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Kultuminskoe Gold–Copper–Iron–Skarn Deposit (Eastern Transbaikalia, Russia): Petrogeochemical Features of Magmatism and Ore-Forming Processes[1]

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Abstract—The Kultuminskoe deposit is located within the Gazimur metallogenic zone in eastern Transbaikalia. Mineralization is associated with the Middle–Upper Jurassic Kultuma pluton composed of subalkaline rock series ranging from quartz monzonites and quartz syenites to granites and of monzodiorite dikes. Dikes of Late Jurassic age are composed of subalkaline gabbro. Analysis of fractionation trends of major and trace elements suggests that the monzonitoids prevailed in the Kultuma pluton and the dike complex formed through the differentiation of subalkaline basaltic melt from an enriched mantle source. The formation of the gold–copper–iron–skarn and medium-temperature veinlet-disseminated polysulfide and epithermal Ag–Te–Bi mineralization as well as iron–magnesia and silica–alkaline metasomatites was a long multistage process during the general evolution of the ore-magmatic system.

Keywords: magmatism, petrogeochemistry, Au–Cu–Fe skarns, polysulfide and epithermal Ag–Te–Bi mineralization, Kultuminskoe deposit, eastern Transbaikalia

INTRODUCTION

The Kultuminskoe gold-sulfide-iron-skarn deposit is located in the Gazimur-Zavod district of the Chita Region in eastern Transbaikalia. The total reserves of categories C1–C2 at the deposit are estimated at 121 tons of gold, 948 tons of silver, 487 thousand tons of copper, 33 million tons of iron ores, making it one of the most economically important type. At present, it is considered as a significant investment object (Kharitonov et al., 2003). The main problems related to the geological structure, magmatism and mineralization of the deposit have been discussed by N.E. Chernyshova (2009, 2011, 2012), A.A. Fedorova, N.E. Chernyshova (2009), A.A. Fedorova and V.S. Salikhov (2009), R.V. Gruzdev (2015), V.S. Salikhov and R.V. Gruzdev (2013). The purpose of this study was to examine the petrogeochemical features, the nature and sources of igneous rocks of the deposit, the mineralogical and geochemical characteristics of ores and the relationship between the processes of ore formation and magmatism.

Eastern Transbaikalia occupies the central part of the Mongol-Okhotsk fold belt and is one of the largest raw material regions where deposits of many metals such as molybdenum, tungsten, tin, gold, silver, bismuth, iron, copper, antimony, lead, zinc, boron, fluorite and uranium are concentrated. The metallogeny of this territory was first reviewed in detail by S.S. Smirnov (1961), who established the belt-based location of the deposits. Later, the metallogenic features of eastern Transbaikalia were considered from the standpoint of tectonic-magmatic activation, which embraced the consolidated Baikalian and early Caledonian folded structures in the Mesozoic time (Scheglov, 1966). In accordance with the modern geodynamic interpretations, the territory of the Mongol-Okhotsk belt is a collisional zone of the junction of the Siberian and Mongol-Chinese continents, the main branch of which is represented by the Mongol-Okhotsk suture and its southwest branch (Onot branch) is traced from the northeast to the southwest (Fig. 1) (Zorin et al., 1998, 2001; Spiridonov et al., 2006). An important ore-localizing role is played by the widespread Mesozoic igneous formations, with which the vast majority of endogenous deposits of nonferrous, rare and noble metals are associated.

By chemical composition, intrusive rocks are the derivatives of high-K calc-alkaline and latite magmas which are probably of mantle origin. It was found that indicators of a mantle hot spot manifested both in the Middle–Upper Jurassic collisional setting and in the Early Cretaceous rifting environment. Under these conditions, collision- and rift-related deposits could have common sources.

One of the economically important regions of eastern Transbaikalia is the territory located to the southeast of the

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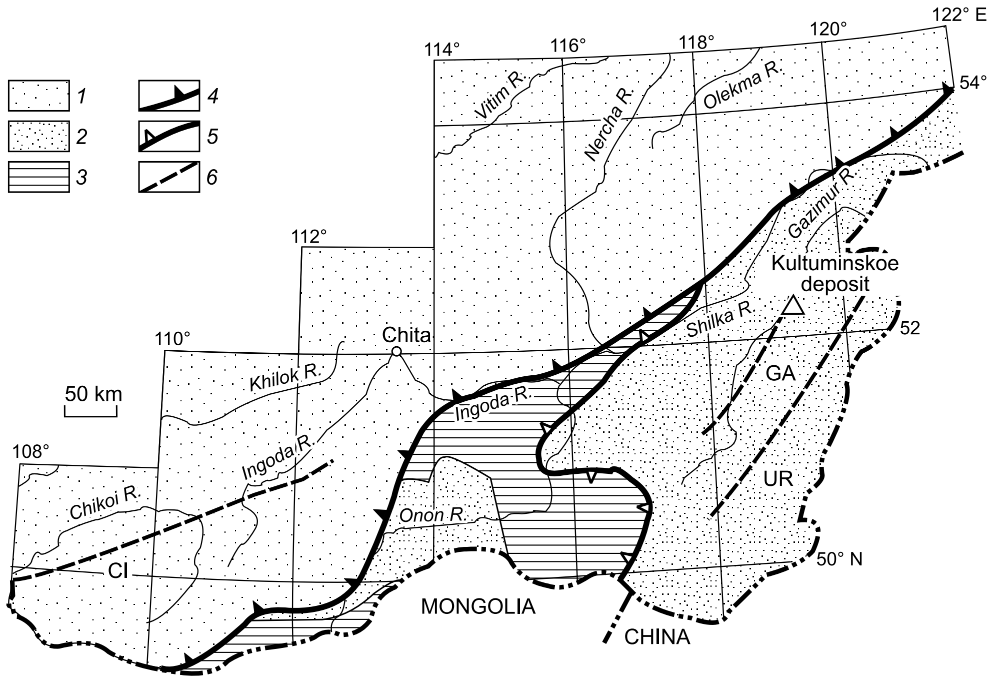

Fig. 1. The location of the Kultuminskoe deposit on the scheme of the main structures of eastern Transbaikalia, simplified after (Zorin et al., 1998; Spiridonov et al., 2006). *1*, Siberian continent; *2*, Mongol-Chinese continent; *3*, Onot island arc terrane; *4*, main branch of the Mongol-Okhotsk structure; *5*, additional branch of the Mongol-Okhotsk structure (frontal part of the Onot overthrust); *6*, faults formed or reactivated during continental collision: CI, Chikoi-Ingoda; GA, Gazimur, UR, Urulyungui.

Borshchevochnyi Ridge, bounded by the Gazimur and Urulyungui faults, which have formed or were renewed during the collision. The Gazimur–Uryumkan metallogenic zone is confined to the Gazimur deep fault and hosts the large ore clusters and deposits of Fe, Cu, Au, W, Mo, Sb (Fig. 2) (Kormilitsyn and Ivanova, 1968). It extends to the NE direction for 350 km, has an average width of ca. 80 km and is characterized by the wide development of major faults and post-orogenic hypabyssal intrusions of middle Paleozoic and Mesozoic age. The Gazimur–Uryumkan zone is partially "ovelapped" by the Pb–Zn Argun' and fluorite Kalangui belts in the southeast, while in the northwest it is coincides with the Sn–W belt (Smirnov, 1961).

ANALYTICAL TECHNIQUES

The XRD, ICP MS, and atomic absorption analysis techniques were used to analyze the composition, REEs, and trace elements of igneous rocks and ores. The relationships between ore and nonmetallic minerals from various mineral associations of ores, their chemical composition and trace elements were examined using a scanning electron microscope (TESCAN MIRA 3LMU) and X-ray microanalyzer (JEOL JXA-800). In addition, isotope-geochemical studies of sulfides have been performed. The analytical measurements were made in the Analytical Center for Multielement and Isotopic Research of the SB RAS (Novosibirsk) and in the laboratory of LLC ALS Chita-Laboratory (Chita).

KULTUMINSKOE ORE FIELD

The Kultuminskoe ore field is located in the central part of the Gazimur–Uryumkan metallogenic zone and lies in-between the Yaromai and Ochunogda Rivers on the left bank of the Gazimur River (Fig. 3). Since the 40-s of the 19th century, placer gold, magnetite ores, silver-bearing polymetallic ores and quartz-arsenopyrite mineralization have been identified on the ore field area. Mineralization is localized within the Vendian–early Paleozoic, late Paleozoic, and Mesozoic structural levels, which correspond to different stages of the geotectonic development of the region.

The main structure of the Vendian–early Paleozoic level is the Budyumkan synclinorium composed of sediments of the Beletui Formation of Vendian age (Vbl), the Bystraya Formation of lower Cambrian age ($Є_1$bs), and the Ernichnaya series of tentatively lower-middle Cambrian age ($Є_{1–2}$?er). It is a double-fold structure consisting of brachianticlinal and linear folds of the 2nd and higher orders. Sandy-shale sediments of the Beletui Formation, dolomites and limestones of the Bystraya Formation are exposed in the cores of anticlines. The brachisynclines and the wings of anticlinal folds are composed of aleuro-arenated sequences of the Ernichnaya Formation. The formations have concordant contacts and their thicknesses vary from a few hundred meters up to 1 km. Stratified rocks near the intrusion are hornfelsed, skarnized and host manifestations of gold-sulfide, silver-polymetallic and gold-sulfide-magnetite mineralization.

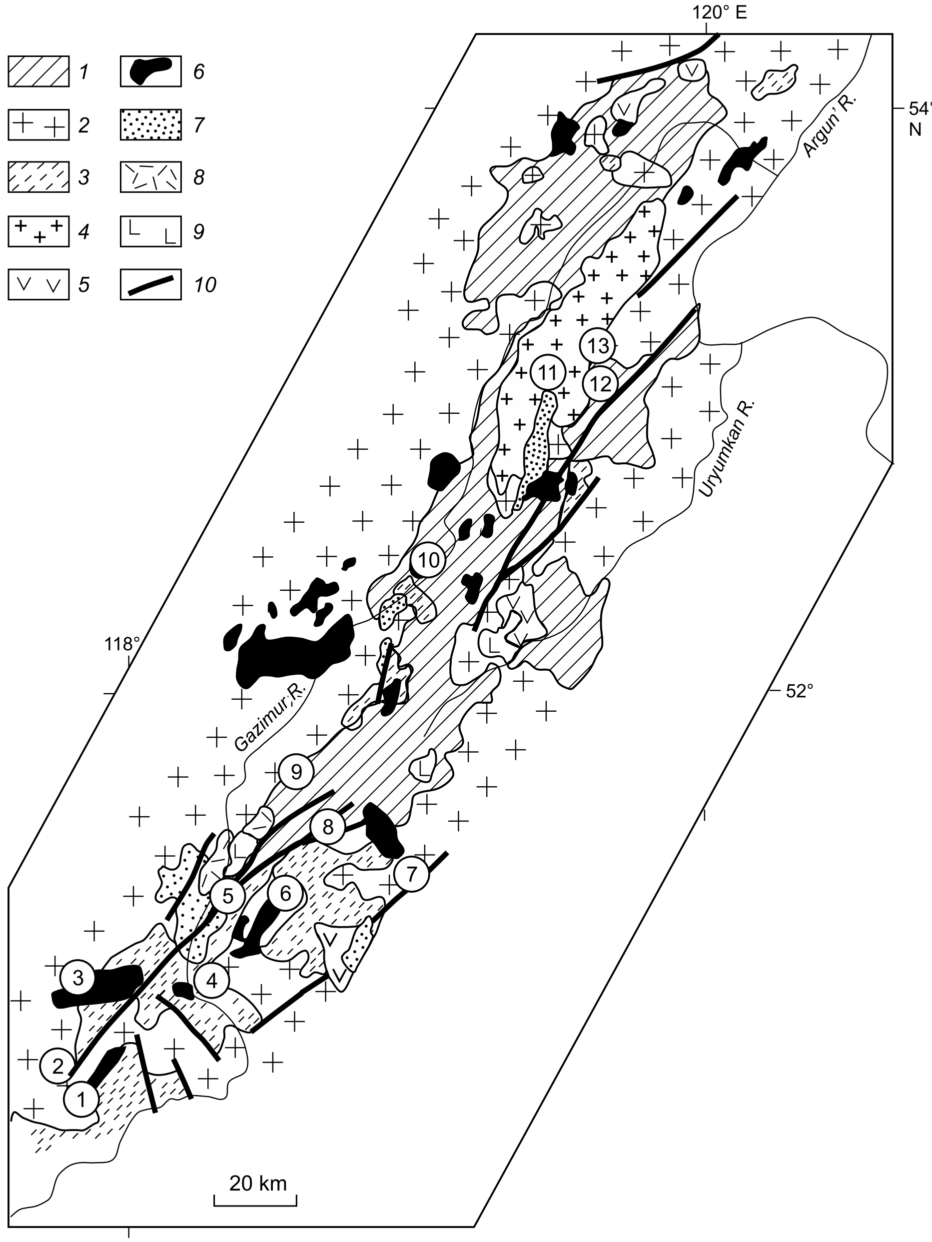

Fig. 2. The scheme of geologic structure and location of ore clusters and deposits in-between the Gazimur and Uryumkan Rivers, modified after (Kormilitsyn and Ivanova, 1968). *1*, early Paleozoic terrigenous-carbonate rocks; *2*, middle Paleozoic granitoids; *3*, Early–Middle Jurassic sandstones and conglomerates; *4*, Mesozoic granites; *5*, Late Jurassic andesites, andesite-basalts and their tuffs; *6*, Late Jurassic granodiorite intrusions; *7*, Cretaceous sedimentary rocks; *8*, Cretaceous effusive rocks; *9*, Quaternary basalts; *10*, main faults. Ore clusters and deposits: 1, Akatuevskoe (Pb, Zn), 2, Bugdaya (W, Mo), 3, Shakhtama (Mo), 4, Krasnoyarsk-Zalinskii ore cluster (Pb, Zn), 5, Taininskoe (Pb, Zn), 6, Byustrinskoe (Cu, Au, Fe), 7, Solonechnoe (Ca, F), 8, Novoshirokinskoe (Au, Zn, Pb), 9, Ushmunskoe (Sn, W), 10, Kultuminskoe (Cu, Au, Fe), 11, Budyumkanskoe (Sn), 12, Solonechenskoe (Sb, Au), 13, Lugokanskoe (Au, Cu).

