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The Kyzyl–Tashtyg Ore Deposit of Eastern Tuva—A Standard for the Ancient Volcanogenic Formation of Pyrite-Polymetallic Ores

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Abstract—The Kyzyl–Tashtyg deposit and the ore field of the same name are included in the Kyzyl–Tashtyg ore cluster, which is located in the southeastern part of the Ulugoi structural-metallogenic zone. The geological section of the ore field consists of lower Cambrian terrigenous and volcanogenic deposits of the Tumat-Taiga and Tapsa Formations that include a homodromous sequence of early andesite-basalts transitioning to acid dacite-rhyolite rocks with widespread subvolcanic intrusions. The pyrite-polymetallic mineralization of the ore field associates spatially with a central-type volcanic structure and is localized within the "motley" unit, consisting of three lithological-stratigraphic horizons. The Kyzyl–Tashtyg pyrite-polymetallic deposit is the main ore occurrence of the ore field, which contains the main reserves of pyrite-polymetallic ores. The mineralization outcrops on the surface are 650 m in length and 60–65 m wide. Reserves of commercial ore are 12,920 mln tons with average concentrations: Pb—2.8%, Zn—10.3%, Cu—0.65%, Au—1.03 ppm, Ag—48.71 ppm. The ores have typically simple mineral compositions consisting of pyrite, chalcopyrite, sphalerite, galena and barite. Secondary minerals include enargite, hessite, sylvanite, proustsite, and native silver. Ores are classified based on the dominant mineral or groups of minerals into sulfur-pyrite (pyrite), copper-zinc (pyrite-chalcopyrite-sphalerite), polymetallic (sphalerite-galena), and barite-polymetallic (barite-sphalerite-galena) varieties. The main commercial type is represented by the copper-zinc mineralization. The widest range of impurity elements and their highest concentrations have been identified in copper-zinc and polymetallic ores, where the main mineral is sphalerite—the carrier of the largest amount of impurity elements. In these ores, commercial concentrations of gold and silver have been detected: Au—0.8; 2.3 ppm, and Ag—26; 78 ppm correspondingly. Formation temperatures of different types of ores of the deposit range from 400–305 °C to 270–150 °C. There is a pattern of decreasing formation temperatures from the sulfur-pyrite to the copper-zinc and to the barite-polymetallic ores. This pattern forms a vertical mineralization zoning from the bottom to the top of the deposit. The formation of the deposit was related to early Cambrian volcanism and included different mechanisms of ore deposition. The hill-like shape of the main ore lode with intense hydrothermal alteration of rocks in its base indicates a mineralization zone with veinlet-disseminated and massive ore structures, which indicates a hydrothermal-metasomatic origin.

Keywords: pyrite-polymetallic deposit, copper-zinc mineralization, volcanism, impurity elements, gold, fluid inclusions

INTRODUCTION

The discovery of the Kyzyl–Tashtyg pyrite–polymetallic ore field in 1946 immediately attracted the attention of geologists, and its subsequent detailed exploration yielded abundant materials for many scientific publications (Berman, 1960; Agentov et al., 1964; Berman and Agentov, 1966; Distanov et al., 1968; Zaikov, 1976; Distanov, 1977; Zaikov et al., 1981). However, in the 1990s and the following years, due to falling interest in studying sulfide deposits formation, the attention to investigations on this deposit decreased as well. Renewed interest in this ore field appeared and open quarry mining began after the government of Tuva concluded a contract with LLS Lusin—an affiliated company of the Chinese mining giant Zijin Mining Group (Fig. 1). The open-cut mining of the ore field made it possible to study it more fully and in more detail, which caused many thematic publications in the recent decade in the geological literature. Because the Kyzyl–Tashtyg field is one of the most representative among the ancient volcanogenic deposits that contain well-preserved primary features of its volcanogenic-sedimentary origin its study continues to be of high interest. This paper attempts to analyze and generalize all obtained materials from the study of the ore field with emphasis on age data and formation conditions.

GEOLOGY OF THE ULUGOY STRUCTURAL-METALLOGENIC ZONE

The Kyzyl–Tashtyg ore deposit and the Kyzyl–Tashtyg ore field are included into the Kyzyl–Tashtyg ore cluster, which is located in the southeastern part of the Ulugoi structural-metallogenic zone (Fig. 2). The Ulugoy zone extends up to ~150 km with a west-east strike, is 30–40 km wide and is bound from the south by the Kaakhem fault and from the

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Fig. 1. General view of the open-pit quarry of the Kyzyl-Tashtyg deposit.

north by the Taskyl and Azas faults. Its structure is that of a linear paleodepression filled with mainly bimodal volcanics (basalts, dacites, rhyolites) and tuffogenic-sedimentary deposits. The formation of this structure is closely related to the prolonged development of the Kaakhem deep fault. The Kyzyl–Tashtyg ore cluster, located in the southern border of this zone, is composed of volcanogenic-sedimentary deposits that are assigned to two structural levels by their composition, magmatism, dislocation and metamorphism (Lebedev, 2012a,b). Lower Cambrian volcanogenic-terrigenous carbonate deposits, whose age was confirmed by multiple finds of archaeocyatha fauna (Distanov, 1977), represent the lower level. These deposits are divided into the Lower Tumat–Taiga and Upper Tapsa (Syynak) formations. The Tu-

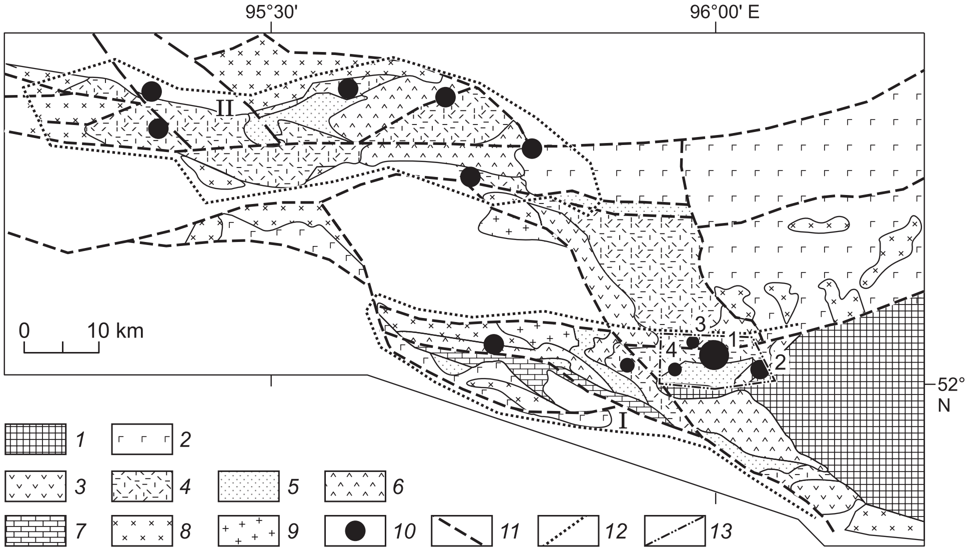

Fig. 2. Geology of the Ulugoy sulfide zone; composed by Zaikov (2006) using materials of the Tuva Geoexploration Expedition. *1*, metamorphosed volcanogenic-sedimentary Meso-Neoproterozoic deposits; *2–4*, Tumat–Taiga rhyolite–dacite–basalt complex, lower Cambrian, Aldan stage (Є$_1$tm): *2*, lower basalt unit, *3*, upper rhyolite–dacite–basalt unit, *4*, undifferentiated deposits (effusives and tuffs of basic and acid composition); *5*, *6*, Tapsa (Syynak) basalt–andesite–rhyolite complex, lower Cambrian, Lena stage (Є$_1$tp): *5*, carbonaceous–siliceous–terrigenous–volcanogenic unit, *6*, basalt–andesite–rhyolite unit; *7*, carbonate–terrigenous deposits of the Tashtyghem Formation (Є$_3$th); *8*, Tannu-Ola tonalite–diorite–granite complex (Є$_2$); *9*, Bren' granite–granosyenite complex (D$_2$); *10*, deposits and ore occurrences of pyrite–polymetallic formation (1, Kyzyl–Tashtyg; 2, Dal'nee; 3, Piritovoe; 4, Yuzhnoe); *11*, faults; *12*, outline of ore regions (I, Kyzyl–Tashtyg, II, Ottug–Taiga); *13*, outline of the Kyzyl–Tashtyg ore field.

mat–Taiga Formation is composed mainly by volcanogenic rocks with a predominance of andesite-basalt porphyries in the base of the section and their pyroclastic differentiates, and dacite and rhyolite-dacite rocks in the upper part of the section with small interlayers and lenses of sedimentary rocks. The total thickness of the formation's deposits is as high as 5 km. The Tapsa Formation rocks are sedimentary and tuffogenic-sedimentary, jasperoids, tuffs and tuffogenic sandstones with subordinate limestones, effusives and pyroclastics. The formation's thickness is ~3 km. The upper structural level, including Ordovician, Silurian and Devonian deposits consists of shallow marine terrigenous rocks represented by red sandstones, gritstones, conglomerates and remains of shallow marine fauna and flora, as well as small bodies of land subaerial volcanogenic rocks of subalkaline acid and basic composition. The deposits of the upper structural level compose mainly blocky depression structures (Ulugoi graben, Derzig-Sailyg graben, etc.).

