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FAHLORES FROM THE KVARTSITOVYE GORKI HYPABYSSAL GOLD–ANTIMONITE DEPOSIT (NORTH OF CENTRAL KAZAKHSTAN)

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The new data on mineral assemblages, evolution, macro- and microelement composition of fahlores of the Kvartsitovye Gorki plutonogene hydrothermal gold deposit, the less deep one in the North Kazakhstan gold-ore province, is given.
Studied fahlores are stoichiometric by chemical composition, their crystals are often zoned; the smooth change of chemical composition form zone to zone is characteristic. Fahlores are poor by Bi, Te, Se, Tl, Cd, Sn; contents of Au, Pb, Ni, Co, Ge, and In in them are below detection limits of analysis.
Fahlores of the productive assemblage are the most diverse. The earlier fahlores are enriched by mercury, especially in the less deep ore body IV (to 7 wt %). In fahlores of late generations of productive assemblage the contents of mercury is low in tens times. Evolution of fahlores of the productive assemblage in the industrial ore bodies I and IV is different: in the ore body IV, from early to late generations the contents of silver and antimony increase; in deep-penetrating ore body I, from early to late generations the relative content of antimony decreases and the silver contents increase. Just among the late generation of fahlores, in ore body I, argentotennantite occurs.
8 tables, 2 figures, 8 references.

Fahlores, $(Cu^{1+},Ag,_{Tl,Au})_{10}$ $(Zn,Fe,Cu^{2+},Hg,Cd,Pb,Mn,_{Ni,Co})_2$ $(As,Sb,Bi,Te,_{Ge,In})_4(S,Se)_{13}$, are widespread minerals of many plutonogene and volcanic hydrothermal gold deposits (Spiridonov, 1987; Chvileva *et al.*, 1988; *etc.*). Because of the widespread isomorphism, the content of fahlores reflects the conditions and evolution of the ore-forming processes (Charlat, Levy, 1974; Mozgova, Tsepin, 1983; Spiridonov, 1985). Fahlores are widespread in the hydrothermal gold deposits of North Kazakhstan.

The North Kazakhstan gold-ore province (NKGP) is the largest in caledonides of Central Kazakhstan, it includes the same type deposits of the Late Ordovician plutonogene gold-quartz formation of different facies of deepness: hyp-, meso-, and abyssal (Spiridonov, 1995). In the present work are the new data on mineral assemblages, evolution, macro- and microelement composition of fahlores of the least deep in this province large deposit Kvartsitovye Gorki.

Geology of the Kvartsitovye Gorki deposit

The deposit is located in the east part of the Stepnyakskii synclinorium, in knot of intersection of the Tselinogradskii deep fault and regional Atansorskii strike-slip fault, in its footwall (Spiridonov *et al.*, 1986). This is a cause of safety of Kvartsitovye Gorki from erosion. The most part of the deposit volume is composed by volcanites with the basalt, picrite, andesite, and dacite composition of the $Є_3$-O_1 Aksui series and covering them greywackes of the Ushtogan suite of upper O_1. In zone of the Tselinogradskii fault are numerous tectonic wedges of gneisses, crystalline schists, and amphibolites of PR, phtanites and carbonaceous siliceous, terrigenous, and carbonate rocks of V-$Є_2$. The small intrusions belong to the Aksui and Krykkuduk complexes. The Aksui O_1 complex is represented by stocks of gabbro-dolerites with a size from tens of meters to first kilometers; they cover volcanites. The Krykkuduk O_3 complex (440-450 MA) is represented by the multiphase bodies of quartz gabbro-diorites, tonalites, granodiorites of the dike and tube-like form and with a square up to 0.3 km^2, and the post-intrusive dikes of granitoid-porphyries, microdiorites, and spessartites. A thickness of dikes is from first meters; their length is to first hundreds meters. The dikes are widespread in ore bodies of the deposit, where the most part of them is pre-ore, another part is intra-ore, and the small part is post-ore. Formation of the Krykkuduk complex was finished by hydrothermalites of the propylite and beresite-listvenite formations. Propylites of the small-deep epidote-chlorite facies are distributed in all area of Kvartsitovye Gorki. The fields of younger beresites and listvenites (445-450 MA), including the gold-bearing metasomatites with streaky-impregnated mineralization, are controlled by a system of large ruptures, branches of zone of the Tselinogradskii deep fault. The deposit includes 9 stockwork ore bodies. The industrial ore bodies (Kvartsitovye Gorki I and IV) are confined to tectonic blocks of molybde-

Table 1. **Chemical composition (wt %) of tennantite (an. 1-6) and tetrahedrite (an. 7) of the first generation of early carbonate-polysulphide assemblage of Gvartsitovye Gorki**