The igneous formations within the ore field are represented by porphyroblastic granites of the Borshchovochnyi complex ($\gamma_1 J_{2-3}b$), as well as rocks of the Shakhtama ($\gamma\delta\pi J_{2-3}\check{s}$), Kukul'bei ($\gamma J_3\kappa$) and Unda complexes ($\gamma_3 P_1 u$). Granitoids of the Borshchovochnyi complex are the products of remobilization of the early Proterozoic sialic basement in the Middle–Late Jurassic and are geochemically specialized in trace elements. The Shakhtama complex, to which the Kultuma pluton belongs, is represented by rocks of the third intrusive phase: granodiorite-porphyries, granite-porphyries and diorite porphyrites. These rocks occur in sites of intersection of fault zones. The rocks of the Kukul'bei complex are exposed in the south part of the ore field. They are represented by an intrusion of leucocratic granites and scattered dikes of acidic composition. The metallogenic specialization of this complex remains uncertain. The Unda complex is represented by the third phase which consists of fine-grained leucocratic biotite granites with poor tantalum-niobate mineral-

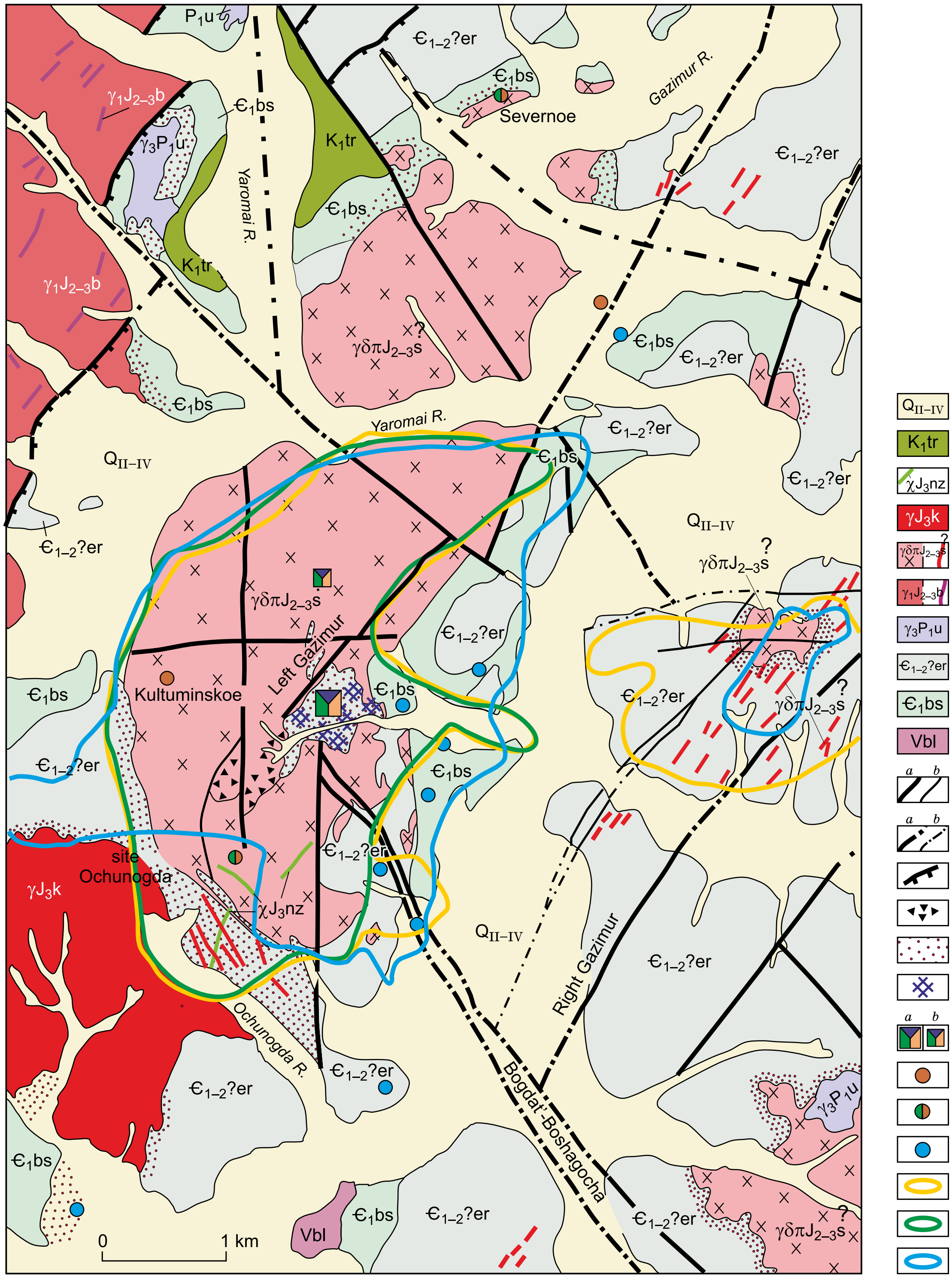

Fig. 3. Schematic geologic map of the Kultuma ore field (modified from the data of geological exploration works, 2008). *1*, alluvial deposits (Q_{II-III}–Q_{IV}); *2*, Turlinskaya Formation (K_2tr): sandstones, tuff sandstones, siltstones, mudstones, gritstones, andesites. Their tuffs, tuff and lava breccias; *3*, Nerchinskii Zavod complex (J_3nz): lamprophyre, microdiorite and diorite dikes; *4*, Kukul'bei granite complex (J_3k): leucocratic and biotite granites; *5*, Shakhtama granite-granodiorite complex, 3 phase (J_{2-3}š): granite-porphyries, porphyraceous granodiorites, diorite-porphyrites; *6*, Borshchovochnyi complex (J_{2-3}b): granites, granodiorites, pegmatite dikes; *7*, Unda granite-granodiorite complex (P_1u): granites, leucocratic granodiorites, granosyenites of the second and third phases; *8*, Ernichnaya series ($Є_{1-2}$?er): sandstones, silty sandstones, siltstones, flinty-argillaceous slates, limestone and dolomite bands; *9*, Bystraya Formation ($Є_1$bs): dolomites, calcareous dolomites, limestones, interbeds of sandstones, siltstones, coaly clay shales; *10*, Beletui Formation (Vbl): quartz-sericite-chlorite and coaly shales, sandstones, siltstones, dolomite and limestone bands; *11*, main (*a*), minor (*b*) faults; *12*, hidden faults; *13*, overthrusts; *14*, explosive breccias; *15*, hornfels; *16*, skarnized rocks; mineral types of mineralization: *17*, Au–Cu–Fe-skarn, *18*, Au–As-hydrothermal, *19*, Cu–Au–As-hydrothermal-metasomatic, *20*, Ag–Pb–Zn-veined hydrothermal; secondary dispersion aureoles: *21*, gold, *22*, copper, *23*, lead and zinc.

ization. The ages of the Shakhtama and Kukul'bei complexes are considered as Middle–Upper Jurassic and Upper Jurassic, correspondingly (Rutshtein and Chaban, 1997). According to K–Ar dating, the ages of different plutons of the Shakhtama complex in eastern Transbaikalia Range from 167 to 155 Ma while those of the Kukul'bei complex vary from 150 to 126 Ma (Spiridonov et al., 2006; Kozlov, 2011). Intrusion of lamprophyre and dolerite dikes tentatively assigned to the Nerchinskii Zavod complex (χJ_3nz) terminates the Late Jurassic stage of development of this region. These formations cut into the rocks of the Shakhtama complex and carry no mineralization.

The main disjunctive structures in the central part of the ore field are the systems of the NE striking Right Gazimur, Left Gazimur and Budyumkan deep faults. The zone of the deep Bogdat'-Boshagocha fault of NW strike controls the location of the intrusions of the Shakhtama complex. In the NW part of the ore field, granitoids of the Borshchvochnyi complex overlap the Cambrian terrigenous-carbonate sediments along the Yaromai thrust.

The ore field includes the Kultuminskoe gold-sulfide-iron-skarn deposit, the Ochunogdinskii site, and the Severnoe ore manifestation with gold-copper-sulfide mineralization as well as numerous ore occurrences of various mineral types, which are concentrated within the Kultuma pluton and host terrigenous-carbonate rocks (Fig. 3). The pluton is framed by secondary dispersion halos of Au (0.01–1.45 ppm), Cu (0.01–1 wt.%), Zn (0.02–0.2 wt.%), and Pb (0.01–0.05 wt.%).

MAGMATISM AND MINERALIZATION OF THE KULTUMINSKOE DEPOSIT

The main economically important mineralization of the Kultuminskoe deposit is confined to the endo- and exocontact skarn zones of the granitoid pluton and to the hornfelsed and skarnized terrigenous-carbonate rocks of the Bystraya Formation and Ernichnaya series. The pluton is 5 × 15 km in size and extends in the NE direction. It was drilled out to a depth of 900 m and seems to be a conformal body with increasing thickness to the north. According to gravimetric and magnetometric data, the Kultuma pluton is of a lopolith-like shape with a feeder in the north, occurring at a depth of about 2500 m, and characterized by a negative gravitational anomaly which repeats the mapped boundary of the intrusion at the surface. According to the results of interpretation of geophysical data, the Kultuma pluton is confined to the axial part of the synclinal fold (Salikhov and Gruzdev, 2013). There is a point of view on the heterogeneous nature of the Kultuma pluton, which is explained by the involvement of the processes of contamination and metasomatism (Chernysheva, 2011, 2012).

Explosive breccia bodies represented by granite-porphyries with quartz-feldspar cement were mapped within the area of the pluton. The nature of these formations is poorly studied. They can serve as an indicator of Au–Cu–Mo mineralization on the flanks and at the depth of the Kultuminskoe deposit in the ore–magmatic model proposed by Gruzdev (2015). These rocks are located in the zone of conjugate faults of submeridional and NE strike, intersect the pluton, have a tectonic nature and are represented by K-feldsparized granite-porphyries with streaky-disseminated quartz-molybdenite mineralization.

The pluton is cut by dikes of lamprophyres, dolerites, diorites, and diorite porphyrites. Most of them are confined to the southern part of the pluton on the area of the Ochunogdinskii site. The dikes have a length up to 900 m, thickness up to 30 m and extend in NW, NE and submeridional direction and gently dip to the east and west at angles up to 45°. By age, the dikes tentatively assigned to the Nerchinskii Zavod intrusive complex and carry no mineralization.