The lower Cambrian deposits are cut by a series of small stock-like and sill-like subvolcanic intrusions that are comagmatic with the stratified volcanogenic rocks and composed of diabases and diabase porphyries, to a lesser extent by dacite porphyries and felsite–porphyries. The subvolcanic intrusions occur unevenly and usually concentrate in weakened zones. Apart from subvolcanic formations, there are also the intrusive rocks of the early Paleozoic Tannu-Ola complex with groups of acid (from plagiogranites to quartz diorites) and basic (melanocratic diorites and gabbros) rocks. Additionally, in the southern and northeastern parts of the Ulugoi structure-metallogenic zone, younger Devonian intrusions have been identified: mainly granites, plagiogranites and granite–porphyries. The development of the various stages of magmatism and endogenic metallogeny of the Ulugoy zone were mainly determined by deep faults most notably the Kaakhem fault that has been identified and characterized in detail by V.A. Kuznetsov (Pinus et al., 1955). It is represented by a series of NW and WE striking disjunctive deformations in the southern part of the Ulugoy zone. In the west, it connects with the regional Sayan–Tuva deep fault, and in the north is the series of dislocation of the Azas fault. According to Kudryavtsev and Agentov (1961), all these faults dissect the region into a series of large tectonic units, one of which contains the Kyzyl–Tashtyg ore field including the Kyzyl–Tashtyg and Dal'nee deposits.

THE KYZYL–TASHTYG ORE FIELD

The Kyzyl–Tashtyg ore field comprising the Kyzyl–Tashtyg and Dal'nee deposits and a number of ore occurrences (Pereval'noe, Piritovyi Kar, Yuzhnoe, Vodopadnoe) associates with the volcano-tectonic depression 4 × 12 km in size on the SE flank of the Ulugoi structure (Fig. 2). The ore field is controlled by fault zones of sublatitudinal and NW strike and has a rather complex geology due to a combination of volcanotectonic, plicative and block structures.

The geology of the ore field is determined by the lower Cambrian terrigenous-volcanogenic deposits of the Tumat-Taiga and Tapsa (Syynak) Formations (Fig. 3). Within the field, the Tumat–Taiga Formation includes three different units (subformations) (Zaikov, 1976; Distanov, 1977). The lower unit mainly consists of lavas and lava breccias of basaltic andesites, often with spherical jointing. In its upper part, there are individual horizons of dacite porphyry lavas several tens of meters thick with a consistent homogeneous porphyry texture. The total thickness of these deposits reaches 1600 m. Upsection there is a complex sequence—the "motley" unit according to Berman (1960), represented by mainly dacite porphyries interlayered with basalt and basaltic andesites porphyries, tuffogenic formations of basic and acidic composition, tuffites and coaly-siliceous slates. These deposits are ore-bearing for the main ore deposits of the field and are characterized by a wide occurrence of subvolcanic intrusions. In the east of the field, this unit contains more sedimentary rocks represented by coaly-siliceous slates, carbonaceous siltstones with sandstones interlayers, black carbonaceous limestones, limestone breccias and marmorized limestones up to 150 m thick. The total thickness of this unit is 600–800 m. The upper part of the Tumat–Taiga Formation consists of basalt porphyries that compose a consistent layer 500 m thick. The Tumat–Taiga deposits are overlaid by the Tapsa Formation deposits with an angular (10°–15°) unconformity, which is most completely represented in the southern part of the ore field. This formation consists mainly of terrigenous-sedimentary deposits with interbeds of volcanogenic rocks of rhyolite–dacite, andesite and basaltic andesite composition. The terrigenous-sedimentary component of this formation is made up of argillaceous and siliceous–argillaceous shales, jasperoids, tuffogenic sandstones and outwashed lithocrystalloclastic tuffs mainly of acidic composition. Thus, in the lower Cambrian section of the Kyzyl–Tashtyg ore field the composition of volcanic rocks changes upsection from monotonous basaltic andesites to contrasted volcanogenic rocks with distinct manifestations of acidic and basic differentiates. Along with stratified volcanogenic formations, subvolcanic intrusions also widely occur in the field: sills, stocks and necks with explosive breccias. These are divided into five groups by composition: (1) dacite porphyries; (2) diabase and diabase porphyrites; (3) rhyolites and rhyolite–dacite porphyries of volcanic vent facies; (4) quartz diabases and gabbro–diabases; (5) explosive breccias of basalt porphyries (Distanov, 1977; Lapin, 1979). Judging by their position, petrographic and petrochemical affinity, the first two groups of subvolcanic bodies are comagmatic with the stratified volcanogenic deposits of the Tumat–Taiga Formation. The third group of vent facies rhyolite and rhyolite–dacite porphyries are comagmatic with the acidic deposits of the Tapsa Formation. The quartz-diabases and gabbro-diabases emplaced as stock-like and sill bodies at the final stage of the early Cambrian volcanism and are intruded only by explosive (automagmatic) breccias of basalt porphyrites.

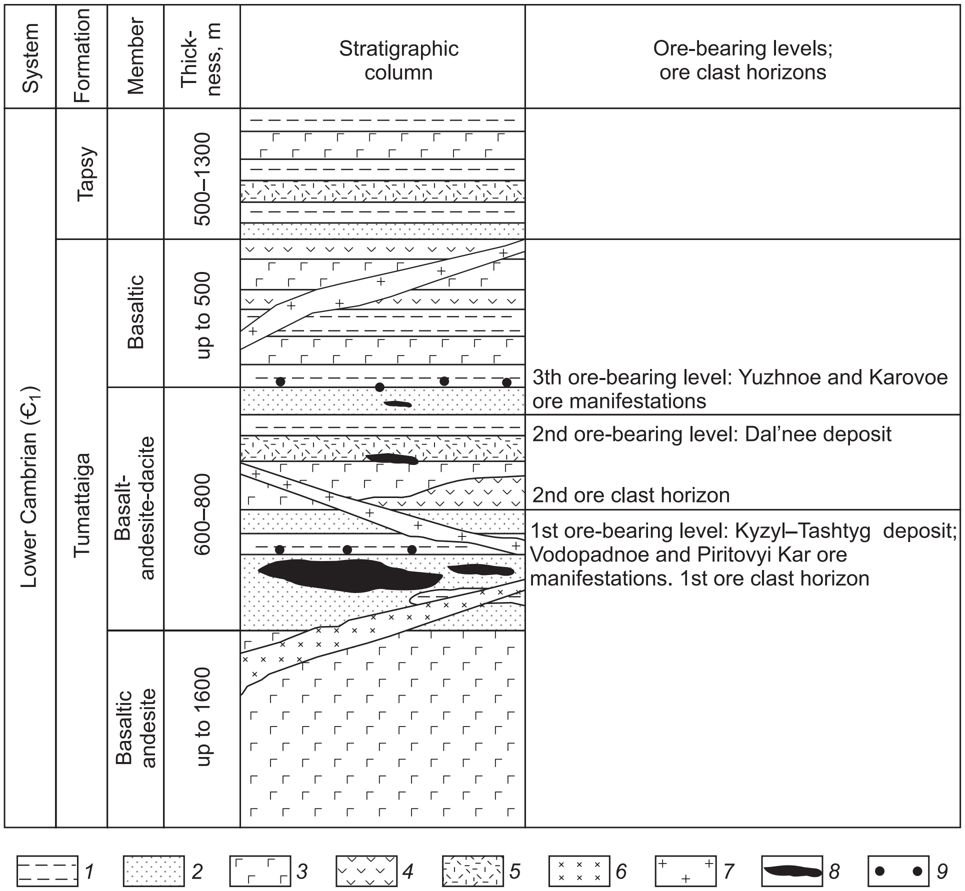

Fig. 3. Stratigraphic column of the Kyzyl–Tashtyg ore field. Composed using (after Berman, 1966; Zaikov, 2006). *1–5*, lower Cambrian ($\mathrm{Є}_1$tm) volcanogenic-sedimentary deposits of the Tumat–Taiga ($\mathrm{Є}_1$tm) and Tapsa ($\mathrm{Є}_1$tp) Formations: *1*, coaly-siliceous and carbonaceous-argillaceous-siliceous siltstones; *2*, volcanomictous sandstones and dacite tuffs; *3*, amygdaloidal basalts and basic tuffs; *4*, basaltic andesites and tuffs of intermediate composition; *5*, acid lavas and tuffs. *6*, *7*, subvolcanic bodies ($\mathrm{Є}_1$): *6*, dacitic, *7*, rhyolitic; *8*, ore bodies of pyrite-polymetallic composition.

All studied lower Cambrian volcanogenic and subvolcanic rocks of the ore field belong to the homodromous series of a differentiated basalt–andesite–dacite formation (Table 1, 2). The composition of the effusive rocks in the section changes from basalts and basaltic andesites to dacites and rhyolite–dacites. Regarding alkali composition, all rocks have a distinct sodium specialization. The absolute potassium content rarely exceeds 2% and, in most samples, does not reach 1% with sodium at the same time averaging 3–5%. Most rocks are supersaturated in silica, including the acid, intermediate and basic differentiates. There is a notably increased calcium oxide content in feldspars, and the acidic variations are supersaturated in alumina. Regarding the ratio of SiO_2 and sum of alkali, the Kyzyl–Tashtyg deposit basic rocks belong to the normal alkalinity series, and are tholeiitic according to the $FeO/(MgO–SiO_2)$ ratio. On a TiO_2–K_2O diagram the effusives fall in the field of back-arc basin basalts (Simonov et al., 1999). Studies of basaltic melts in homogenized melt inclusions showed that their chemical compositions are more acidic in comparison with origin rocks. Higher deviation patterns are were determined for melt inclusions from andesitic quartz, which are analogous to rhyolites. Ion probe determinations of the ore element contents in these acid rhyolites showed high content of copper (408–3227 ppm), and REE patterns are close to that of the Kurile–Kamchatka rhyolites, which can indicate their island arc origin (Gas'kov et al., 2009; 2008). Homogenization temperatures of inclusions correlate well with the basicity of the rocks. Higher homogenization temperatures (1085–1210 °C) have been determined in clinopyroxenes of basalts from the "sub-ore" unit; slightly lower ones (1130–1190 °C) in basaltic andesites of the "supra-ore" unit; and they do not exceed 920–1150 °C in quartz from andesite-basalts of the ore-bearing unit.