Analyses	1	2	3	4	5	6	7
Elements							
Cu	44.92	44.98	42.19	42.89	40.83	39.43	39.86
Ag	0.18	–	0.04	0.39	0.05	0.11	0.22
Tl	–	–	0.13	–	0.20	0.08	–
Zn	2.53	2.02	5.34	3.11	5.21	3.86	4.67
Fe	4.59	5.41	2.84	4.08	2.79	3.40	2.44
Hg	–	0.20	–	0.31	0.09	0.04	0.71
Cd	–	–	0.02	–	0.04	–	–
As	17.29	16.63	14.19	13.20	12.11	11.08	3.46
Sb	4.37	4.39	7.78	9.94	11.90	13.20	23.95
Bi	–	–	0.09	–	0.06	0.05	–
Te	–	–	0.01	–	–	0.08	–
Sn	–	–	0.02	–	0.10	0.03	–
S	28.35	28.49	28.42	27.61	26.77	26.80	26.03
Se	–	–	0.06	–	0.10	0.04	–
Total	102.23	102.12	101.10	101.53	100.24	98.19	101.34
Formula units at calculation on 29 atoms							
Cu^{1+}	9.98	10.00	9.94	9.95	9.95	9.80	9.97
Ag	0.02	–	–	0.05	0.01	0.02	0.03
Tl	–	–	0.01	–	0.02	–	–
Total	10.00	10.00	9.95	10.00	9.98	9.82	10.00
Zn	0.57	0.45	1.22	0.72	1.23	0.93	1.15
Fe	1.20	1.42	0.76	1.10	0.77	0.97	0.70
Cu^{2+}	0.38	0.35	–	0.25	–	–	0.12
Hg	–	0.01	–	0.03	0.01	–	0.06
Cd	–	–	–	–	0.01	–	–
Total	2.15	2.23	1.98	2.10	2.02	1.90	2.03
As	3.38	3.25	2.83	2.66	2.50	2.34	0.75
Sb	0.53	0.53	0.96	1.24	1.53	1.72	3.16
Bi	–	–	0.01	–	–	–	–
Te	–	–	–	–	–	0.01	–
Sn	–	–	–	–	0.01	–	–
Total	3.91	3.78	3.80	3.90	4.04	4.07	3.91
S	12.95	12.99	13.26	13.01	12.94	13.20	13.06
Se	–	–	0.01	–	0.02	0.01	–
Total	12.95	12.99	13.27	13.01	12.96	13.21	13.06
Sb#	13	14	25	32	38	42	81
Cu#	18	16	0	12	0	0	6

Note: *dash means the element was not detected. Au, Pb, Ni, Co, In, Ge were not detected. Sb#=Sb/(As+Sb), %, Cu#=Cu^{2+}/(Zn+Fe+Cu^{2+}+Hg+Cd), %. Numeration of analyses in tables is through*

num-vanadium-bearing phtanites-radiolarites, phtanites-spongiolites, pyrite-carbonaceous-siliceous schists of $Є_2$. During processes of beresitization these rocks were transformed in beresites, i.e. microquartzites, which clearly stand out in relief: it was a reason for the deposit name.

Deposit was not practically affected by epigenetic metamorphism.

Mineral assemblages of ore bodies

The process of ore formation had a multiphase character. The following mineral assemblages occur: 1) assemblage of relic minerals; 2) assemblage of beresites, listvenites, and connected quartz and ankerite-quartz veinlets (quartz, ankerite, muscovite, phengite, fuchsite, chlorites, pyrophyllite, rutile); 3) assemblage of early sulphides (pyrite, arsenopyrite, kaolinite, anatase); 4) early calcite-polysulphide assemblage (main minerals are pyrrhotite, cubanite, chalcopyrite, bornite, pyrite, graphitoid; accessory minerals are Fe-sphalerite, arsenopyrite, galena, gersdorffite, Ni-Co-pyrite, fahlores); 5) late calcite-polysulphide assemblage (Sb-As-pyrite, Sb-arsenopyrite, sphalerite); 6) productive gold-antimonite assemblage (antimonite, berthierite, jamesonite, zinkenite, bournonite, chalcostibite, fahlores, Hg-gold, andorite, roshchinite, miargirite, *etc.*) (Naz'mova *et al.*, 1971; Spiridonov *et al.*, 1986; Spiridonov, 1995). First four assemblages are the same type within the bounds of the whole deposit. Pyrrhotite, cubanite, chalcopyrite, bornite, and galena of the early calcite-polysulphide assemblage are kept mainly at the periphery of Kvartsitovye Gorki. Within the bounds of ore columns, mineral aggregates of the first four assemblages are brecciated and partly or completely substituted by intergrowths of spherocrystals (ore body IV) and/or small cubes (ore body I) of Sb-As-pyrite, short-prismatic Sb-arsenopyrite, low-iron sphalerite, antimonite. Here, the reactionary minerals are widespread, the products of influence of the Au-Sb solutions on early sulphides: berthierite (after pyrrhotite), zinkenite and jamesonite (after galena), chalcostibite and tetrahedrite (after chalcopyrite, bornite, cubanite). The productive assemblages of Kvartsitovye Gorki I and IV are different: andorite, roshchinite, and miargyrite are absent in the ore body I, but there is argentotennantite (Spiridonov *et al.*, 1986) in assemblage with Hg-gold and galena.