Rock composition of the Kultuma pluton and dike complex. The rocks of the pluton, denoted as granite-porphyries on the geological maps, have a gray and greenish-gray color and medium-grained and porphyry structure. Porphyry phenocrysts are represented by plagioclase up to 3–4 cm in size and often with a zonal structure, potassium feldspar and hornblende up to 2–3 cm in size. A detailed petrographic description of rocks is presented in the work of Chernyshova (2011). The mineral composition of a typical granite-porphyry is as follows (wt.%): plagioclase—25–30, quartz—20–25, K-feldspar—20–25, biotite—5–8, and hornblende—5–10. The rock groundmass has a micro-granite or felsite texture and is composed of isometric grains of quartz, K-feldspar, plagioclase plates with biotite flakes and often actinolitized hornblende. Accessory minerals include magnetite, rutile, sphene, apatite, and zircon. Rocks of the dike complex are represented by diorites and dolerites. They have a black and dark green color, dense fine-grained structure and occasionally contain porphyry phenocrysts of feldspar. The groundmass texture is doleritic, aphyric, microgabbrous. The latter one is represented by laths or idiomorphic grains of plagioclase, biotite, and substituted grains of pyroxene and hornblende. There are impregnations of apatite and rutile.

The rocks of the Kultuma pluton vary widely in silicic acid content (SiO_2 = 60.4–69.5%), correspond chemically and mineralogically to the subalkaline rock series and on the TAS diagram are represented by predominant monzodiorites, quartz monzonites and quartz syenites to granites (Fig. 4*a*). According to the Frost classification (Frost et al., 2001), these rocks are metaluminous (0.91–1.1), magnesian ($FeO^*/(FeO^* + MgO)$ = 0.47–0.86) and predominantly calc-alkaline to alkaline ($Na_2O + K_2O–CaO$ = 0–6.5). The elevated K_2O content suggest that they belong to the high-K/shoshonite rock series (Fig. 4*c*). The rocks of intermediate composition are characterized by inverse correlation between SiO_2 and MgO, FeO, CaO, TiO_2, and P_2O_5 (Fig. 4*b*) and direct correlation with K_2O, whereas in granites as SiO_2 increase the concentrations of MgO, FeO, TiO_2, P_2O_5 and K_2O decrease.

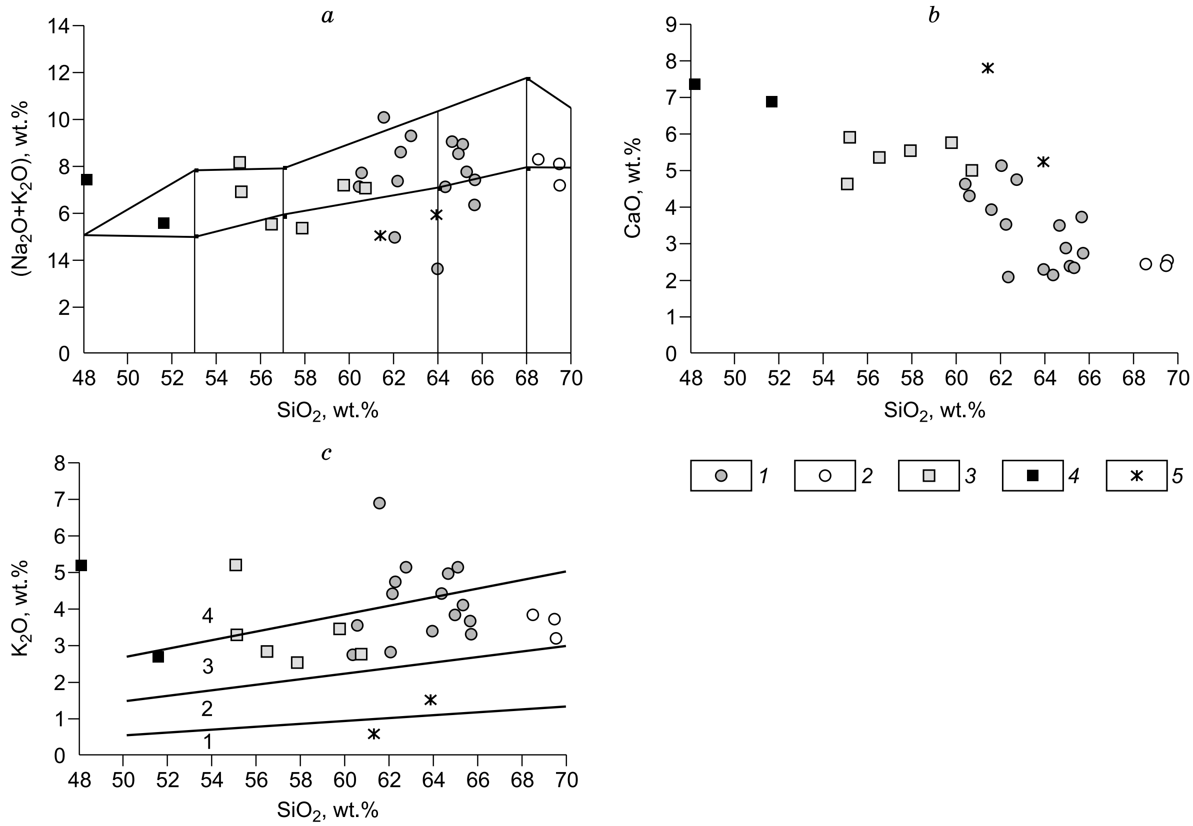

Fig. 4. The SiO_2 vs. Na_2O+K_2O (*a*), SiO_2 vs. CaO (*b*) and SiO_2 vs. K_2O (*c*) plots for rocks of the Kultuma pluton and dike complex. Kultuma pluton: *1*, monzodiorites, quartz monzonites, quartz syenites, *2*, granites; dike complex: *3*, diorites, monzonites, *4*, subalkaline gabbro; *5*, average adakite compositions after (Drummond et al., 1996; Stern and Killian, 1996). Rock series in *c*: 1, low-K, 2, moderately-K, 3, high-K, 4, shoshonitic.

Rocks of the dike complex vary from subalkaline gabbros to subalkaline diorites and monzonites. Trends of figurative points on the Harker diagrams for diorites and monzonites of the dike complex are similar to those for rocks of the pluton and their most silicic varieties is compositionally close to monzonites of the Kultuma pluton (Fig. 4). In contrast, subalkaline gabbros from dikes deviate from general trends (Fig. 4) and are drastically enriched in TiO_2 (1.7–1.6%) and P_2O_5 (0.71–0.86%) as compared to rocks of intermediate composition (TiO_2 = 0.85–0.93%; P_2O_5 = 0.22–0.33%).

The rocks of intermediate composition of the Kultuma pluton and the dike complex have a high content of Ba (500–1200 ppm) and Sr (350–710 ppm), which are typical of monzonite rock series (Ba—1700 ppm, Sr—700 ppm) (Tauson, 1977). In monzonites and syenites, Ba concentration continuously increases with increasing SiO_2, but decreases drastically in granites (Ba ≤ 640 ppm) with decreasing K_2O (Fig. 5*a*). Wide variability in Sr and Rb content in rocks of intermediate and acid composition do not show a clear correlation with SiO_2, which is apparently caused by secondary rock alterations. The Zr, Th, light and heavy REEs, and Y contents in rocks of the Kultuma pluton decrease from quartz monzonites and quartz syenites to granites with decrease in TiO_2 and increase in SiO_2 content (Fig. 5*b*, *c*). Concentration of Nb decreases with decrease in TiO_2 in rocks of intermediate composition and increases again in granites. (Fig. 5*g*). By the HFSE, Th, and light REE contents, diorites and monzonites of the dike complex are generally close to the rocks of intermediate composition of the Kultuma pluton, but do not fit into the general trends relative to SiO_2 and TiO_2, and are separated into independent clusters. Subalkaline gabbros with highly enriched Zr, Nb, La, and Y contents differ drastically from rocks of the Kultuma pluton and rocks of the dike complex (Table 1).

Quartz monzonites and quartz syenites of the Kultuma pluton are characterized by moderately fractionated REE spectra ($(La/Yb)_n$ = 18–58) with a weak europium minimum (Eu/Eu* = 0.95–0.64) (Fig. 6*a*). Granites have a similar REE spectra $(La/Yb)_n$ = 17–35, Eu/Eu* = 0.86–0.7). In monzonites and syenites there is a distinct depletion of heavy lanthanides and Y with SiO_2 increase (Figs. 5*c*, 6*a*), whereas in granites the decrease in concentrations of these elements is not observed. By the REE patterns, diorites and monzonites of the dike complex are similar to rocks of the Kultuma pluton with analogous silica content ($(La/Yb)_n$ = 14–33, Eu/Eu* = 0.74–0.8), while subalkaline gabbro are enriched with light lanthanides (Fig. 6*c*).

The multielement spectra of the rocks of the Kultuma pluton and those of the dike complex are similar and are

Table 1. The major (wt.%) and trace element (ppm) contents in rocks of the Kultuma pluton and dike complex

Component	kul-14	817/50.5	865/691	856/37.5	kul-2	864/753.2	kul-1	856/48.5	864/710.5	864/732.8	k-10-42	ku-2	ku-1	856/191	864/706.5	kul-10	kul-20	kul-7	865/433.1
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SiO_2, wt.%	60.55	62.04	62.19	62.31	62.75	64.36	64.66	65.10	65.31	65.65	68.53	69.52	69.49	55.06	55.13	56.48	57.87	48.11	51.60
TiO_2	0.87	0.68	0.57	0.65	0.52	0.55	0.46	0.47	0.52	0.51	0.39	0.39	0.41	0.86	0.93	0.85	0.85	1.59	1.72
Al_2O_3	15.5	14.63	14.64	15.40	14.81	15.26	15.2	15.05	15.31	15.06	15.27	14.01	14.88	13.93	14.39	14.00	14.88	15.12	15.82
Fe_2O_3*	4.94	4.84	3.84	4.82	3.53	3.72	2.74	3.09	3.81	3.45	2.78	5.27	2.61	5.42	6.70	7.25	7.12	9.00	8.64
MnO	4.44	4.36	3.45	4.34	3.17	3.35	2.46	2.78	3.43	3.10	2.50	4.74	2.35	4.88	6.03	6.52	6.41	8.09	7.78
MgO	0.05	0.05	0.03	0.02	0.06	0.04	0.03	0.02	0.04	0.05	0.02	0.05	0.02	0.03	0.05	0.10	0.10	0.13	0.10
CaO	5.14	5.26	3.53	3.72	2.83	2.87	2.22	2.33	2.81	2.96	1.73	1.54	1.69	6.61	7.62	8.44	7.06	8.27	4.23
Na_2O	4.30	5.14	3.52	2.08	4.75	2.14	3.51	2.38	2.33	3.72	2.44	2.54	2.42	4.62	5.89	5.37	5.55	7.35	6.88
K_2O	4.12	2.18	2.89	3.87	4.12	2.72	4.06	3.81	3.64	3.72	4.49	3.97	4.37	2.91	3.62	2.72	2.80	2.22	2.88
P_2O_5	3.54	2.79	4.44	4.74	5.15	4.42	4.99	5.13	4.10	3.67	3.83	3.19	3.69	5.22	3.28	2.82	2.54	5.17	2.70
Loi.	0.27	0.23	0.18	0.20	0.15	0.17	0.13	0.14	0.16	0.15	0.12	0.09	0.12	0.29	0.33	0.27	0.22	0.86	0.71
Sum	0.60	0.79	3.52	1.27	0.74	3.05	1.35	1.57	1.46	0.57	0.67	0.00	0.60	4.22	1.32	1.49	0.83	1.43	3.59
Th, ppm	12.4	13.2	13.6	11.6	9.2	11.5	11.7	10.1	7.8	10.5	9.7	8.4	9.8	9.5	10.5	9.0	8.7	9.7	5.9
U	3.23	3.75	3.65	3.77	2.74	4.24	3.47	3.69	2.66	3.84	2.88	2.76	3.0	3.2	2.9	2.69	2.52	2.34	1.52
Rb	96	157	139	199	114	150	115	121	159	120	134	117	127	206	213	125	76	305	63
Ba	937	525	738	930	772	890	936	1218	1010	695	643	335	583	905	467	520	679	1180	891
Sr	709	693	399	514	349	479	487	563	658	667	654	446	622	446	628	607	620	837	839
La	47.8	43.9	33.5	92.8	19.9	26.4	27.5	28.7	25.7	30.6	27.2	15.4	29.6	28.7	40.1	38.5	32.8	65.9	61.4
Ce	91.1	85.0	67.1	148.2	43.9	52.6	53.8	53.5	50.6	59.4	53.9	32.8	56.7	53.5	81.6	75.0	65.7	144.1	126.3
Pr	10.3	9.7	7.7	14.7	5.5	6.2	6.2	6.0	5.8	6.8	6.3	3.8	6.5	6.0	9.9	10.0	8.8	18.0	15.7
Nd	39.8	34.3	28.0	46.3	22.6	23.1	24.0	20.1	21.7	25.6	21.4	13.7	21.4	20.1	36.8	37.2	31.8	71.6	58.8
Sm	6.5	6.0	4.7	6.7	4.1	4.5	3.8	3.5	3.9	4.9	3.4	2.5	3.8	3.5	6.8	6.5	5.5	11.3	10.6
Eu	1.73	1.31	1.22	1.23	0.99	0.8	1.09	0.79	0.92	1.09	0.71	0.63	0.83	0.79	1.51	1.66	1.41	3.24	2.61
Gd	5.1	4.7	3.4	4.9	3.1	2.9	3.1	2.4	3.0	3.5	2.6	1.8	2.7	2.4	5.5	6.0	5.2	9.0	8.2
Tb	0.6	0.56	0.45	0.48	0.33	0.4	0.38	0.29	0.31	0.45	0.33	0.24	0.3	0.29	0.73	0.75	0.63	1.02	0.93
Dy	2.98	2.98	1.97	2.42	1.79	2	1.96	1.46	1.64	2.14	1.47	1.3	1.51	1.46	3.56	3.74	3.36	4.96	5.19
Ho	0.48	0.59	0.33	0.42	0.33	0.39	0.32	0.28	0.27	0.42	0.27	0.24	0.26	0.28	0.69	0.75	0.66	0.84	0.83
Er	1.27	1.53	0.84	1.16	0.93	0.92	0.84	0.75	0.69	1.07	0.7	0.63	0.7	0.75	1.88	1.91	1.74	2.07	2.06
Tm	0.19	0.21	0.12	0.17	0.13	0.13	0.12	0.09	0.09	0.15	0.09	0.1	0.09	0.1	0.25	0.27	0.24	0.28	0.27
Yb	1.08	1.25	0.72	1.08	0.74	0.75	0.69	0.59	0.52	0.83	0.6	0.63	0.57	0.59	1.46	1.79	1.62	1.76	1.49
Lu	0.14	0.18	0.1	0.16	0.11	0.11	0.1	0.09	0.07	0.12	0.1	0.1	0.08	0.09	0.2	0.24	0.24	0.25	0.21
Zr	202	195	177	191	162	189	143	146	184	165	169	134	168	172	208	161	176	229	340
Hf	5.3	5.5	4.8	5.3	4.4	5.1	4.1	4.3	4.6	4.6	4.1	3.7	4.2	4.9	5.6	5.3	5.6	5.1	7.6
Ta	0.71	0.75	0.57	0.76	0.53	0.69	0.67	0.59	0.45	0.66	0.60	0.67	9.6	0.66	0.76	0.63	0.57	1.16	0.92
Nb	10.7	9.6	7.5	9.1	7.4	8.8	7.5	6.9	7.3	7.7	9.4	9.08	9.6	8.5	10.9	7.7	6.7	17.7	16.9
Y	14.7	16.4	10.3	12.4	9.7	10.1	9.6	8.1	8.2	11.7	8.7	8.22	8.3	14.4	18.5	17.8	15.3	24.6	23.6
$(La/Yb)_n$	29.8	23.7	31.4	57.9	18.2	23.8	26.8	32.8	33.3	24.8	30.6	16.5	35.0	32.8	18.5	14.5	13.7	25.2	27.8
Eu/Eu*	0.89	0.73	0.89	0.63	0.82	0.64	0.95	0.79	0.80	0.77	0.70	0.86	0.76	0.79	0.74	0.80	0.80	0.95	0.83