The pyrite–polymetallic mineralization of the ore field is spatially connected to a central-type volcanic structure and subvolcanic intrusions. Stratigraphically it is localized in the middle "motley" unit, forming three lithological-stratigraphic horizons, which are distinguished by the appearance of volcanogenic-clastic rocks that reflect interruptions in volcanic activity (Berman and Agentov, 1965). The lower horizon is associating with caldera deposits and includes the main ore bodies of the Kyzyl–Tashtyg deposit (Fig. 3). The second horizon corresponds to the Dal'nee deposit and is

Table 1. Chemical composition (%) of the lower Cambrian stratified volcanogenic rocks of the Kyzyl–Tashtyg ore field (Distanov, 1977)

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O	P_2O_5	S	LOI	Total
Andesite, basaltic andesite and basalt porphyrites of the lower unit of the Tumat–Taiga Formation														
63.00	0.34	14.74	0.5	2.43	0.07	3.72	7.42	4.92	0.38	n.a.	0.06	0.15	2.84	100.57
60.28	0.15	13.51	2.92	7.62	0.10	2.30	3.03	4.45	3.70	0.27	0.05	n.a.	2.21	100.59
47.63	0.19	15.73	2.16	8.16	0.12	7.71	7.63	4.31	0.13	0.15	0.03	n.a	5.18	99.13
51.68	1.11	15.38	5.85	7.33	0.27	4.78	5.69	3.68	0.27	0.18	0.21	n.a	3.12	99.55
38.50	0.43	14.65	1.09	6.61	0.17	7.57	8.35	2.32	0.84	0.23	0.07	n.a	18.73	99.56
44.20	0.25	13.71	2.52	6.92	0.07	6.71	12.23	4.45	0.10	0.16	0.04	n.a	8.23	99.59
Dacite and rhyolite–dacite porphyries of the middle unit of the Tumat–Taiga Formation														
71.21	0.08	13.36	0.50	3.01	0.03	0.69	2.30	5.19	2.53	n.a.	0.04	n.a.	1.29	100.23
71.18	0.32	13.93	0.52	3.00	0.06	1.06	1.62	3.91	2.86	n.a	0.10	0.06	0.84	99.46
68.44	0.38	14.37	2.39	2.02	n.f.	1.74	1.64	5.26	1.99	n.a	0.14	n.a.	1.16	99.53
Acid tuffs and basaltic andesite porphyrites of the upper unit of the Tumat–Taiga Formation														
71.96	0.29	9.79	4.06	3.24	0.07	1.57	1.24	5.53	0.39	n.a.	0.11	n.a.	1.32	100.27
71.79	0.24	14.10	3.51	1.51	0.17	0.25	1.11	3.91	0.91	n.a	0.07	0.24	2.46	100.26
71.82	0.24	12.88	4.68	0.22	0.08	2.18	0.27	4.91	0.78	0.22	0.11	0.15	1.72	100.38
71.24	0.41	13.03	1.66	4.48	0.08	1.45	0.86	4.33	0.36	0.61	0.093	n.a.	1.78	100.25
70.40	0.40	13.35	0.83	4.43	0.05	3.5	1.22	0.96	2.24	n.a.	0.07	n.a	2.8	100.25
47.11	0.07	15.94	2.35	8.45	0.02	6.27	6.02	3.77	0.42	0.38	0.77	n.a	8.13	99.70
46.20	0.65	17.23	5.82	5.16	0.14	6.22	10.45	3.42	0.27	n.a.	0.14	n.a	4.24	99.94
Tuffs of rhyolite–dacite composition of the Tapsa Formation														
65.11	0.30	12.89	1.06	4.05	n.f.	2.04	4.38	4.62	0.88	0.09	0.10	n.a.	4.76	100.28
69.08	0.38	14.38	0.76	4.24	0.13	0.91	0.68	5.66	0.93	0.22	0.07	n.a	1.82	99.16

Note. n.a., Not analyzed; n.f., not found; LOI, loss on ignition.

associating with the middle part of the unit's section, while its upper part contains the Yuzhnoe ore occurrence that marks the third ore-bearing horizon. In addition, the ore field, which are of specific formations, and represented by sulfide-carbonaceous deposits and siliceous-ferrous sediments. The sulfide-carbonaceous deposits have a sedimentary and diagenetic nature and are widespread in the whole section of the ore-bearing sequence, indicating general reducing conditions of sedimentation (Kuzebnyi et al., 2001). Sulfides from these formations are represented by crystalline and framboidal pyrite, rarely – sphalerite. Siliceous-ferrous sediments, according to Zaikov (2006), are the products of low-temperature hydrothermal activity of the hyaloclastic halmyrolysis type described in detail at the Uralian deposits in (Maslennikov, 1999). They have been identified on two horizons of the ore-bearing unit. In the unit's lower part, composed of lavas, agglomerate breccias and hyaloclastites of basaltic composition, the siliceous-ferrous sediments form lens-like and sheet-like bodies up to 30–50 m long and 0.3–0.6 m thick. In the upper part of the ore-bearing unit, these deposits have been identified in the bottom of the main ore lode. In addition, they have been determined in the bottom of the ore-clastic horizon in the Pyritovyi Kar (western part of the ore field). The thickness of the lenses is 0.4–1.5 m, length: 5–7 m. In these ferrous-siliceous formations, Terleev et al. (2014) have identified a significant diversity of Cambrian biota, including monocytes, cyanobacteria colonies and sponges spicules, which, judging from the existence of fluid inclusions, developed in close proximity to the ore-forming system of the Kyzyl–Tashtyg deposit, and were strongly altered by hydrothermal solutions. Biota also occurred in non-lithified sediments hosting the sulfide Kyzyl–Tashtyg deposit, that is to say, in zones of activity of hydrothermal ore-forming systems that are close in characteristics to present-day “black smokers” on the ocean floor.

Most of the ore deposits of the Kyzyl–Tashtyg ore field are spatially related to hydrothermal-metasomatic rocks, whose formation is also related to volcanogenic-hydrothermal processes and preceded or accompanied the mineralization. The distribution of the pyrite-polymetallic mineralization on several stratigraphic horizons is indicative of the multistage character of the ore formation process. Hydrothermal-metasomatic rocks are also distributed on various levels and are closely related to ore deposits, forming mainly their underlying zones. Zones of near-ore altered rocks the sheet-like form of the deposits and exceed them up to 1.5–2 times in size. The entire diversity of hydrothermal-metasomatic alteration of ore-bearing rocks manifested in various states of silicification, sericitization, chloritization,

Table 2. Chemical composition (%) of the subvolcanic and intrusive rocks of the Kyzyl–Tashtyg ore field (Distanov, 1977)

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O	P_2O_5	S	LOI	Total
Rhyolite–dacite porphyries														
78.46	0.06	10.03	n.f.	3.03	0.03	1.04	1.08	4.72	0.24	0.03	0.16	n.a.	1.11	99.99
76.81	0.02	11.66	n.f.	3.03	0.04	0.6	0.63	5.39	0.6	n.f.	0.11	n.a.	0.8	99.69
Dacite porphyri**es**														
72.64	0.15	11.03	0.93	2.8	0.25	1.79	1.82	4.04	0.42	0.19	0.08	n.a.	3.75	99.89
73.68	0.25	12.29	0.56	3.59	0.19	2.29	0.45	3.15	1.35	0.16	0.1	n.a.	2.15	100.21
Diabase and diabase porphyrites														
54.57	1.65	14.09	6.49	7	0.18	2.68	4.36	4.88	1.27	n.f.	0.61	0.04	2.34	100.16
47.28	1.77	14.83	4.57	10.77	0.32	3.77	5.54	3.98	0.06	n.f.	0.96	n.a.	6.8	100.65
46.16	1.45	16.25	4.43	8.93	0.15	6.71	8.26	3.27	0.64	n.f.	0.43	0.1	3.56	100.34
53.04	0.57	12.1	4.84	4.31	0.18	8.27	9.32	2.23	n.f.	0.3	0.11	0.01	4.31	99.59
46.64	0.05	16.26	1.71	10.25	0.17	7.69	8.69	3.37	0.12	0.1	0.3	n.a.	4.36	99.71
46.08	0.06	14.72	2.94	8.16	0.18	6.65	10.76	3.03	0.36	0.2	0.26	n.a.	6.34	99.74
Gabbro–diabases														
46.94	0.83	22.64	3.64	6.21	0.12	2.93	11.11	1.34	2	n.f.	0.16	0.06	1.72	99.70
47.36	0.95	19.38	4.25	6.25	0.2	3.15	8.47	4.34	0.72	0.35	0.17	n.a.	4.14	99.73
47.17	0.85	20.06	4.38	7.02	0.27	3.38	8.56	3.2	1.58	n.f.	0.17	0.1	3.67	100.41
47.78	0.75	18.15	5.82	6.78	0.2	3.2	8.61	2.64	1.91	n.f.	1.15	0.07	2.6	99.66
54.34	0.5	12.43	3.73	5.03	0.03	6.4	5.29	1.65	0.1	0.29	0.01	1.01	8.77	99.58
53.5	0.7	15.21	2.53	7.47	0.02	7.96	1.21	3.85	0.4	0.36	0.01	n.a.	6.42	99.64
37.15	0.78	16.55	5.15	4.31	0.06	7.09	10.23	3.6	0.9	0.29	0.02	1.48	12.1	99.71
41.57	0.58	13.03	4.87	3.02	0.08	6.4	10.83	5.27	0.05	0.36	0.09	1.35	12.1	99.60