Genesis of the deposit

By geological data (Spiridonov *et al.*, 1986), the deposit was formed at the depths of 1-2 km in conditions of pressure. The ore body IV was formed in less deep conditions, the industrial mineralization in it is found at a depth up to 600 m. The ore body I was formed in less deep conditions, the industrial mineralization in it is traced to the depth more than 1300 m, without evident features of the vertical mineral-geochemical zoning. By the results of study of fluid inclusions with liquid carbon dioxide in early quartz, the temperature of its formation

Table 2. **Chemical composition (wt %) of tennantite (an. 8-10) and tetrahedrite (an. 11-19) of the second generation of early carbonate-polysulphide assemblage of Gvartsitovye Gorki**

Elements	8	9	10	11	12	13	14	15	16	17	18	19
Cu	40.37	38.88	39.49	39.42	38.60	39.05	37.38	36.59	36.79	35.50	35.60	36.30
Ag	2.03	2.13	2.15	2.21	1.87	2.44	1.46	1.60	1.75	2.59	2.45	2.36
Tl	–	–	–	–	–	–	0.18	0.09	0.02	0.08	–	0.08
Zn	3.89	4.09	4.24	5.43	3.30	4.84	6.87	5.57	5.40	4.13	4.31	5.08
Fe	2.98	3.45	3.46	2.54	4.15	2.97	1.12	1.60	1.95	2.53	2.31	2.39
Hg	–	–	0.02	–	–	–	0.20	0.11	–	0.36	0.89	0.32
Cd	–	–	–	–	–	–	–	0.01	–	–	–	0.03
As	14.07	11.70	11.03	9.58	8.54	7.00	3.63	2.60	2.39	1.09	1.06	0.04
Sb	8.01	11.72	13.03	15.69	16.58	19.10	23.97	25.80	26.36	27.88	27.75	29.12
Bi	–	–	–	–	–	–	0.04	0.06	–	0.08	0.17	0.06
Te	–	–	–	–	–	–	–	0.08	–	0.02	–	0.07
Sn	–	–	–	–	–	–	0.14	0.12	0.12	0.17	0.20	0.16
S	26.39	26.30	26.46	26.18	26.13	26.59	25.68	25.26	25.13	24.95	24.49	24.73
Se	–	–	–	–	–	–	0.06	0.06	–	0.05	0.02	–
Total	97.74	98.27	99.88	101.05	99.17	101.99	100.73	99.56	99.92	99.44	99.24	100.74
Formula units at calculation on 29 atoms												
Cu^{1+}	9.70	9.69	9.69	9.68	9.71	9.64	9.60	9.58	9.61	9.43	9.54	9.58
Ag	0.30	0.31	0.31	0.32	0.28	0.36	0.22	0.25	0.28	0.40	0.39	0.36
Tl	–	–	–	–	–	–	0.01	0.01	–	0.01	–	0.01
Total	10.00	10.00	10.00	10.00	9.99	10.00	9.83	9.84	9.89	9.84	9.93	9.95
Zn	0.94	0.99	1.02	1.31	0.81	1.16	1.71	1.42	1.37	1.07	1.12	1.30
Fe	0.84	0.98	0.97	0.71	1.18	0.84	0.33	0.48	0.58	0.76	0.70	0.71
Cu^{2+}	0.28	0.02	0.07	0.09	–	0.02	–	–	–	–	–	–
Hg	–	–	–	–	–	–	0.02	0.01	–	0.03	0.08	0.03
Cd	–	–	–	–	–	–	–	–	–	–	–	0.01
Total	2.06	1.99	2.06	2.11	1.99	2.02	2.06	1.91	1.95	1.86	1.90	2.05
As	2.95	2.48	2.31	2.01	1.82	1.47	0.79	0.58	0.52	0.25	0.24	0.01
Sb	1.02	1.52	1.68	2.03	2.18	2.47	3.21	3.53	3.60	3.87	3.88	4.02
Bi	–	–	–	–	–	–	–	–	–	0.01	0.01	–
Te	–	–	–	–	–	–	–	0.01	–	–	–	0.01
Sn	–	–	–	–	–	–	0.02	0.02	0.02	0.02	0.03	0.02
Total	3.99	4.00	3.99	4.04	4.00	3.94	4.02	4.14	4.14	4.15	4.16	4.06
S	12.95	13.01	12.95	12.85	13.02	13.04	13.07	13.11	13.02	13.14	13.00	12.94
Se	–	–	–	–	–	–	0.01	0.01	–	0.01	–	–
Total	12.95	13.01	12.95	12.85	13.02	13.04	13.08	13.12	13.02	13.15	13.01	12.94
Sb#	26	38	42	50	54	63	80	86	87	94	94	100
Cu#	14	1	3	4	0	1	0	0	0	0	0	0