Note. Fe_2O_3*, total iron. Kultuma pluton: 1–10, quartz monzonites, quartz syenites, 12–14, granites; the dike complex: 15–18, monzonites, 19–20, subalkaline gabbro. Samples: 817/50.5, well number and depth (m), other from surface mine workings. Analysts N.G. Karmanova, I.V. Nikolaeva and S.V. Palesskii.

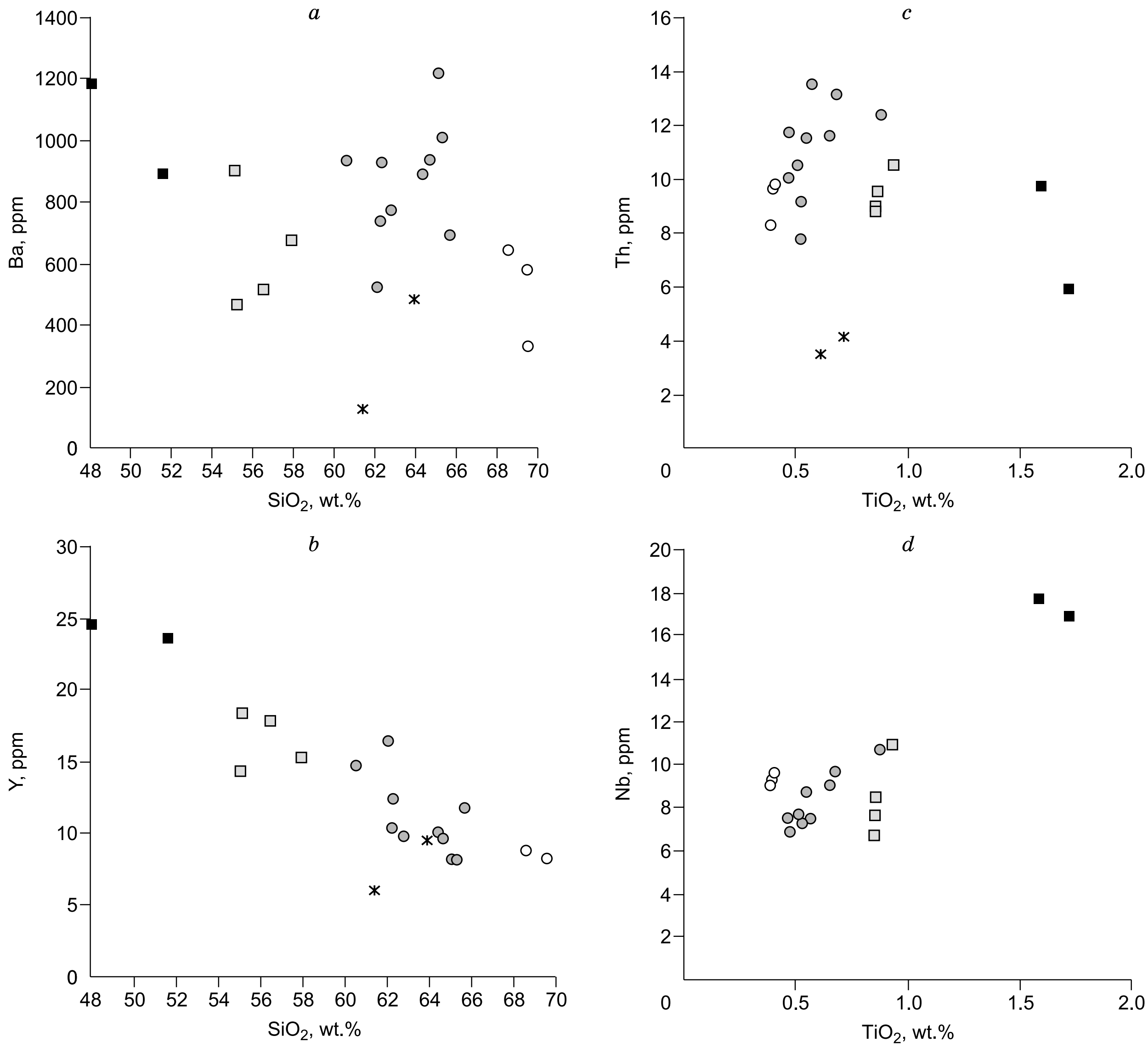

Fig. 5. SiO_2 vs. Ba (*a*), SiO_2 vs. Y (*b*), TiO_2 vs. Th (*c*) and TiO_2 vs. Nb (*d*) plots for rocks of the Kultuma pluton and dike complex. Symbols as in Fig. 4.

characterized by negative anomalies of Nb, P, Ti, and positive anomalies of Sr and Zr (Fig. 7). Subalkaline gabbros are distinguished by weaker negative Nb and Ti anomalies and the lack of a positive Sr anomaly (Fig. 7*c*).

Contact and hydrothermal-metasomatic processes. Products of contact-thermal alteration within the ore field and at the deposit are represented by quartz-plagioclase-cordierite-biotite and quartz-plagioclase-biotite-hornblende hornfels (after siltstones) with disseminated pyrite-pyrrhotite mineralization. Contact-metasomatic processes were accompanied by the formation of high-medium and low-temperature skarns and skarnized rocks. Commercial deposits of gold-chalcopyrite-magnetite ores are mostly associated with serpentine-bearing and pyroxene-actinolite-phlogopite skarns, developed upon dolomitic limestones (exoskarns) and, to a lesser degree, upon granodiorite-porphyries and diorite porphyrites (endoskarns). High-temperature diopside and diopside-garnet skarns occur as relicts in medium- and low-temperature skarns composed of amphibole of actinolite-tremolite group, as well as epidote, phlogopite, and serpentine. Magnesian chlorite (Mg—21.75 wt.%, Fe—1.84 wt.%), magnesite and siderite are also abundant in these rocks. Carbonates are enriched in Mn (up to 3.33 wt.%) while magnetite is enriched in Mg (1.7 wt.%).

Hydrothermal streaky disseminated gold-polysulfide mineralization is confined to metasomatically altered igneous and sedimentary rocks and superimposed on skarns and skarnized rocks. The thickest alteration zones of NE strike occur in the southern part of the Kultuma pluton in the area of the Ochunogdinskii site, where quartz-biotite metasomatites and biotitized intrusive and terrigenous rocks with tourmaline and impregnated sulfide mineralization are widely

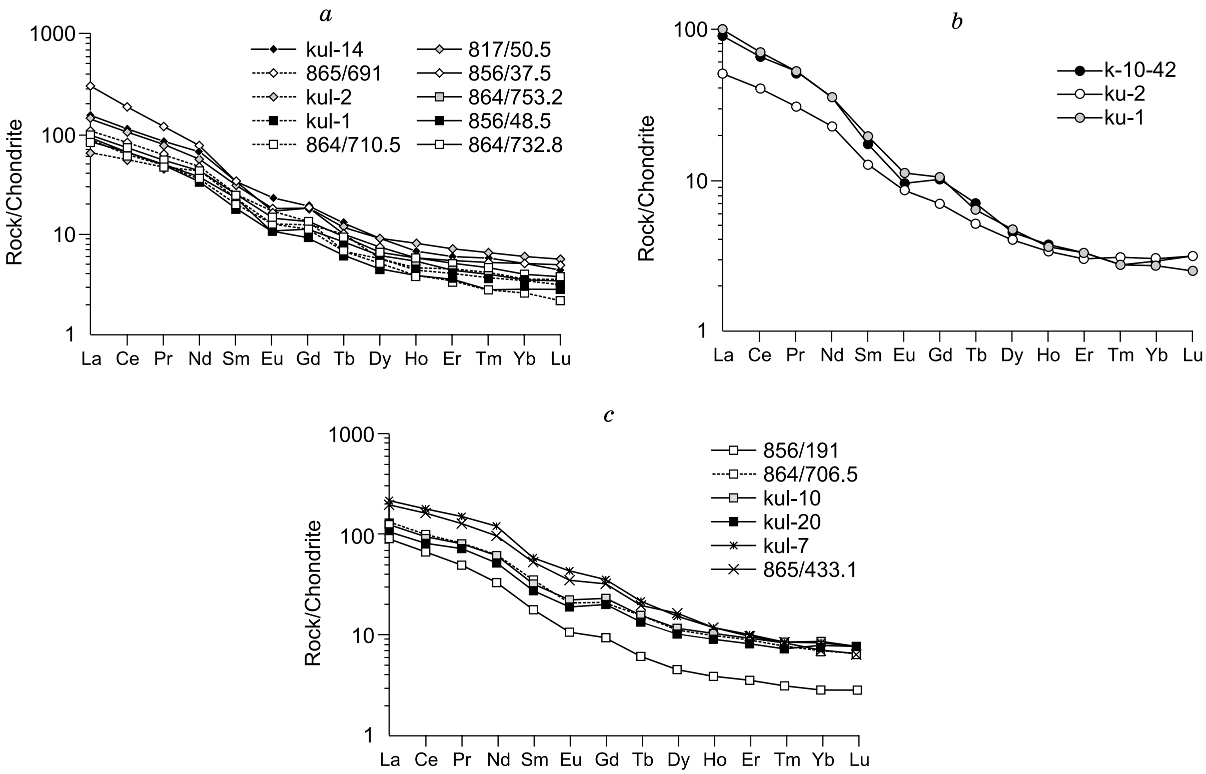

Fig. 6. REE patterns for rocks of the Kultuma pluton and dike complex. *a*, Monzodiorites, quartz monzonites, quartz syenites; *b*, granites; *c*, rocks of the dike complex. Sample numbers as given in Table 1.

developed. Beresitized rocks and quartz-sericite metasomatites with streaky-disseminated gold-arsenopyrite-pyrite mineralization occur predominantly in the zones of NW strike in the northern part of the pluton.