Note. n.a., Not analyzed; n.f., not found; LOI, loss on ignition.

talcification, dolomitization, and carbonatization (Ontoev, 1960; Berman and Agentov, 1965; Kovalev, 1968; Distanov, 1977; Kuzebnyi et al., 1989, 1990). The widest aureoles of altered rocks are developed in root areas and often have a zonal structure. The central part of the alteration zones usually have quartzites, quartz–sericite and quartz–chlorite metasomatites, and the peripheral zones have less altered, variously sericitized and chloritized variations. Visually, the metasomatites are characterized by a variety of textures, including oolitic, porphyric, breccia-type and breccia-like–reticulate that reflect the multistage formation. Often, in the base of copper–sulfide and chalcopyrite–sphalerite ore bodies there are products of magnesian metasomatosis represented by talc–carbonate and chlorite metasomatites. Thermal and X-ray structural analysis indicates that chlorite is of the magnesian alumosilicate variation of the prochlorite–corundophyllite and pennine–clinochlore groups (Kuzebnyi et al., 2001), and dolomite dominates calcite in the carbonates. During the superposition of the later stages of the hydrothermal process onto the earlier ones, the picture becomes more complicated. Often, altered rocks contain vein and veinlet-disseminated pyrite and chalcopyrite–pyrite mineralization, less often—veins of polymetallic and barite-polymetallic ores. To a lesser extent the ore fields contains post-ore hydrothermal formations associating mainly with fractures of northwestern strike and represented by quartz–carbonate, baryte–carbonate, baryte veinlets, sometimes with galena dissemination. Post-ore carbonates have a mostly dolomite–calcite composition.

LOCALIZATION FEATURES OF MINERALIZATION ON THE KYZYL–TASHTYG ORE DEPOSIT

The Kyzyl–Tashtyg pyrite–polymetallic deposit is the main ore body of the field, in which the main reserves of pyrite–polymetallic ores are concentrated. The extent of ore outcrops is 650 m with a width of 60–65 m. The commercial ore reserves are 12,920 mln tons with average contents of: Pb—2.8%, Zn—10.3%, Cu—0.65%, Au—1.03 ppm, Ag—48.71 ppm. The metals reserves in the ore are: zinc—1294.8 thous. tons; lead—202.3 thous. tons; copper—82.3 thous. tons; gold—15.4 tons and silver—730.6 tons; cadmium—2.2 thous. tons; selenium—0.67 thous. tons (Lebedev, 2012a,b; Voitov and Veti, 2012). The ore nodes associate with the juncture area of sublatitudinal and northwestern striking structures and are located in a tectonic zone 200 m long and 130–260 m thick. They all have a strike of 260°–300° and dip south with angles of 60°–80° (Fig. 4). The deposit's mineralization is localized in the rocks of the "motley" unit of the Tumat–Taiga Formation, which is represented by alternating dacite porphyries, basalt and basaltic andesite porphyrites with tuffogenic formations of basic and acid composition, tuffites and coaly-siliceous shales (Fig. 3). Over 40 lens-like and tabular bodies have been determined on the deposit. They are located on three stratigraphic horizons of this series. The most valuable is the main sulfide lode (Fig. 5), which has a lens-like shape 300–500 m across and 100 m thick. It is composed of mainly pyrite and copper–pyrite ores with subordinate pyrite–polymetallic differentiates. At the base of the main ore lode, tube-like bodies have been identified perpendicular to the bedding of rocks and ores, and probably corresponding to ore conduits. These are cylindrical bodies with diameters from 10–12 cm to 25–30 cm and over 1 m in length. In the cut of the outcrop, they have a rounded or flattened ellipsoidal form emphasized by an outer siliceous fringle up to 1–2 cm thick (Fig. 6). The inner structure of these bodies is made up of sulfide minerals, mainly pyrite, less often sphalerite, chalcopyrite, and even less often galena that forms small inclusions in pyrite. Analysis of the mineral's composition revealed the most distinctive regular alterations only in sphalerite. In this mineral, from both border zones to the center there is an increase of copper and iron content and a decrease of zinc contents, which indicates the significant role of copper and iron in the hydrothermal solutions during the early mineralization stage. By their parameters, these bodies are close to the "black smokers" sulfide structures that form in present-day hydrothermal fields of oceanic back-arc basins (Herzig et al., 1993; Simonov et al., 2003).

A series of smaller lens-like and sub-tabular ore bodies has also been identified on the deposit—they have thicknesses up to 40 m and are located in the top and on the flanks of the main ore lode. Generally, the ore bodies have distinct and abrupt boundaries with the host rocks, a sublatitudinal strike and northward dip at angles 50°–70°. The inner structure of the ore bodies is typically highly complex due to the combinations of various texture and mineral types of ores. However, in general, in the section of the deposit and specifically in the main lode, there is a clear unidirec-

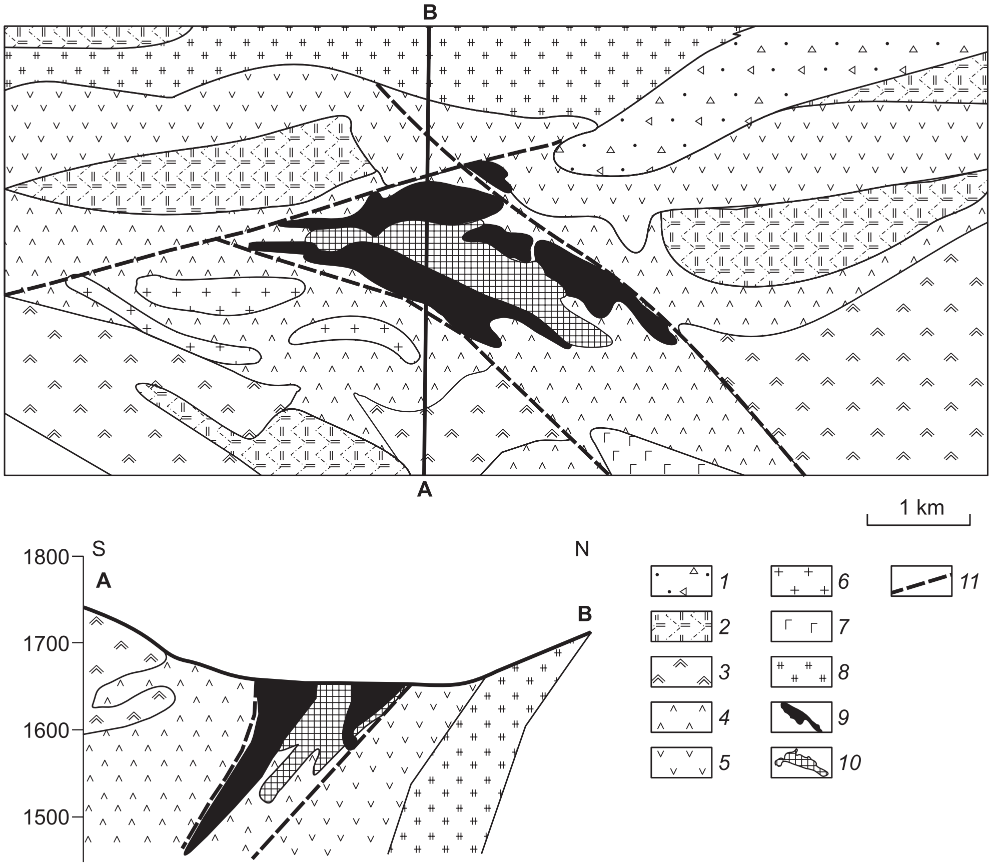

Fig. 4. Schematic geological map and section of the Kyzyl–Tashtyg deposit. Based on data of the Tuva Geoexploration Expedition (Lebedev, 2012a,b). *1*, sands, gravel, conglomerates (Q); *2*, Tapsa Formation (Є$_1$tp): acid and basic lavas and tuffs, sandstones, siltstones and limestones; *3–6*, Tumat–Taiga Formation (Є$_2$tm): *3*, basaltic andesits and basalt porphyrites with interlayers of coaly-siliceous siltstones (upper unit); *4*, alternation of dacite porphyries, basaltic and basaltic andesits porphyrites with tuffogenic formations of basic and acid composition, tuffites, coaly-siliceous and coaly-siliceous-carbonaceous shales (middle ore-bearing unit); *5*, lavas and lava breccias of basaltic andesits, often with spherical jointing (lower unit); *6*, subvolcanic bodies of rhyolite and rhyolite-dacite porphyries; *7*, subvolcanic bodies of diabase porphyrites; *8*, hydrothermal-metasomatic rocks of quartz-sericite, quartz-chlorite-sericite composition, quartzites; *9*, *10*, ores: *9*, polymetallic, *10*, sulfur-pyrite; *11*, faults.

