. All ore bodies are in a close genetic relationship with emerald-bearing mica shales but are located in different geological and structural settings, they seem to intersect mica veins [13]. Therefore, significant series of quartz-plagioclase veins with commercial rare-metal (Ta-Nb-Be) mineralization are found in large emerald-beryl deposits (Mariinsky, Krasnoarmeisky). In smaller occurrences, the veins are represented by single bodies. In composition they are close to rare-metal pegmatites of the area but differ by structural-textural characteristics and mineral associations of secondary minerals. Late beryllium mineralization (euclase, bavenite, bertrandite, behoite, clinobehoite, ginzburgite, bityit) reaches its maximum diversity in sublatitudinal fractures, zones of extension, and tectonic crushing of quartz-plagioclase veins containing beryl, is described at the Mariinsky deposit. The impetus for the mass discovery of mineralization in the faces was the use of photoneutron sampling (gamma-neutron method, which is based on the photonuclear reaction characterized by the absorption of  $\gamma$ -rays by beryllium nuclei followed by the neutron emission) both in the host rocks and in the ore bodies. Late Beryllium mineralization completes the Be-mineral formation stage in the UEB area and is an important direct mineralogical signature for rare-metal and gem-quality beryllium mineralization [36].

**Discussion.** The formation of the main mineral associations in the eastern frame of Murzinsko-Aduysky anticlinorium at different times is associated with the development of Triassic-Early Jurassic riftogenesis [9, 11] and an uneven depth fluid regime. The characteristic feature of activation is also zoning of mineral associations, which is well visible not only in ore bodies but also in granites of Murzinsko-Aduysky anticlinorium. All this contributed to the formation of major post-collision mineral associations and ore concentrations in the form of rare-metal (Ta-Nb-Be) and gemstone (chrysoberyl, emerald, and phenakite) mineralization. All of them were formed after the formation of Late Permian granite intrusions (Murzinsky, Aduysky, and Malyshevsky massifs). The earliest, with an age of 268 Ma (Late Permian), is the quartz-muscovite-feldspar mineral association, which was



formed at the end of Murzinsko-Aduysky granite-gneisses complex formation. Further, the talc-actinolite-phlogopite mineral association (230-190 Ma, Triassic-Early Jurassic) was formed. The duration of its formation is associated with repeated exposure to fluid solutions formed after the formation of Late Permian granites. This fact is well manifested in the form of coarse and fine color zoning in the emerald crystal raw material. A similar pattern is observed on the known emerald-beryl objects [26, 37].

The geological and structural position determines the occurrence of deposits confined to areas of uplift or dip of the roof of the Adua pluton. Complex mineralization is often observed in the areas of kinks and transitions from one structural element to another. According to the scale and relative amount of beryl and emerald reserves, quality and gem-quality of ores and raw materials, paragenetic associations, and correlation of vein and metasomatic rocks, the known objects differ significantly in their geological structure, structural position, and composition of host rocks. Geological and structural features of the area, identification of the main mineral associations of promising rare-metal (Be-Nb-Ta) mineralization in the eastern framing of Murzinsko-Aduysky anticlinorium can be considered as search criteria for geological prospecting works.

### Conclusions

1. During the Triassic-Early Jurassic development stage of the Southern and Middle Urals (stretching and riftogenesis), various mineral associations and industrial rare-metal (Ta-Nb-Be) and gemstone (alexandrite-chrysoberyl, emerald-beryl, and phenakite) mineralization occurred at different times in the eastern rim of Murzinsko-Aduysky anticlinorium.

2. The mineral formation is associated with pneumatolite-hydrothermal fluids enriched with beryllium, tantalum, lithium, cesium, molybdenum, and fluorine.

3. Rare-metal mineralization has different types, genetically related to the formation of Late Permian granite massifs and between them, but it has also different temporal and spatial positions. The age of rare-metal pegmatites is 268-262 Ma (U-Pb dating, 28 samples); the age of mica shales and veins is 190-250 Ma (Rb-Sr method, 24 samples). Types of mineralization have different spatial position relative to granite massifs and are located in different systems of tectonic disturbances.

4. Rare-metal minerals within EUB occur in pegmatite deposits and occurrences (in individual small pegmatite bodies) and quartz-plagioclase veins (in emerald-beryllium deposits).

5. Important direct mineralogical indications for rare-metal and gem-quality beryllium mineralization are findings of secondary beryllium minerals (bavenite, bertrandite, Be-margarit, euclase). Indirect mineralogical signatures in the eastern rim of Murzinsko-Aduysky anticlinorium are findings of mica veins and complexes of predominantly phlogopite composition.

6. The study of geological and structural features of the UEB area and the identification of promising rare-metal (Be-Nb-Ta) mineralization within the eastern Murzinsko-Aduysky anticlinorium can be considered as a search criterion for exploration work aimed at finding new deposits and occurrences.

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