The presence of F, Cl, B, P and Sr as well as their native minerals as admixtures in nonmetallic minerals is the specific feature of hydrothermal-metasomatic processes at the deposit. In the apatite, the F, Cl and Sr contents (wt.%) are 4.18, 0.41, and 0.39, while muscovite and serpentine contain 0.59 and 2.49 wt.% of F, respectively. In addition, ores include boron mineralization represented by ludwigite, ascharite, fluoborite, tourmaline and fluorite.

In general, ore deposition at the Kultuminskoe deposit was accompanied by the formation of iron-magnesian metasomatites at the early stages and silica-alkaline metasomatites at the late stages.

Structural and morphological features of mineralization. The bulk of economic gold-copper-iron skarn ores and streaky-disseminated sulfide mineralization of the Kultuminskoe deposit is localized in the eastern downthrown block of the pluton. The ore zone of the deposit has a complex structure. It is represented by subtabular bodies of metasomatically altered sulfidized and silicified granodiorite porphyries, dolomites, limestones, terrigenous rocks, magnetite skarns and skarnized rocks with quartz-sulfide mineralization. The ore zone contains a complex Au–Ag–polymetallic–Fe mineralization with a rare occurrence of Mo–B mineralization. The structure of the deposit is determined by the combination of the folded Cambrian terrigenous-carbonate rocks and fractures. The anticlines play the main ore-localizing role in the morphology of orebodies, while the high-order synclines are less common. The rupture structure is a result of intersection of multidirectional fractures. Dislocations of NW strike occur in the southern block of the site, have SW dip at angles of 50°–60°, complicate the morphology of the intrusion edge and control the lenses of magnetite skarns and the zone of beresite alteration in granodiorite porphyries. The NE oriented faults occur mainly in the northern block, dip at NW under angles of 55°–70° and are represented by zones of crush and argillization in granodiorite porphyries. The area of mineralized rocks is elongated in the meridional direction for 2400 m, with a width of up to 1200 m in the center and 150–400 m at flanks. In general, commercial ore shoots have a sheet-like form with a thickness of up to 56 m and an area of 500 × 1000 m and occur mainly in magnetite and actinolite-phlogopite-diopside skarns (Fig. 8). Streaky-disseminated gold-polysulfide mineralization at the deposit occurs both within and outside the sheet deposits, concentrates in zones of tectonic dislocations and is accompanied by processes of hydrothermal-metasomatic alterations.

Structural-mineral types of ore occurrence and the nature of mineralization. Ores are represented by massive, breccian, impregnated, and streaky texture types and are mainly characterized by a fine-grained structure. The following ore types are distinguished by mineral composition:

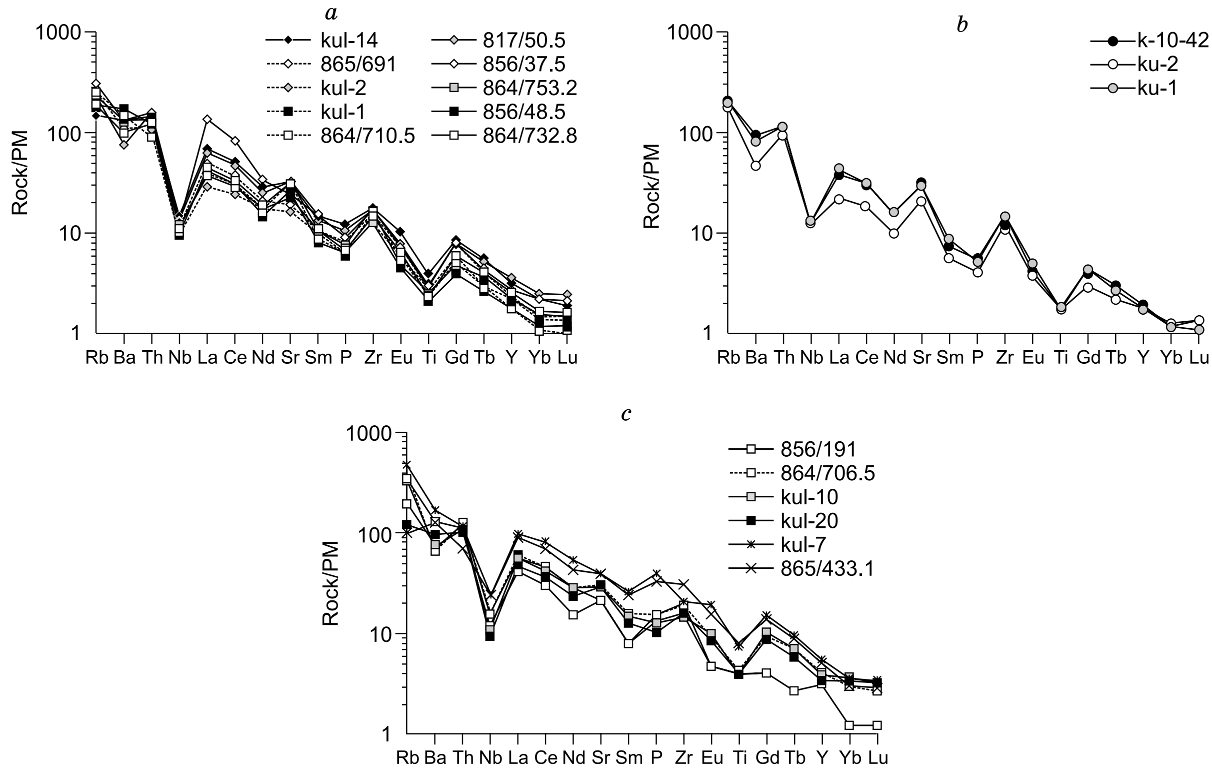

Fig. 7. Multielemental spectra for rocks of the Kultuma pluton and dike complex. *a*, Monzodiorites, quartz monzonites, quartz syenites; *b*, granites; *c*, rocks of the dike complex. Sample numbers as given in Table 1. Normalized by primitive mantle (PM) (Sun and McDonough, 1989).

essentially magnetite, serpentine-magnetite, phlogopite-magnetite, pyrite-chalcopyrite-magnetite, pyrite-arsenopyrite-dolomite, chalcopyrite-galena-sphalerite with sulfosalts, disseminated and streaky with chalcopyrite-tellurium-bismuth and quartz-molybdenum mineralization (Fig. 9). The sulfide content in ore bodies varies widely, reaching 5–10% in some areas. Gold was found in all textural-mineral types. Its distribution in ores is extremely nonuniform. The Fig. 10 shows the distribution of Au, Ag and Cu concentrations through the central part of the ore zone at the deposit. It was found that ores have a high correlation between Au and Cu ($r = 0.9$). No correlation between Au and Ag was found. In addition to the main commercially significant elements, Au, Ag, Cu, and Fe, ores contain also As, Pb, and Zn, while Bi,

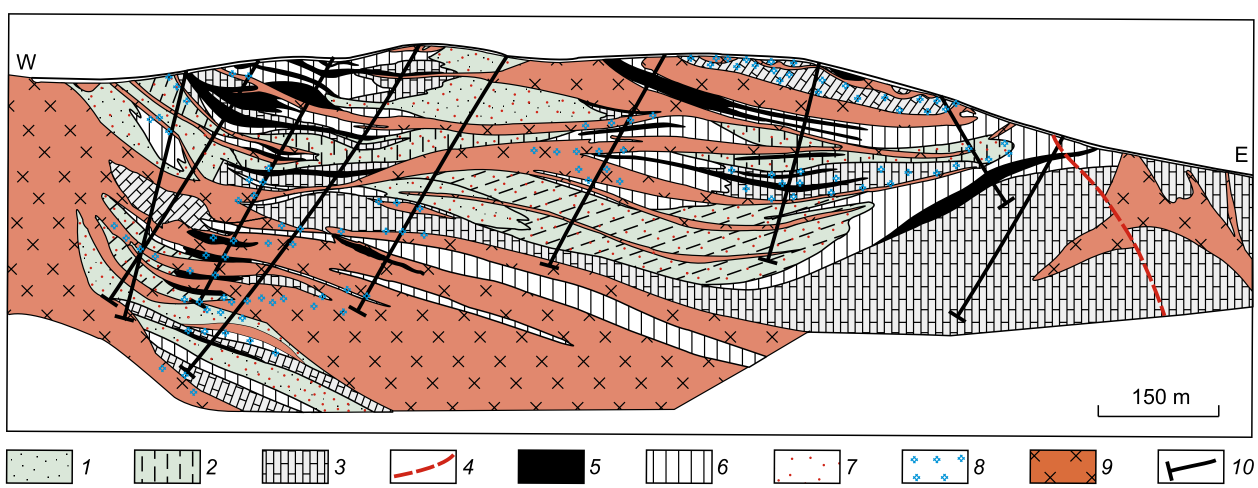

Fig. 8. Geological cross section through the central part of the main ore body of the Kultuminskoe deposit (based on data of geological exploration works, 2008). *1*, sandstones, siltstones; *2*, siltstones, mudstones; *3*, limestones, calcareous dolomites; *4*, faults; *5*, quartz-plagioclase-cordierite-biotite, quartz-biotite-plagioclase-hornblende hornfels; 6, magnetite-serpentine, magnetite skarns; *7*, diopside-actinolite-serpentine skarns; *8*, skarnized rocks; *9*, granodioritic porphyrites; *10*, drill holes.

Table 2. Elemental composition of the main mineral types of ores of the Kultuminskoe deposit according to ICP-MS determinations

Element	Siderite-magnetite ore 91-1018	Garnet-carbonate-magnetite ore C-301	Dolomite-arseno-pyrite-pyrite ore, Ku-327	Polymetallic ore, Ku-865/376	Carbonate-polymetallic ore 865/349.8	Quart-carbonate vein with Cu-Bi mineralization Ku-23/1
Au, ppm	1.5	1.3	7.9	0.84	0.20	7.6
Ag	17.4 (11)	46.0 (25)	1.5 (45)	>100 (204)	>100 (133)	1.5 (1.7)
Al %	1.01	0.99	0.01	0.57	1740	0.01
As, ppm	98	188	13	3060	<10	13
B	1710	<10	<10	<10	20	<10
Ba	10	10	20	40	<0.1	20
Be	<0.5	1.8	<0.5	<0.5	<0.5	<0.5
Bi	300	8	973	19	103	973
Ca, %	0.14	4.19	4.76	4.48	7.54	5.82
Cd, ppm	2.4	3.2	2.6	184.5	137.5	0.6
Co	80	341	2	8	15	2
Cr	15	5	13	31	16	<1
Cu	>10,000	>10,000	5570	110	2930	4290
Fe, %	>50	37.80	18.60	4.95	9.75	0.62
Ga, ppm	10	<10	<10	<10	<10	<10
Hg	1	<1	5	40	15	<1
K, %	0.01	0.03	0.02	0.29	0.08	0.01
La, ppm	<10	<10	<10	10	<10	<10
Mg, %	6.38	1.16	2.57	1.88	6.13	1.14
Mn	623	548	1940	7510	6770	235
Mo	6	3	2	1	2	11
Na, %	0.01	0.02	<0.02	0.01	0.01	0.01
Ni, ppm	12	12	7	17	5	8
P	70	180	70	230	10	50
Pb	64	42	50	>10,000	>10,000	211
S, %	2.99	6.66	>10.0	6.15	9.05	0.30
Sb, ppm	<2	<2	1830	770	1150	6
Sc	2	1	<1	1	1	1
Sr	21	57	51	171	130	48
Th	<20	<20	<20	<26	<20	<20
Ti, %	0.03	0.01	<0.01	0.01	<0.01	<0.01
Tl, ppm	<10	20	10	<10	<10	<10
U	<10	10	<10	<10	<10	<10
V	22	27	1	7	1	<1
W	10	<10	<10	30	30	<10
Zn	1390	500	325	>10,000	>10,000	27

Note. Gold was determined by the atomic absorption technique. Analyst V.N. Il'ina. Parenthesized are AAS data.

Co, and Ni are less common. In some ore samples, high concentrations of Mo (4040 ppm) and B (1710 ppm) are obtained. The results of ICP-MS analysis of samples of various types of ores are given in Table 2. Siderite-magnetite and garnet-carbonate-magnetite ores are distinguished by the higher Cu, Co, Ti, V, and B contents are noted. Streaky-disseminated ores are characterized by elevated Au, Ag, As, Bi, Pb, Zn, Cd, and Hg concentrations.