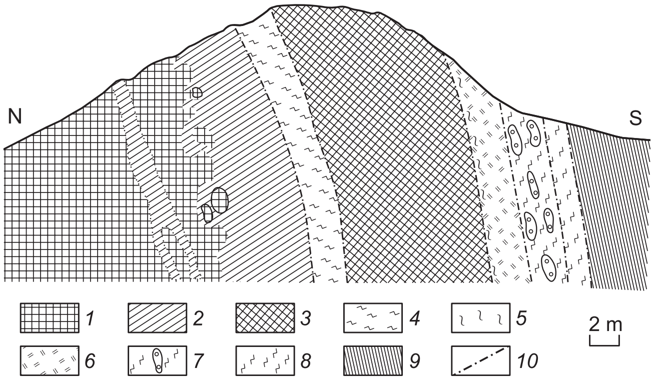

Fig. 5. Structure of the main ore lode of the Kyzyl–Tashtyg deposit (drawing from the surface (Distanov, 1977)). *1–3*, ores: *1*, sulfur–pyrite, *2*, copper–zinc, *3*, polymetallic and baryte–polymetallic; *4–9,* hydrothermal-metasomatic rocks: *4*, talc-dolomite, *5*, chlorite and chlorite–sericite, *6*, mixed composition; *7*, boudinaged quartz–sericite formations with pyrite impregnation, *8*, sericite and quartz–sericite, *9*, quartzites and siliceous shales; *10*, faults.

Fig. 6. Tube sulfide bodies in a silica shell—ore conduits in the base of the main ore body.

tional zoning that manifests from bottom to top in pyrite and copper–pyrite ores with polymetallic and baryte–polymetallic ones (Fig. 5). According to V.V. Zaikov (2006), the ores located at the top of the section have twice as much baryte and lead contents than in lower ones, which is clearly observed through the change in the Zn : Pb ratio varying from 7 : 1 in the bottom to 5 : 1 in the top. Also from bottom to top, the ores contain less copper, which is reflected in Zn : Cu ratios changing from 5 : 1 to 15 : 1.

MINERALIZATION TYPES ON THE DEPOSIT

As was shown above, the ores of the Kyzyl–Tashtyg deposit are characterized by diverse mineral composition resulted from the multiple stages of the volcanogenic mineralization process, as well as to the regular development of the pyrite mineralization process in time with the formation of various compositions of ore associations. Additionally, the superposition of late ore generations onto the early ones resulted in their recrystallization and the formation of different structural-textural and mineral types of ores. The main ore minerals of the deposit are pyrite, chalcopyrite, sphalerite, galena, baryte and subordinate enargite, hessite, sylvanite, proustsite, native silver (Berman, 1960; Kudryavtsev and Agentov, 1961; Berman and Agentov, 1965; Kovalev, 1966, 1968; Distanov, 1977; Kuzebniy et al., 1989, 2001; Zaikov, 1991, 2006; Melekestseva et al., 2007; Kuzhuget et al., 2015, 2016). By the dominance of one or the other main ore mineral or their group, most researchers identify sulfur–pyrite (pyrite), copper–zinc (pyrite–chalcopyrite–sphalerite), polymetallic (sphalerite–galena), and baryte–polymetallic (baryte–sphalerite–galena) variations. It should be noted that the formation of these types of ores occurred generally in this particular order, which is evidenced by their division during tectonic motions accompanied by fragmentation of ores and the formation of breccia textures. The copper–zinc mineralization generally determines the commercial mineralization profile of the deposit. The ores are characterized by massive, veined-disseminated, layered-banded and breccia structures and crystalline-grained, colloform and relict-framboidal texture. The ores underwent relatively weak metamorphism and regenerative alterations. However, in zones of tectonic dislocations there is noticeable foliation and cataclasis with the formation of brecciated and cataclastic structures, and the contacts of diabase dikes display recrystallization with the formation of granoblastic textures.

Sulfur–pyrite ores are widespread on the deposit and are mostly present in its lower horizons. They form the lower part of the main ore lode, where they form a stock-like body with sizes 50 × 320 m in plan view. These ores also form small individual bodies within the ore-bearing unit and occur as clasts (Fig. 7) in ore-clast horizons in the northern part of the deposit (Zaikov, 2006). Moreover, the pocket-veined pyrite-mineralization is widely developed in root zones below the ores, in hydrothermal-metasomatic rocks. The sulfur–pyrite ores are mainly composed of pyrite with chalcopyrite admixtures and, to a lesser extent, sphalerite and galena. Barren minerals include quartz, sericite, chlorite, talc, and carbonaceous matter. The ores are characterized by massive, veined-disseminated, layered and layered-banded structure (Fig. 8, 1), and by fine-grained, relict nodular and framboidal textures. Massive pyrite ores are mainly aggregates of various grain sizes with zonal grains and various morphology – zonal-banded, festoon, nodular, rosette etc. In zones of tectonic dislocations and dynamometamorphism, the ores underwent plastic deformations, cataclasis, foliation and boudinage. In zones of hydrothermal activity of the late mineralization stages, there is a recrystallization of pyrite ores with superposed sphalerite, chalcopyrite and galena in the form of cutting microveinlets.

Copper-zinc ores of the Kyzyl–Tashtyg deposit are the main commercial type and represent most of its value.

Fig. 7. Ore breccia composed fragments of ores and host rocks.

There, ores are widely distributed on the deposit and form both independent veins and lens-like bodies (thicknesses 15–90 m), and also veined and veinlet-disseminated zones 1–5 m thick among the sulfur–pyrite ores, forming transitional zones between sulfur–pyrite and polymetallic variations (Fig. 5). Copper-zinc ores are characterized mainly by massive, spotted, layered, breccia-like and veinlet-disseminated structures (Fig. 8, 2) and are composed of a fine-medium-grained sulfide aggregate with a hypidiomorphic, emulsive, corrosion and crystalloblastic textures. The ores are typically simple in mineral composition, represented mostly by chalcopyrite, sphalerite, pyrite, with minor amounts of quartz and dolomite forming pockets and impregnations up to 1 cm. Quantitative ratios of main ore minerals change drastically, and according to the dominant ones, we can identify sphalerite–pyrite–chalcopyrite and chalcopyrite–sphalerite types, which often have a different spatial affinity. The ores composed mainly of the sphalerite-pyrite–chalcopyrite association (copper–sulfide) tend to occur in the lower parts of ore bodies, including in the main ore lode, and also form veined and veinlet-disseminated zones at significant depths, marking ore conduit root zones. The ores are dominated by chalcopyrite (up to 60%) and pyrite (up to 40%), with subordinated sphalerite with contents less than several percent. Other than the main ore minerals, the ores contain galena (PbS), clausthalite (PbSe), tellurobismuthite (Bi_2Te_3) (Kuzhuget and Ankusheva, 2016). Barren minerals include dolomite, quartz, chlorite, and calcite. In contrast, the chalcopyrite-sphalerite types occur mostly in the upper part of the main ore lode and occupy an intermediate position between the pyrite ores and the polymetallic and baryte–polymetallic ores. Less often, these ores form individual bodies in the upper horizons of the deposit. In the ores sphalerite–chalcopyrite proportions vary, but in general, sphalerite dominates and occupies about 50–70%. The ores also typically contain pyrite, less often – galena and in subordinate quantities—tennantite-tetrahedrite. Barren minerals include quartz, dolomite, calcite and chlorite.

The polymetallic and baryte–polymetallic ores of the deposit have a subordinate role and have been identified in the top of the main ore lode (Fig. 5), as well as in the cabs between copper–zinc ore bodies. They rarely form angular and rounded 1–8 cm fragments of pyrite–sphalerite, baryte–sphalerite–pyrite and barite composition in the ore-clasts horizon (Zaikov, 2006). The ores are characterized mainly by disseminated, veinlet-disseminated, massive and less often breccia-like structures (Fig. 8, 3 and 4), and allotriomorphic-grained, nodular and emulsive textures. The main ore minerals of polymetallic ores are sphalerite, galena, chalcopyrite, and pyrite; secondary ones are tennantite, less often – tetrahedrite, and sometimes gold (electrum) and silver minerals – cervelleite (Ag_4TeS), acanthite (Ag_2S) (Kuzhuget and Ankusheva, 2016). Barren minerals are dominated by carbonates (calcite, ankerite, dolomite, siderite), as well as quartz, sericite, albite and baryte. Ores containing 30% baryte are classified as baryte–polymetallic type, which in addition to the above mentioned minerals contains more native gold, silver, as well as rarer sulfides and tellurides – pearceite ($Ag_{15}Cu_2As_2S_{11}$), rucklidgeite ($PbBi_2Te_4$), and tellurobismuthite (Bi_2Te_3) (Zaikov, 2006). The main minerals of these ore types – galena and sphalerite form close intergrowths and have mainly a fine-grained structure and an allotriomorphic-grained texture with grain sizes ranging from tenths of millimeters to rarely 1 mm. Sphalerite forms small, sometimes twinned grains, usually without emulsive inclusions of chalcopyrite that are typical for sphalerites from copper–zinc ores. Secondary minerals, such as tennantite and tetrahedrite, are more widespread in baryte–polymetallic ores in xenomorphic segregates together with galena and baryte, often in association with native gold, often forming small drop-like segregates of electrum (up to 0.1 mm) in tennantite.

GEOCHEMICAL CHARACTERISTICS OF ORES AND ORE MINERALS

In addition to the main ore components (Cu, Pb, Zn, Ba) the pyrite–polymetallic deposits are known to contain a wide range of impurity elements: Mn, As, Sb, Bi, Cd, In, Ge, Se, Te, Co, Ni, Au and Ag (Herzig et al., 1993; Gas'kov et al., 2001, 2005; Vikent'ev, 2004). The main concentrators of these elements are the main ore minerals – sphalerite, galena, chalcopyrite, and they sometimes form individual mineral phases. The same is true for the Kyzyl–Tashtyg deposit. Analysis of its main ore minerals (Table 3) demonstrates that sphalerite always contains Fe ranging from tenths of percent to 2.13%. There are elevated concentrations of Mn, Cd, Ag, and concentrations close to detection limit level (0.01%) of Ge, Te, In, and Au. Galena has elevated contents of As, Sb, Bi, and Ag, and to a lesser extent – Cd, and Tl. Chalcopyrite has high concentrations of Mn, Cd, and Ag. The mineral most sterile in impurity elements is pyrite, in which only insignificant contents of As, Co, Ag, and Au

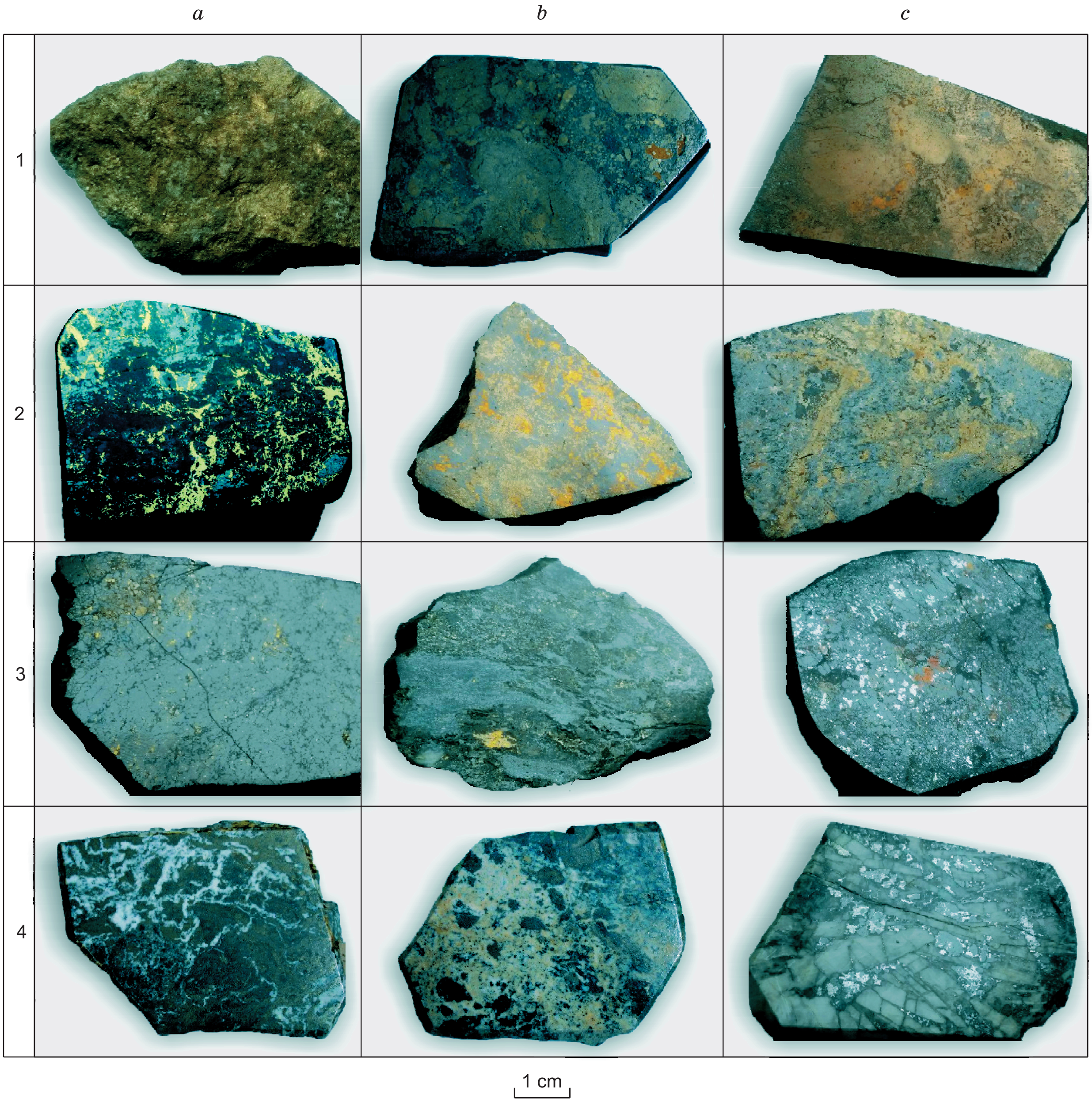

Fig. 8. Mineral and texture types of ores of the Kyzyl–Tashtyg deposit (half-scale). 1, sulfur–pyritic ores of massive (*a*), breccia-like (*b*) and spotted (*c*) texture; 2, copper–zinc ores: pocket-disseminated (*a*), massive-spotted (*b*) and striated (*c*) texture; 3, polymetallic ores of massive (*a*), banded (*b*) and pocket-disseminated (*c*) texture; 4, baryte–polymetallic ores: spotted-breccia-like (*a*), pocket (*b*) and disseminated (*c*) texture.

have been identified. Levels of impurity elements concentrations in the main ore minerals also determine the geochemical specifics of the mineral types of the ores. Thus, the widest range of impurity elements and their highest concentrations have been determined in copper–zinc and polymetallic ores, where the main mineral is sphalerite – the most impurity enriched mineral. At the same time, the significant content of galena in polymetallic ores explains the higher concentrations of Ag, Tl, Bi, Sb, and As in them, and the existence of chalcopyrite and pyrite in copper–zinc ores indicates high Mn and Co contents. In contrast, sulfur–pyrite ores, composed mainly of pyrite, typically have a limited range and low content of impurity elements.

Ores of the Kyzyl–Tashtyg deposit have been shown to contain commercial contents of gold and silver. Gold reserves are estimated approximately to be 15 tons, and silver ~700 tons, with average contents of Au—1.03 ppm and Ag—48.71 ppm. Because of this, Kuzebnyi et al. (2001) even determined a special gold–sulfide–quartz stage in the formation of the gold ore mineralization, even though it is known, that elevated gold contents in sulfide deposits of the entire world are their typical feature and are related to the

Table 3. Content of the main elements (%) and impurity elements (ppm) in the main ore minerals and in various types of ores of the Kyzyl–Tashtyg deposit

Element	Sphalerite	Galena	Chalcopyrite	Pyrite	Sulfur–pyrite ore	Cu–Zn Ore	Ba–Pb–Zn ore
	(12)	(3)	(5)	(3)	(15)	(19)	(14)
Fe	0.21 – 2.13 0.59	n.f.	31.5 – 32.0	46.5–47.3	n.a.	n.a.	n.a.
Cu	n.f.	n.f.	33.5 – 35.7	n.f.	0.36	0.95	0.70
Zn	61.8 – 66.2	n.f.	n.f.	n.f.	1.87	13.3	10.48
Pb	n.f.	83.9 – 87.6	n.f.	n.f.	0.11	0.36	2.8
S	32.4 – 33.1	13.0 – 13.5	32.9 – 33.5	52.4–53.3	39.6	27.3	19.5
Ba	n.a.	n.a.	n.a.	n.a.	0.30	1.7	8.5
Mn	10 – 1200 200	30 – 60 50	50 – 600 300	n.f.	n.f.	800 – 2800 1600	100 – 1500 840
Co	n.f.	n.f.	0.1 – 5 1	50 – 200 100	40 – 500 160	40 – 200 26	3 – 15 6
Ni	n.f.	n.f.	n.f.	1 – 10 5	0 – 9 5	n.f.	1 – 7 4
Cd	1600 – 2900 2400	10 – 500 80	1 – 1000 300	n.f.	19 – 200 80	90 – 1000 312	800 – 1700 1200
As	n.f.	100 – 2000 900	1 – 100 40	10 – 200 70	30 – 700 240	100 – 5000 2800	300 – 7000 3100
Sb	n.f.	300 – 2000 1100	1 – 30 6	n.f.	10 – 150 26	10 – 500 100	20 – 1500 230
Bi	n.f.	8 – 200 120	1 – 10 5	n.f.	0 – 20 9	1 – 100 15	7 – 200 50
Ge	1 – 50 10	n.f.	n.f.	n.f.	0 – 10 3	0 – 7 2	1 – 10 3
In	0.1 – 36 17.0	n.a.	0.6 – 8.0 4.3	n.a.	0 – 15 4	0 – 19.5 6.9	0 – 21.5 9
Tl	n.f.	10 – 250 50	n.f.	n.f.		n.f.	3 – 20 7
Te	5.9 – 27.5 14.75	n.f.	15 – 34 24.6	n.f.	0 – 100 24	0 – 100 15	0 – 20 5
Se	n.f.	Up to 14.38%	n.f.	n.f.	0 – 400 70	0 – 700 160	0 – 200 70
Ag	5 – 200 86	200 – 300 230	5 – 300 140	1 – 10 7	0 –30 4	24 – 77 26	7 –300 78
Au	0.03–3.6 1.26 (3)	0.43(1)	0.06 – 4.3 2.01(4)	0.03 – 4.8 1.68(6)	0.02 (19)	0.8 (28)	2.3 (44)

Note. Gold contents in ores are given according to data of group samples from the Tuva expedition. Values in brackets indicate the number of samples. Bold font indicates the main elements, above the line is the values range, below it—the mean composition.

formation of these ores (Herzig et al., 1993; Gas'kov et al., 2001, 2005, 2006; Moss et al., 2001; Kovalev et al., 2004; Vikent'ev, 2004). Gold and silver contents in the ores of the deposit are extremely uneven and different in various kinds of ores. According to data obtained from the bulk samples from the Tuva expedition, mean content values of Au and Ag correspondingly are 0.8 ppm and 26.0 ppm, and their highest contents have been determined in polymetallic (baryte–galena–sphalerite) ores—2.3 ppm and 78.0 ppm. Gold and silver contents vary significantly event in a single ore type, which is clear from results of grab samples analyses from ores of different types (Fig. 9). In the main ore minerals, Au contents have generally close values, and Ag contents are different (ref. Table 3). By its composition, the gold is typically of low fineness. Data of X-ray measurements on a Camebax-Micro analyzer shows that in the native phases, contents of Au itself vary between 51.24% and 61.62%, Ag—36.25–45.71%, which indicates a predominance of low fineness of gold (electrum) in the ores (Table 4).