There is no clear pattern of ore-metasomatic zonality in the orebodies of the Kultuminskoe deposit. The nature of distribution of gold-sulfide mineralization in magnetite ores, skarns and skarnized host rocks is most likely determined by the processes of intramineralization tectonics. Structural control of sulfide mineralization in magnetite orebodies is also established by microscopic study of ores. Gold, chalcopyrite, submicroscopic precipitates of bismuth minerals, and silver tellurides are controlled by microfolds and microdislocations of discontinuous and shear nature in cataclastically deformed magnetite aggregates (Fig. 11).

Specific features of the mineral composition of ores. Ores of the Kultuma deposit have a quite varied mineral composition reflecting the mineral assemblages and para-

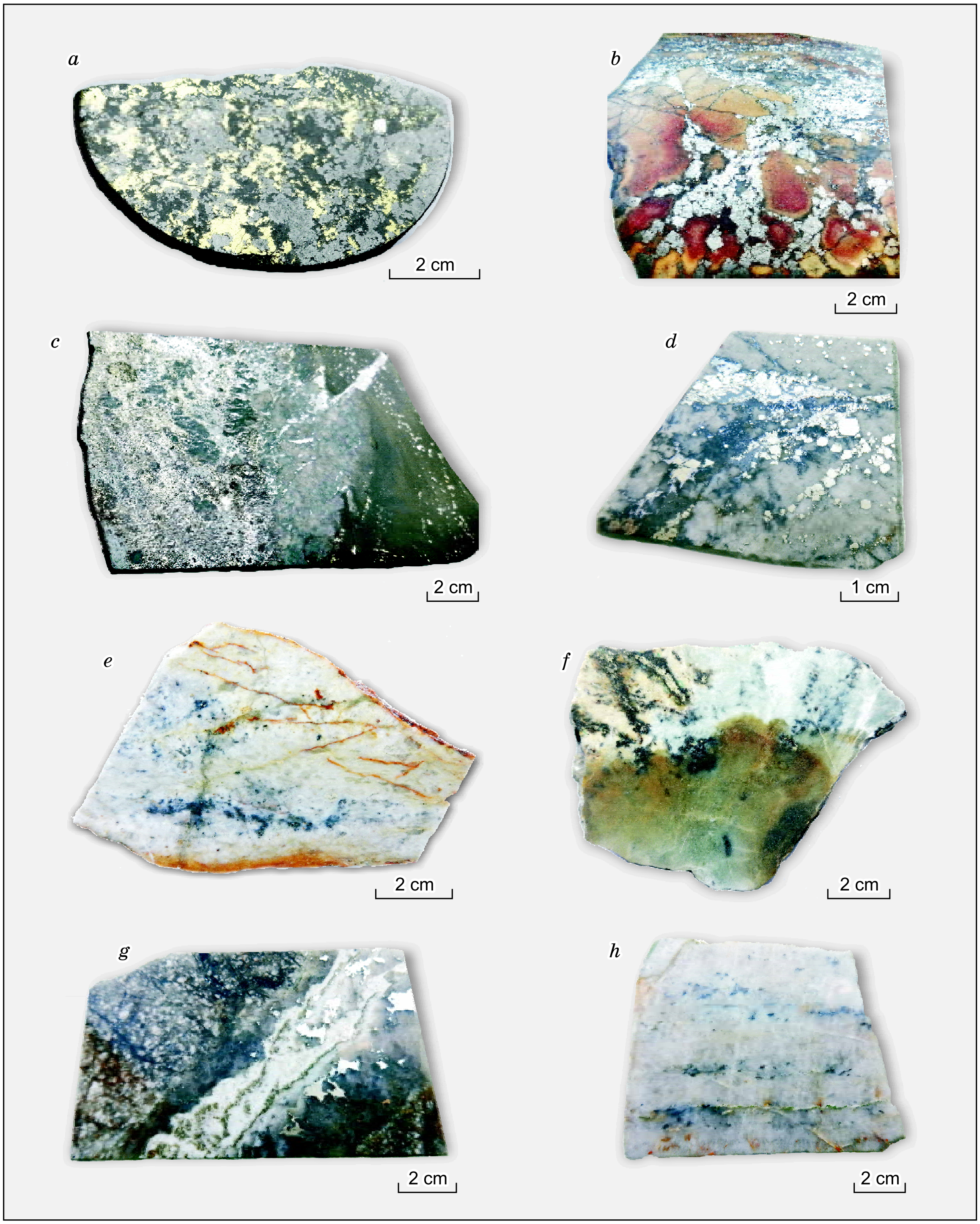

Fig. 9. The main textural-mineral types of mineralization in the Kultuminskoe deposit. *a*, Massive sulfide-magnetite ore (C-301); *b*, brecciated arsenopyrite-pyrite-dolomite ore (Ku-327); *c*, massive polymetallic ore (865/376); *d*, streaky-disseminated polymetallic ore (Ku-865/349.8); *e*, disseminated sulfide-dolomite ore (Kul-14/1c); *f*, oxidized disseminated chalcopyrite-bismuthic mineralization in dolomite with pyroxene and amphibole relics (Kul-23/1); *g*, quartz-carbonate veinlet with native bismuth impregnations in granite-porphyry (853/210.3; *h*, quartz-molybdenite vein (97/1018).

geneses of different temperatures of formation. The main, minor and rare ore and nonmetallic minerals are distinguished (Table 3). The main ore minerals are magnetite, chalcopyrite, pyrite and arsenopyrite. They make up mostly the early skarn-magnetite and hydrothermal gold-pyrite-chalcopyrite assemblages with carrolite, cubanite, bornite, and pyrrhotite. The gold-pyrite-arsenopyrite and polymetallic assemblages correspond to the medium temperature con-

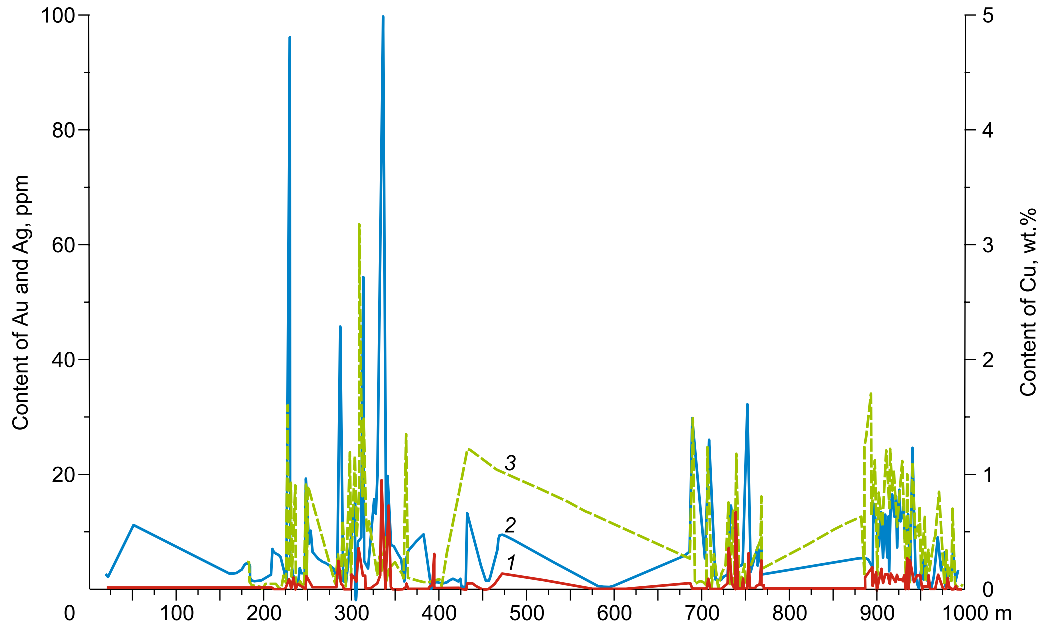

Fig. 10. The histogram of gold, silver and copper distribution based on trench No. 1 sampling data in the central part of the main ore body of the Kultuminskoe deposit (based on data of geological exploration works, 1998). *1*, Au; *2*, Ag; *3*, Cu. Geological cross section is shown in Fig. 8.

ditions of ore deposition. The final low-temperature epithermal assemblage is represented by native bismuth, native gold, hessite, and a group of Cu–Pb–Ag–Te–Bi-minerals. These assemblages often coincide in space (Fig. 11).

Below are given some characteristics of the chemical composition of separate ore and non-metallic minerals. A high-temperature ferriferous sphalerite variety, wurtzite, with 9–11 wt.% of Fe is widespread in ores of the deposit. The chalcopyrite-sphalerite and bornite-chalcopyrite exsolution structures are also characteristic. Less common is a low-temperature sphalerite variety, cleiophane, with 1.5–3.5 wt.% of Fe. The monomineral sphalerite samples contain admixtures (wt.%): Ni (0.25), Co (0.57), Cd (0.35), and Ag (0.14).

The polymetallic assemblage is characterized by presence of antimonic minerals tetrahedrite, famatinite, meneghinite, boulangerite, as well as Sb-bearing tennantite and pyrite (up to 14 and 0.8 wt.% of Sb, correspondingly). The ores also contain the Cu–Pb–Ag–Te–Bi-sulfosalt group minerals such as gladite, krupkaite, emplectite, hammarite, kobelite and unidentified minerals X and Y (Table 4). The host minerals for Ag are both silver minerals and silver-bearing sulfides and sulfosalts. Native Ag is present as submicroscopic inclusions in galena, as well as in hessite, Ag-bearing tetrahedite (20.47 wt.% Ag), tetradimite (3.65 wt.% Ag), in minerals X (11.23 wt.% Ag) and Y (9.25 wt.% Ag) and in gold (more than 40 wt.% Ag). Molybdenite and scheelite are scarce and distributed extremely unevenly in ores with average Mo and W contents of 0.0001 and 0.005 wt.%.

It should be noted that different mineral assemblages may often contain several generations of pyrite, chalcopyrite, sphalerite, arsenopyrite and gold.

Gold occurs exclusively in native form and was found in all mineral assemblages. The most productive is the early gold-chalcopyrite-magnetite assemblage. The most high-grade ores occur in the areas where they coincide with the later mineral assemblages. Gold impregnations were found in minerals of skarns, dolomite metasomatites and in ore minerals of different temperature assemblages (Fig. 11*b*, *c*, *e*, *z*). Microscopically, the bulk of gold are of a fine-grade class with a grain size less than tens of microns, rarely larger. The shape of grains is mainly determined by the structure of host medium; the most typical are elongated, isometric, rarely crystalline shapes. The bulk of the analyzed gold grains from various structural-mineral ore types is characterized by medium fineness (746–867‰), rarely by high fineness (968–1000‰). Low-fineness gold (577‰) was also found at the deposit. The impurity elements are represented by Cu (up to 1.4 wt.% in gold from the chalcopyrite-magnetite assemblage) and Hg (3.75 wt.% in gold from the polymetallic assemblage).

Sulfide sulfur isotopic composition. The fine-grained structure of ores and close structural intergrowths of sulfide minerals do not allow to characterize the isotopic composition of the main ore minerals. Only 4 samples of monomineral pyrite from various mineral types of ore and one sample of chalcopyrite were analyzed. The $\delta^{34}S$ values of pyrite from pyritized granite-porphyry, massive pyrite ore, earthy varieties from carbonate-pyrite ore, and massive arsenopyrite-pyrite-dolomite ore are (‰): 4.7, 9.4, 7.2, and 14.3, respectively. The estimated $\delta^{34}S$ value for chalcopyrite from massive chalcopyrite-pyrite-magnetite ore is +11.3‰. All sulfide sulfurs are enriched in the heavy isotope.