The isotopic composition of sulfur from the sulfides of the Kyzyl–Tashtyg deposit ores was described in detail in our work (Kovalev et al., 2000), as well as in the works of

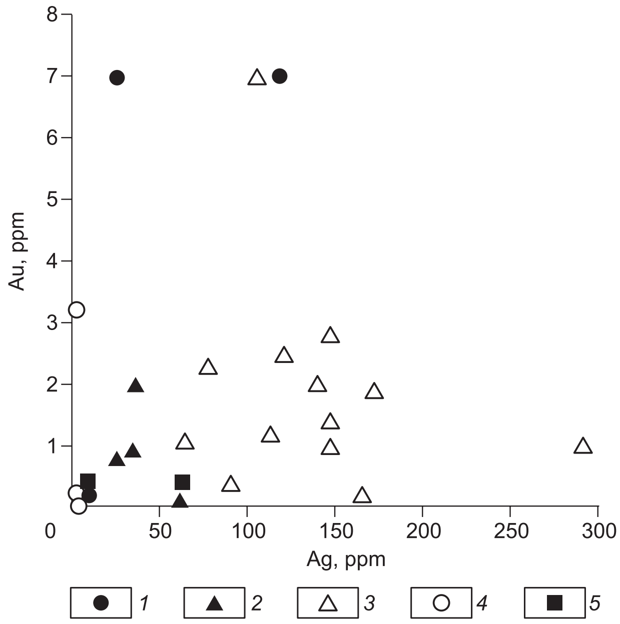

Fig. 9. Gold and silver content in ore grab samples of the Kyzyl-Tashtyg deposit. *1–5*, ore: *1*, pyrite–chalcopyrite, *2*, chalcopyrite–sphalerite, *3*, baryte–galena–sphalerite, *4*, pyrite, *5*, baryte–pyrite.

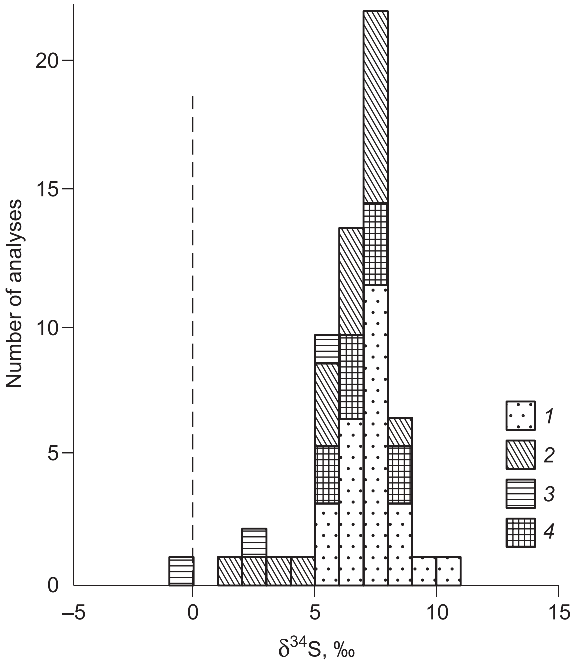

Fig. 10. Isotope composition of sulfur from the main sulfide minerals of the Kyzyl–Tashtyg ores. *1*, pyrite; *2*, sphalerite; *3*, chalcopyrite; *4*, galena

Kuzebnyi et al. (1991, 2001). The sulfur from the sulfides has a stable heavier composition and quite low variation of δ^{34}S (Fig. 10). Approximately 90% of analyzed samples fall into a rather narrow range of δ^{34}S from +5.0 to +9.00‰. The mean value of δ^{34}S from the sulfur of sulfides of the deposit is +6.4‰, and that of sulfates (barite) +28.7‰. The isotopic composition of sulfur (δ^{34}S) from the sulfides of the main ores is similar to that of sulfides from ore fragments in the ore-clasts horizon, and well as of sulfides from the veinlet-disseminated pyrite–chalcopyrite mineralization of root zones, measuring +6.8‰ for pyrite and +7.6‰ for chalcopyrite. In general, for the Kyzyl–Tashtyg ore field, a stable increase in the weight of sulfur is noted from the lower ore-bearing horizons to the upper ones (Kuzebnyi et al., 1991), which is probably related to the increase of the fraction of exogenous sulfate sulfur from seawater during mineralization.

PHYSICO-CHEMICAL CONDITIONS AND PARTICULARITIES OF ORE FORMATION

Studies of physical-chemical conditions, and in particular the *PT*-parameters of ore formation of the Kyzyl–Tashtyg deposit were performed by many researchers during the en-

Table 4. Gold composition (%) in ores of the Kyzyl-Tashtyg deposit (Kovalev et al., 2004)

Ore	No. sample, grain	Au	Ag	Hg	Cu	Total
Polymetallic	K-155, 1	55.22	44.48	0.0	0.0	99.70
	K-155, 2	49.77	50.41	0.04	0.0	100.22
	K-155, 3	56.22	44.97	0.13	0.02	101.34
	K-155, 4	58.38	42.15	0.01	0.01	100.55
Baryte–polymetallic	KT-L4, 1	61.62	39.36	0.01	0.0	100.99
	K-24, 1	54.63	45.71	0.0	0.26	100.60
	K-24, 2	60.93	38.51	0.03	0.01	99.48
	K-24, 3	51.96	48.13	0.07	0.0	100.16
	KT588, 1	61.12	36.25	n.a.	0.50	97.87
	KT588, 2	52.49	45.17	n.a.	0.53	98.18
	KT588, 3	56.36	41.55	n.a.	1.15	99.06
	KT588, 4	56.34	41.67	n.a.	1.77	97.78
	KT588, 5	51.24	44.92	n.a.	2.14	98.30

tire history of its investigation (Berman et al., 1965; Kovalev, 1966; Distanov, 1977; Kaleev, 1988; Simonov et al., 1999; Kuzebniy et al., 2001; Gas'kov et al., 2006, 2008; Melekestseva et al., 2007; Simonov and Kotlyarov, 2013; Kuzhuget et al., 2015; Kuzhuget and Ankusheva, 2016). Various methods were used for this goal, including homogenization, decrepitation, isotope thermometry, and various mineral geothermometers and geobarometers.

According to the gas-liquid inclusion homogenization method from various authors, in vein quartz from the ores, the formation temperatures of sulfur–pyrite ores vary as 400–305 °C. Inclusions in pyrite decrepitate mainly in the temperature interval of 300–200 °C, rarely 400 °C. The pressure of the mineralization fluid forming sulfur–pyrite ores of root zones was 850 atm. (Kuzebnyi et al., 2001). According to data of fluid inclusion studies in quartz by homogenization, the formation temperatures of copper–zinc ores vary in the range 280–243 °C (Melekestseva et al., 2007). Similar temperature conditions were established for polymetallic ores—300–250 °C (Berman and Agentov, 1965) and 300–180 °C (Kovalev, 1966). For baryte–polymetallic ores, the homogenization temperatures of fluid inclusions in barite were 270–150 °C (Simonov et al., 1999; Simonov and Kotlyarov, 2013). Data from the electrum–sphalerite geothermometer, based on a determination of the composition of native gold (atomic quantity of Ag in gold) and of ferruginosity (*X*FeS) of sphalerite associating with, it indicate that their formation temperatures were 250–183 °C (Kuzhuget and Ankusheva, 2016). As the presented data show, the formation temperature of various ore types of the deposit is in the range from 400–305 to 270–150 °C. We determine a regular decrease of formation temperatures from sulfur–pyrite ores to copper–zinc and baryte–polymetallic ones, which distinctly corresponds to the vertical ore zonation. The highest formation temperatures (400–305 °C) have been determined for sulfur–pyrite ores developed in root parts of the deposit. Copper–zinc ores located between sulfur–pyrite and polymetallic ores formed at temperatures 280–243 °C, polymetallic ones – in the interval 300–162 °C, and baryte–polymetallic variations developed in the upper horizons of the deposit and on the flanks of ore bodies formed at temperatures 250–183 °C. The vertical paleotemperature gradient was 12 °C per 100 m on the flanks of the deposit and 29 °C per 100 m in the central zone (Kaleev, 1988). The most abrupt decreases in temperatures are in the upper horizons of the deposit, where highly concentrated mineralization formed as rich massive ores. Data of cryometric studies show that the salinity of solutions decreased in this direction. Sulfur–pyrite ores formed from solutions with salinity of 7–10 wt.% of NaCl-equiv. (Kuzhuget et al., 2015; Kuzhuget and Ankusheva, 2016). NaCl sharply dominates the composition of the solutions with insignificant admixtures of KCl and Na_2SO_4. During the formation of copper–zinc ores the salinity of the hydrothermal solution was 3.0–8.5 wt.%, and for barite-polymetallic ones—3.0–5.2 wt.% of NaCl-equiv. (Simonov et al., 1999). Higher salts concentrations (up to 10 wt.%) and the presence of potassium in the solutions, from which sulfur–pyrite ores formed on the early stage of mineralization, probably, corresponded to the primary composition of the deep magmatic fluid. During the formation of baryte–polymetallic ores on the final mineralization stage, the composition of hydrothermal solutions corresponded more to that of seawater.