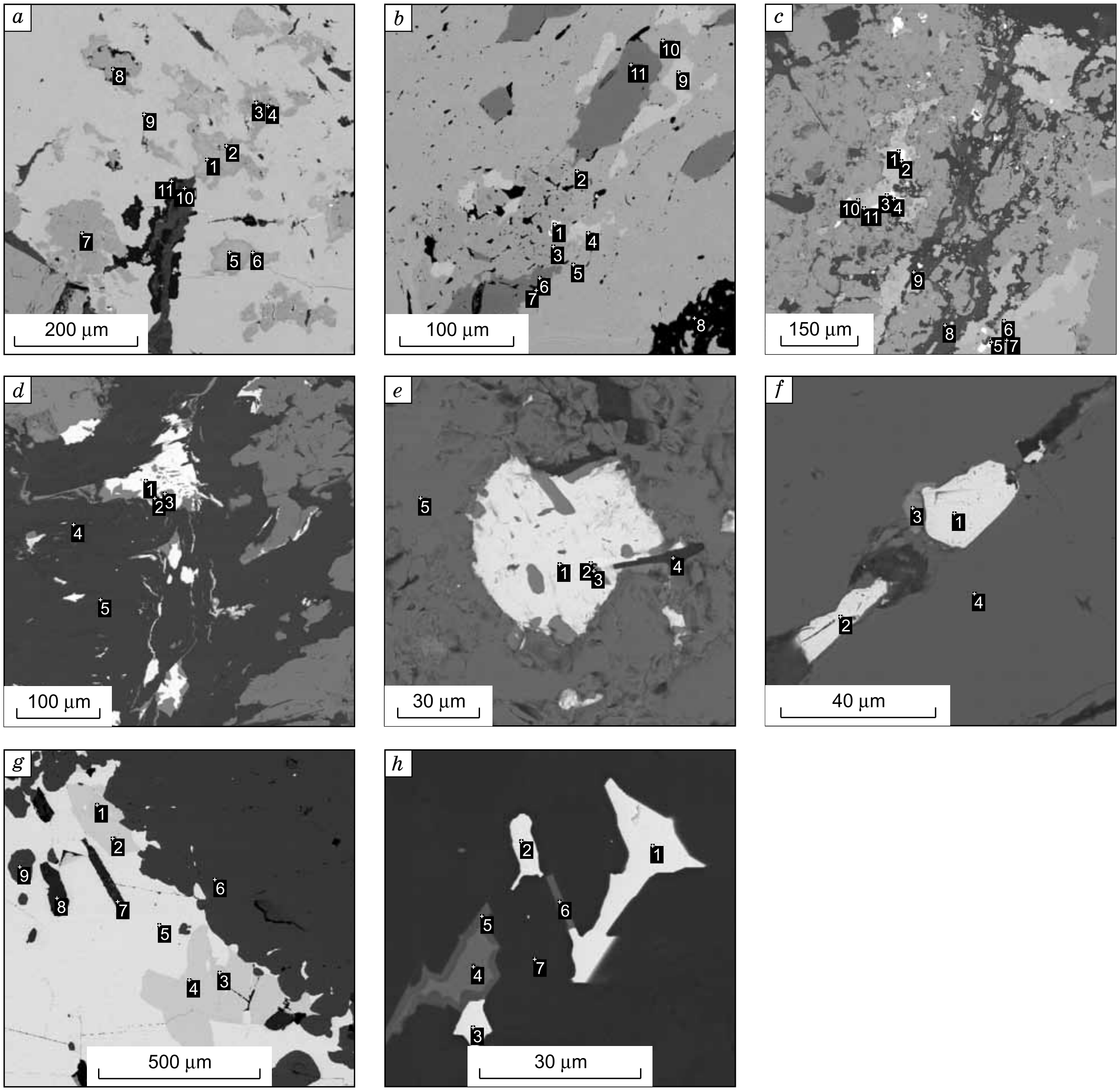

Fig. 11. Structural relationships of ore minerals in different textural-mineral types of ores. Sulfide-magnetite ore: *a*, xenomorphic separations of cubanite (1, 4, 5, 6), villiaumite (2) and Co-pyrite (3, 7, 8) in chalcopyrite (9) with chlorite (10) and quartz (11) inclusions; *b*, submicroscopic gold impregnations (1, 2) in fletcherite (3), in chalcopyrite aggregate (5, 10) with sphalerite (4–9), magnetite (6, 11) and magnesite (7, 8) inclusions; *c*, gold separation (1,5) with bismuthite (3) in emplectite (2, 4), in sphalerite (6, 11) and chalcopyrite (7, 10) aggregate with serpentine (8) и magnesite (9) inclusions; *d*, nest-like and net-like separations of bismuthite (1), Ni-cobaltite (2) and chalcopyrite (3) in chlorite (5) and fluoborite (4) aggregate; *e*, bismuthite (1) with tetradymite (2), chalcopyrite (3) and chlorite (4) inclusion in magnetite (5). Pyrite-arsenopyrite-dolomite ore: *f*, veinlet with idiomorphic gold grains (1, 2) and fahl ore (3) in pyrite (4). Sericite-quartz-carbonate-polymetallic ore: *g*, boulangerite (1, 3, 4) and meneghinite (2) in galena (5) with sphalerite (6, 9) and pyrite (7, 8) relics. Disseminated sulfide-carbonate ore: *h*, xenomorphic gold separations (1, 3) with chalcopyrite (4) and bismuth oxides (5, 6) in pyroxene (7).

DISCUSSION

Geochemical types of melts for rocks of the Kultuma pluton and dike complex. Analysis of the fractionation trends of petrogenic and trace elements suggests that three types of melts were involved in the formation of the Kultuma pluton and the associated dike complex. The predominant quartz monzonites of the pluton and quartz syenites and monzodiorites of the dike complex are probably the products of differentiation of subalkaline basic melt. A decrease in MgO, FeO, CaO, TiO_2 and P_2O_5, as well as heavy REEs, Y and Eu contents as SiO_2 increase indicates the fractionation of clinopyroxene/amphibole, plagioclase and accessory minerals, sphene and apatite. Since rocks of the pluton

Table 3. Mineral composition of ores of the Kultuminskoe deposit

Major	Minor	Rare
Ore minerals		
Chalcopyrite		Hessite Ag_2Te
Pyrite	Pyrrhotite	Tetradymite Bi_2Te_2S
Arsenopyrite	Sphalerite	Carrollite $Cu(Co,Ni)_2S_4$
Magnetite	Galena	Fletcherite $Cu(Ni,Co)_2S_4$
	Tennantite	Villiaumite (Co,Ni)SbS
	Tetrahedrite	Hodrushite $Cu_8 Bi_{12}S_{22}$
	Boulangerite	Gladite $CuPbBi_5S_9$
	Bornite	Krupkaite $CuPbBi_3S_6$
	Cubanite	Paarite $Pb_{1.7}Cu_{1.7}Bi_{6.3}S_{12}$
	Bismuthite (Bi_2S_3)	X-phase (Cu,Ag,Pb,Bi,S)
	Molybdenite	Y-phase (Cu,Ag,Bi,S)
	Hematite	Emplectite $CuBiS_2$
	Muschketowite	Hammarite $Cu_2Pb_2Bi_4S_9$
	Rutile	Meneghinite $Pb_{13}CuSb_7S_{24}$
		Famatinite Cu_3SbS_4
		Kobellite $Pb_6FeBi_4Sb_2S_{16}$
		Cobaltite (Co,Ni,Fe)AsS
		Haycockite $Cu_{16}Fe_{20}S_{32}$
		Native gold
		Native silver
		Native bismuth
		Cassiterite
		Wolframite
Barren minerals		
Diopside	Apatite	Ludwigite
Hedenbergite	Ankerite	Ascharite
Actinolite	Calcite	Fluoborite
Tremolite	Tourmaline	Fluorite
Hornblende	Garnet (andradite)	
Serpentine		
Mg-chlorite		
Fe-chlorite		
Biotite		
Phlogopite		
Muscovite		
Magnesite		
Siderite		
Dolomite		
Calcite		
Quartz		

and the dike complex form independent clusters on the variation diagrams of petrogenic (CaO) and trace (Nb, Th, etc.) elements (Figs. 4, 5), they can represent the products of differentiation of separate portions of a basic melt. The formation of granites as final products of differentiation of a subalkaline basic melt contradicts the decreased content of K_2O and the amount of incompatible trace elements (Ba, Th) in granites as compared to rocks of intermediate composition (Figs. 4, 5). These geochemical characteristics indicate that granites originated from an independent melt, probably of crustal origin. It is assumed that intrusions of the Shakhtama complex have formed in a collisional setting (Zorin et al., 1998, 2001; Spiridonov et al., 2006), therefore, the formation of granites could be related to melting of Paleozoic subduction-related volcanic rocks. The third melt type is represented by subalkaline gabbros of the dike complex which are drastically enriched in TiO_2, P_2O_5, Zr, Nb, REE and Y as compared to the monzonitoid rock group. Thus, the dike complex contains both monzodiorites which are similar in initial melt composition with rocks of the Kultuma pluton, and subalkaline gabbros which have a more enriched source and probably genetically unrelated with rocks of the intrusion.

Sources and formation conditions of rocks of the Kultuma pluton and dike complex. Low silicic acidity and increased contents of femic components and alkalis, primarily K_2O, in the predominant rocks of the pluton and dike complex indicate that they resulted from melting/differentia-

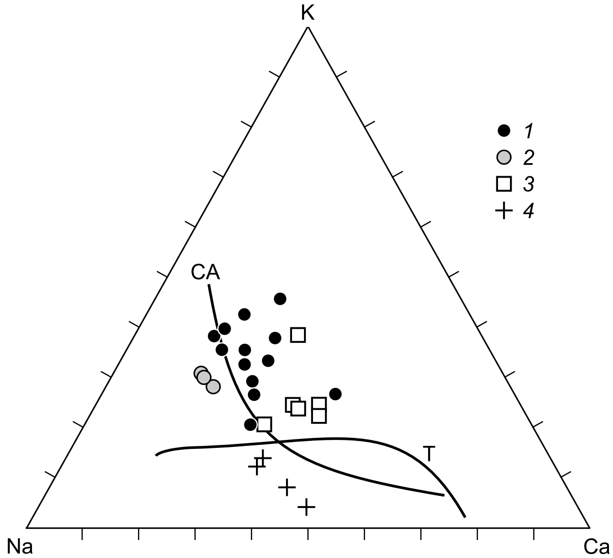

Fig. 12. The Na–K–Ca ternary diagram for rocks of the Kultuma pluton and dike complex. Kultuma pluton: *1*, quartz monzonites, quartz syenites, *2*, granites; dike complex: *3*, diorites, monzonites; *4*, the mean compositions of adakite complexes after (Smithies, 2000). Trends: CA, calc-alkaline, T, trondhjemitic.

tion of the mafic source. High concentrations of incompatible trace elements in dikes of monzodiorites and rocks of the intrusion favor the formation of parental mafic magmas from an enriched mantle source. Multielemental spectra show that subalkaline rocks of intermediate composition are characteristically enriched in Ba (up to 1200 ppm) and Sr (up to 700 ppm) and relatively depleted in Nb and Ti, which is typical of subduction-related basalts and suggests metasomatism of the mantle source affected by aqueous fluids/melts. The similarity between subalkaline rocks of the Kultuma pluton and dike complex with rocks of the subduction environments, the presence of amphibole and magnetite in their composition, as well as the fact that rocks belong to the calc-alkaline, rather than tholeiitic rock series or the magnesian type of granitoids indicates an increased H_2O activity and the oxidizing conditions of formation. The characteristic enrichment of the studied rocks in K_2O, Ba, and Sr is typical for monzonite/latite rock series, which is considered potentially ore-bearing on polymetals, Mo, W, and Au (Tauson, 1977).

Subalkaline gabbros of the dike complex, which differ from rocks of the Kultuma pluton by higher Ti, P, light REEs, Zr, and Nb contents, have probably had a much more enriched mantle source and were admittedly related to a later rift stage.

A comparison between rocks of the Kultuma pluton and dike complex and adakites. Over the last years, igneous rocks associated with large porphyry Au–Cu–Mo deposits are often regarded as analogues of adakites, which in turn are considered indicators of highly productive copper-porphyry systems (Oyarzun et al., 2001). This comparison is based on some characteristics of the trace elemental composition of rocks of the porphyry complex, most notably, elevated $(La/Yb)_n$ and Sr/Y ratios (Kovalenker et al., 2016; Zhang et al., 2017). Adakites are volcanic rocks of moderately acidic composition with a low K content (K_2O/Na_2O~0.42) (Martin, 1999). On the K–Na–Ca diagram, adakites are located in the area of trondhjemite trend, which differs from the typical calc-alkaline trend with K accumulation (Fig. 12). The K–Na–Ca proportion in adakites determines their average low Rb (30 ppm), moderate Ba (485 ppm) and high Sr (869 ppm) contents (Drummond et al., 1996). Typical features of the trace elemental composition of adakites are the depletion in heavy REEs and Y, which results in an increased $(La/Yb)_n$ (14) and high Sr/Y (68) ratios (Martin, 1999). These compositional features, in

Table 4. The chemical composition of the Cu–Ni–Co, Ag and Cu–Pb–Te–Bi–bearing ore minerals of the Kultuminskoe deposit (wt.%)

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Fe	1.01	33.03	1.32	0.8	33.09	5.84	4.24	–	–	–	–	–	–	0.74	4.8	0.56	–	0.6	0.48
Ni	5.07	–	3.47	5.34	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Co	40.02	7.01	31.96	38.39	14.25	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cu	12.95	16.48	–	13.36	0.25	22.22	38.43	–	–	0.87	0.66	1.0	4.36	4.64	19.18	6.63	1.81	9.84	10.24
Zn	–	–	–	–	–	1.82	3.39	–	–	–	–	–	–	–	–	–	–	–	–
Cd	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pb	–	–	–	–	–	–	–	–	–	1.90	1.62	6.56	13.8	19.32	–	25.94	40.72	4.46	0.7
Ag	–	–	–	–	–	20.87	1.62	62.76	3.65	–	–	–	–	–	–	–	0.14	11.25	9.63
Bi	–	–	–	–	–	–	–	–	54.68	81.07	78.09	71.38	60.14	55.64	55.79	47.89	31.99	56.36	59.23
As	–	–	42.22	–	–	–	10.43	–	–	–	–	–	–	–	–	–	–	–	–
Sb	–	–	–	–	–	26.40	14.11	–	–	–	–	–	0.47	–	–	–	6.6	–	–
Te	–	–	–	–	–	–	–	36.65	34.71	–	–	–	–	–	–	–	–	–	–
Se	–	–	–	–	–	–	–	–	1.08	–	–	–	–	–	–	–	–	–	
S	41.96	41.92	22.38	41.32	53.12	23.63	27.22	–	4.11	14.78	18.67	14.4	18.77	17.75	18.73	17.0	18.30	17.46	18.30
Total	101.01	98.44	101.35	99.11	100.71	100.78	99.41	99.74	99.02	99.35	99.58	99.18	97.72	98.09	98.5	98.02	99.56	101.38	100.16

Note. 1, fletcherite; 2, cubanite; 3, cobaltite; 4, carrollite; 5, Co-bearing pyrite; 6, tetrahedrite; 7, tennantite; 8, hessite; 9, tetradymite; 10, bismuthate; 11, cupriferous-leaded bismuthate; 12, leaded bismuthate; 13, gladite; 14, krupkaite; 15, emplectite; 16, hammarite; 17, kobellite; 18, phase X; 19, phase Y. Analyst M.V. Khlestov.

accordance with the experimental data (Rapp and Watson, 1995; etc.), suggest that adakites resulted from melting of a low-K metabasite source under high pressure conditions (~10 kbar) in equilibrium with a garnet-bearing restite with a small fraction of plagioclase.

The rocks of the Kultuma pluton and dike complex have many compositional characteristics that distinguish them from adakites. Their main and fundamental distinction is belonging to the subalkaline potassium series with a high K_2O/Na_2O ratio. Rocks of the intrusion and dike series have average K_2O/Na_2O ratios of 1.2 and 1.0, respectively. In the K–Na–Ca diagram quartz monzonites, syenites and granites are grouped around the calc-alkaline trend (Fig. 12). The increased K_2O content correlates with higher concentrations of Rb (76–213 ppm) and especially Ba (525–1218 ppm) in comparison with their average contents in low-K adakites (Rb = 30 ppm, Ba = 485 ppm) (Fig. 5*a*). In contrast to adakites (Th = 2.9–4.9 ppm), rocks of the Kultuma pluton and dike complex are characterized by elevated Th concentrations (Fig. 5*c*). These differences are due to the nature of the sources/initial melts. It is assumed that adakites of both subductional and collisional origin resulted from melting of low-K metabasites depleted by the most incompatible elements (Rb, Th), as well as MORB-type basalts with a limited proportion of terrigenous sedimentary material. On the contrary, as shown above, the initial magmas for rocks of the Kultuma pluton and monzodiorite dikes were subalkaline in nature and were related to melting of the enriched mantle source. The elevated $(La/Yb)_n$ and Sr/Y ratios in the studied rocks show their similarities with adakites. However, HREE and Y concentrations (Yb = 1.8–1.1 ppm, Y = 18–15 ppm) in the most melanocratic varieties exceed these in adakites (Yb = 0.9–0.6 ppm, Y = 9.5–6.0 ppm) (Smithies, 2000) (Fig. 5*b*), and their concentrations decrease during differentiation due to amphibole fractionation. Thus, rocks of the Kultuma pluton and the dike complex lack the typical features of adakites and were formed by differentiating the subalkaline basitic melt from an enriched mantle source, rather than melting of low-K mafic substrate under an increased pressure.

Model features and the formational type of mineralization. Gold-copper-iron-skarn, gold-polysulfide and silver-polymetallic mineralization is spatially associated with the Kultuma pluton. The main model features of the Kultuminskoe deposit are described below. Mineral assemblages are distributed zonally with respect to the pluton, which is related to endo- and exocontact alteration of the pluton and host terrigenous rocks and postmagmatic hydrothermal-metasomatic processes controlled by the reactivated deep faults after the pluton emplacement. Weak veined quartz-K-feldspar-molybdenite mineralization is manifested in the central part of the pluton. The main commercial subtabular deposits of gold-chalcopyrite-magnetite-skarn ores are confined to NE-strike zones in the eastern part of the pluton. The products of Fe–Mg metasomatism, expressed in serpentinization, phlogopitization, biotitization, Mg-chloritization and Fe–Mg carbonatization of rocks, are also confined to the NE faults. Hydrothermal-metasomatic streaky-disseminated gold-chalcopyrite-pyrite-arsenopyrite, sulphosalt-polymetallic and Cu–Pb–Ag–Te mineralization is manifested in metasomatically altered rocks in exo- and endocontact parts of the pluton, controlled by NW-strike zones. Hydrothermal veined silver-sphalerite-galenite mineralization occurs on the periphery of the intrusion, predominantly in carbonate rocks. Secondary dispersion halos of Au, Cu, Pb and Zn are confined to the pluton, while the established Au, Cu, As, and W contents in the host terrigenous rocks are two to three times higher than the clarke values. Thus, it is possible to consider the ore-forming processes in a direct spatial and temporal relation with the formation of a pluton, and the formation of various mineral assemblages in a wide temperature range. Other igneous rocks (of the Kukul'bei and the Unda complexes) occurring in the ore field, as well as the Late Jurassic basic dikes of the Nerchinskii Zavod complex, do not bear any signs of gold-sulfide mineralization.

The multistage metasomatic and ore-forming processes at the deposit were accompanied by repeated reactivation of faults, cataclasis, and plastic deformations of deposited minerals as well as spatial superposition of mineral assemblages from high-temperature skarn to low-temperature epithermal ones. A similar character of the stage mineralization and zonality with respect to the pluton was established in the large Bystrinskoe gold-copper-iron-skarn deposit located in the same metallogenic zone (Fedorova and Chernyushova, 2009; Kovalenker et al., 2016).

The typical minerals of the early high-temperature assemblage include chalcopyrite, marmatite, magnetite, pyrrhotite, cubanite, bornite, Co and Ni minerals carrollite, fletcherite, villiaumite, cobaltite, Co-pyrite while those of the medium temperature assemblage are galena, sphalerite, tennantite, tetrahedrite, and boulangerite. Epithermal Ag–Te–Bi mineralization in ores is scarce, but mineralogically quite diverse and represented by hessite, bismuthite, tetradimite, and Cu–Ag–Pb–Te–Bi minerals. Gold deposited at all stages of ore-forming process. The presence of gold of different fineness in mineral assemblages can be considered as a spatial superposition of the earlier high-grade and the later low-grade gold. The duration of gold deposition was previously considered on the example of polymetallic and gold-polymetallic deposits of eastern Transbaikalia (Vakhrushev et al., 1971), gold-sulfide-skarn deposits of the Altai–Sayan Region (Vakhrushev, 1972), and gold-bearing skarns of the Ryabinovoe deposit (Palazhchenko et al., 2005).

A specific feature of the Kultuma ore-magmatic system is the enrichment of such elements as F, Cl, B, and P, which are present as admixtures in the minerals of hydrothermally altered rocks. An essential component of ore-bearing solution is fluorine, which is present in apatite, biotite, serpentine as well as independent minerals, fluoborite and fluorite. The important role of these elements in the ore-forming processes was previously considered on the example of porphyry Cu–Mo deposits (Sotnikov and Berzina, 1993).

The weighted isotope composition of sulfur from main ore sulfides suggests the involvement of sulfate sulfur from host terrigenous rocks in the process of ore deposition. Similar values of the sulfur isotopic composition of sulfides were reported for ores of the Novoshirokinskoe, Lugiinskoe and Kochkovskoe deposits in the Gazimur metallogenic zone (Ali et al., 2014; Abramov et al., 2017).

The formational classification of the Kultuminskoe deposit is still a problem of debate, taking into account the metallogenic specificity of the Gazimur zone and spatial coincidence of Au–Cu, Au–Cu-Fe-skarn, Au-polymetallic deposits and porphyry Mo (Bugdainskoe) and porphyry Cu-Mo (Shakhtaminskoe) deposits (Sotnikov et al., 1995; Berzina et al., 2013). The deposit was previously considered as a potential object of the Au-porphyry type or as a representative of the complex porphyry Au–Cu geological-commercial type (Kharitonov et al., 2003; Khomich and Boriskina, 2011). Salikhov and Gruzdev (2013) assigned this deposit to the complex skarn-copper-porphyry type with gold. However, as it was shown in subsequent works and is indicated by our data, the deposit lacks the typical features of porphyry systems reported in (Sillitoe, 2010). According to Fedorova and Salikhov (2009), the deposit corresponds to the Fe–Cu Au–Ag-bearing skarn type. We suppose a prolonged multistage process of formation of Au–Cu–Fe skarn and streaky-disseminated medium temperature polysulfide and epithermal Ag–Te–Bi mineralization as well as iron-magnesian and silica-alkaline metasomatites, which proceeded in the background of general evolution of the Kultuma ore-magmatic system. The rocks of the Kultuma pluton are specifically related to subalkaline monzonite/latite, rather than plagiogranite (adakite) rock series. The sources of ore components are presumably magnesian monzonitoids being the products of differentiation of basic magma, and granites with a crustal source. In addition, these different sources determine the multielement nature of ores with elements inherent to both the basites (Fe, Cu, Au, Ni, Co) and granites (Mo, Pb, Zn, Ag, Sb, Bi, Te).

The Kultuminskoe deposit can be attributed to the intrusion-related gold ore (Lang and Baker, 2001) or hydrothermal-magmatic (Robert, 2001) formation type. Examples of the relation of Au–Cu and Au–Cu-skarn deposits to high-Mg alkaline magmatism are known in various regions of the world. The multistage Au-skarn deposits are spatially and temporally associated with the postorogenic high-Mg monzodiorite-syenitic intrusions of mantle origin (Mueller et al., 2008), while Au–Cu-endoskarn deposits are associated with monzodiorite-tonalite intrusions (Mueller, 2007) in Australia. Endoskarn Fe–Cu–Au deposits related to monzodiorite porphyries are also known in eastern China (Zhang et al., 2017), while Au-polymetallic deposits associated with alkaline porphyries occur in southwestern China (Li et al., 2016).

CONCLUSIONS

The Kultuminskoe deposit is situated within the Gazimur metallogenic zone in eastern Transbaikalia. Mineralization is confined to the Kultuma pluton of Middle–Upper Jurassic age, represented by subalkaline rock series varying from monzodiorites, quartz monzonites and quartz syenites to granites and dikes of monzodiorites. Dikes of Late Jurassic age are represented by subalkaline gabbro. Analysis of fractionation trends of petrogenic and trace elements suggests that monzonitoids dominating in the Kultuma pluton and dike complex formed by differentiating the subalkaline basic melt from an enriched mantle source. The rocks of the Kultuma pluton are specifically related to the subalkaline monzonite/latite, rather than plagiogranite (adakite) rock series. The sources of ore components are presumably magnesian monzonitoids being the products of differentiation of basic magma, and granites with a crustal source. As such, these different sources determine the multielement nature of ores with elements inherent to both the basic rocks and granites. It is assumed that intrusions of the Shakhtama complex have formed in a collisional setting. In contrast to rocks of the Kultuma pluton, subalkaline gabbros from the dike complex have probably had a much more enriched mantle source and were admittedly related to a later rift stage. The process of formation of Au–Cu–Fe-skarn and streaky-disseminated medium-temperature polysulfide and epithermal Ag–Te–Bi mineralization, as well as Fe-Mg and Si-alkaline metasomatites had a prolonged multistage development during the general evolution of the Kultuma ore-magmatic system. The Kultuminskoe deposit can be attributed to the intrusion-related gold ore or the hydrothermal-magmatic formation type.

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