The data obtained from thermobarogeochemical studies show regular changes in the physical-chemical parameters during the formation of various ore types of the Kyzyl–Tashtyg deposit, which indicates a single stage of the mineralization process related to cyclic development of the early Cambrian volcanism.

The question of the deposition mechanism of the Kyzyl–Tashtyg deposit ores is still a matter of considerable debates. B.I. Berman (Berman, 1960; Berman, Agentov, 1966) attributed the early pyrite ores to be of the exhalative-sedimentary type, and the copper–zinc and polymetallic ones to later hydrothermal-metasomatic types. A close interpretation is shown in (Kuzebnyi et al., 2001), where three genetic types of mineralization are determined in the deposit at various stages: sulfur–pyrite volcanogenic-sedimentary, pyrite–polymetallic hydrothermal-metasomatic and baryte–polymetallic hydrothermal. Kovalev (1966) and Distanov (1977) proposed that all ores of the deposit formed in hydrothermal-metasomatic processes caused by the emplacement of subvolcanic intrusions in the Cambrian. Zaikov (1991, 2006) disagreed and considered the main mass of the deposit's ores as volcanogenic-sedimentary, and only the root zones ores to have formed by hydrothermal-metasomatic processes. However, all researchers agree that the formation of the deposit was related to early Cambrian homodromous volcanism developing on the territory of the Kyzyl–Tashtyg ore field with the formation of stratified lavas and subvolcanic bodies from basic to acidic composition. Unfortunately, the age data obtained in recent years by Gusev (2011) for igneous rocks of the Kyzyl–Tashtyg ore field complicated the understanding of this process. The early Cambrian (510 ± 14 Ma) U–Pb age obtained for zircons from rhyodacites is in good agreement with the early Cambrian age of sedimentary rocks of the Tumat–Taiga and Tapsa formations determined from archaeocyatha fauna (Distanov, 1977). At the same time, the age of zircons from the so-called "intra-ore" dacite–porphyry dike that supposedly cuts sulfur–pyrite ores, which are overlaid by copper–zinc ores, corresponds to the Early Ordovician (476 Ma) and indicates that the copper–zinc ores are post-Ordovician in age. Zaikov (2006) described fragments of copper–zinc and baryte–polymetallic ores in the ore-clasts horizon at the base of the series that overlaps the ore-bearing horizon, which suggests that these ores existed and were being destroyed in the early Cambrian. The relationship between the mineralization and the early Cambrian volcanism is also manifested in the close connection of ore bodies with products of this volcanism, the association of the main ore lodes to synvolcanic structures, the stratification of ore lodes, and their zonal distribution in the section and lack of magmatic formations in the overlying terrigenous deposits (O–D). The early Cambrian volcanogenic source of ore elements is indicated by elevated concentrations of copper (325–1028 ppm) determined in acid melt of inclusions that exceed clark values 30–100 times (Gas'kov et al., 2006). At the same time, the existence of veined copper–zinc mineralization in the dike, whose age was determined as Ordovician, is probably related to the regeneration of galena–chalcopyrite–sphalerite mineralization as more mobile in comparison to pyrite during the emplacement of the dike in the ore horizon.

As for the ore deposition mechanisms, we can state with assurance that the above described ore deposition mechanisms described above took place during the formation of the deposit. The hill-like morphology of the main ore lode with intense hydrothermal alteration of rocks in its base indicates its hydrothermal and hydrothermal-sedimentary genesis at the bottom of a marine basin. The occurrence of tube-like ore bodies in the root part of the ore zone, their veinlet-disseminated and massive structures point to a hydrothermal-metasomatic formation.

The formation of aureoles of hydrothermally altered rocks in the hanging part of ore lodes, which contradicts the hydrothermal-sedimentary formation of ores at a seafloor, is related to the multistage discrete development of volcanism and hydrothermal mineralization. The latter involves the infiltration of mineralization solutions of the later stages through already formed ore lodes and overlying strata, changing their composition and structural appearance. The multiple stages of the mineralization process are supported by the unidirectional zonation of the ore zone represented by the change from bottom to top of the section of sulfur-pyrite and copper–pyrite ores into polymetallic and baryte–polymetallic ones, sometimes separated by barren interlayers. Considering all the above data, we can conclude that the formation of commercial lodes of pyrite–polymetallic ores of the Kyzyl–Tashtyg deposit took place on the final stages of the early Cambrian volcanism in close paragenetic relation with subvolcanic intrusions. The appearance of the multistage volcanism process with the intrusion of subvolcanic bodies not only accommodated the mineralization but also caused its destruction with the formation of ore-clasts horizons.

There is still no consensus on the paleogeodynamic setting, in which the volcanogenic processes took place and the Kyzyl–Tashtyg deposit formed. Distanov et al. (2006) connected the formation of the deposit with Cambrian island arc settings. Zaikov (2006) believes that the development of pyrite-bearing zones of Tuva took place in rifts of the Sayan–Tuva back-arc basin. According to Simonov et al. (1999), on a $SiO_2/100–TiO_2–Na_2O$ diagram the clinopyroxenes of basalts from the ore field fall into the field of island arc tholeiites, and on a (Ti + Cr)–Ca diagram they correspond to back-arc basin settings. The paleotectonic position of the Kyzyl–Tashtyg pyrite–polymetallic deposit is linked by some authors (Ilyin, 1982; Belichenko and Boos, 1988) to the paleorift zone of the Tuva–Baikal lineament, which was emplaced on the flank of the covered microcontinent in conditions of mature continental crust. According to our data (Gas'kov et al., 2006) obtained from studying melt inclusions in quartz from dacite, the REE pattern configuration in the inclusion melt is generally similar to their configuration of the rhyolites from the Kurile–Kamchatka island arc, which can indirectly point to island arc formation setting.

CONCLUSIONS

The generalization and analysis of the materials obtained for the Kyzyl–Tashtyg deposit allowed us to identify and specify its main features.

1. The Kyzyl–Tashtyg deposit is related to early Cambrian volcanism and spatially associates with a central type volcanic structure. The genetic relationship of the mineralization and volcanism is indicated by the affinity of the main ore lodes to synvolcanic structures, the close link of mineralization to products of this volcanism, the stratification of ore lodes among lower Cambrian volcanogenic sedimentary rocks of the Tumat–Taiga Formation, and the existence of Cambrian biota (monocytes, cyanobacteria colonies and sponges spicules) in ferrous–siliceous hydrothermal formation of the ore horizon.

2. The volcanism process developed in stages and produced homodromous stratified volcanogenic and subvolcanic bodies whose composition varied from basalts and basaltic andesites to dacites and rhyolite–dacites. All rocks of the differentiated basalt–andesite–dacite formation have a clearly manifested sodium specialization.

3. The formation of commercial ore lodes of the deposit took place on the final stages of the early Cambrian volcanism and was paragenetically related to subvolcanic intrusions. The multistage character of the volcanism and subvolcanic bodies were responsible for the formation of a multilevel mineralization as well as its partial destruction with the formation of ore-clasts horizons.

4. Ore deposition mechanisms were diverse and included a hydrothermal-sedimentary process with the emplacement of the main ore lode at the floor of a marine basin, as well as hydrothermal and hydrothermal-metasomatic genesis with the emplacement of veinlet-disseminated ores and tube-like ore bodies in the root area of the mineralization zone.

5. Ores of sulfur–pyrite, copper–zinc and baryte–polymetallic composition are identified in the deposit. Formation temperatures of different types of ores are in the range between 400–305 °C and 270–150 °C. There is a noticeable decrease in emplacement temperatures from the sulfur–pyrite to the copper–zinc and to the baryte–polymetallic ores, which form a vertical mineralization zoning.

6. The widest range of impurity elements and their higher concentrations are in copper–zinc and polymetallic ores, where the main mineral is sphalerite—the carrier of the larg-

est amount of impurity elements. The highest concentrations of Au (2.3 ppm) and Ag (78 ppm) have been determined in the baryte–polymetallic ores. In contrast, the sulfur–pyrite ores typically have a limited range of impurity elements and their low contents.

7. According to various researchers, the development of pyrite-bearing volcanism took place in Cambrian island arc or the back-arc settings.

The described characteristic of the Kyzyl–Tashtyg deposit show that despite its early Cambrian age it preserved the features of its volcanogenic genesis and can be used as a reference object for studying the ancient volcanogenic hydrothermal pyrite formation. Many of its genetic particularities are similar to those of Devonian pyrite deposits of Southern Urals and Rudny Altai (Seravkin, 1986; Gas'kov, 2015), and have close traits with volcanogenic deposits of Australia (Large, 1992), Japan (Halbach et al., 1993) and present-day pyrite-polymetallic formations of the Pacific and Atlantic oceans (Grichuk, 2000).

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