Note: *Au, Pb, Ni, Co, In, Ge were not detected*

was 310-290° C, pressure was 0.3 kbar for Kvartsitovye Gorki IV and 0.5-0.6 kbar for Kvartsitovye Gorki I, salinity of the KCl-NaCl-$MgCl_2$ solutions was 3-8% of NaCl equivalent. The productive mineral assemblage formed from solutions of the close chemical composition, without liquid carbon dioxide, at the temperature 195-160° C (Spiridonov, 1995).

Fahlores of the Kvartsitovye Gorki deposit

Chemical composition of fahlores was studied with the electron microprobe instruments with the wave analyzer CAMECA SX-50 (analyst N.N. Kononkova) and Camebax (analyst E.M. Spiridonov). The analysis conditions were as follows: accelerating voltage – 20 kV, electron current – 30 nA. The analysis on all chemical elements was made with two programs, without change of the electron beam position (in one point). Standards were as follows: Cu (Kα) – $CuSbS_2$, Ag (Lα) – Ag, Tl (Mα) – $TlAsS_2$, Au (Lα) – Au, Fe (Kα) – FeS_2, Zn (Kα) – ZnS, Pb (Mα) – PbS, Hg (Lα) – HgS, Cd (Lα) – Cd, Mn (Kα) – $MnTiO_3$, Ni (Kα) – Ni, Co (Kα) – Co, As (Lα) – AsGa, Sb (Lα) – $CuSbS_2$, Te (Lα) – Te, Bi (Mα) – Bi, Sn (Lα) – SnO_2, Ge (L) – Ge, S (Kα) – $CuSbS_2$, Se (Lα) – Se. The lower detection limit of detected elements by the K line was 0.02 wt %, by the L line was 0.1 wt %, and by the M line was 0.3 wt %.

The nomenclature of fahlores is given after the article (Spiridonov, 1985).

Fahlores of the early carbonate-polysulphide assemblage. These fahlores do not have the wide diversity of a set of

Table 3. **Chemical composition (wt %) of mercury-zinc tennantite (an. 20-27) and tetrahedrite (an. 28-31) of the first generation of productive assemblage in intergrowth with antimonite, jamesonite, zinkenite, low-silver Hg-gold, Kvartsitovaya Gorka IV**

Elements	20	21	22	23	24	25	26	27	28	29	30	31
Cu	38.53	35.98	34.34	35.09	38.03	35.87	34.78	36.09	35.21	34.56	35.74	35.37
Ag	2.82	4.83	4.79	5.24	3.39	4.83	5.07	4.78	5.50	5.74	4.13	3.02
Tl	–	–	–	–	–	0.12	0.09	–	–	–	–	–
Zn	6.44	4.97	5.39	5.10	6.64	5.89	5.19	5.56	5.25	5.43	4.89	3.51
Fe	1.13	1.15	1.07	1.61	0.87	0.58	0.65	1.50	1.64	1.45	1.92	2.69
Hg	2.40	5.79	6.80	4.68	2.23	3.76	4.77	2.97	3.43	4.49	3.12	3.50
Cd	–	–	–	–	–	0.06	0.04	–	–	–	–	–
As	12.45	11.24	11.00	10.81	10.98	10.37	10.08	9.34	8.36	7.55	6.19	2.66
Sb	10.98	11.52	11.40	11.91	12.51	12.90	12.94	14.16	15.79	17.18	19.29	24.14
Bi	–	–	–	–	–	0.05	0.07	–	–	–	0.22	0.22
Te	–	–	–	–	–	–	0.08	–	–	–	–	–
Sn	–	–	–	–	–	0.04	0.15	–	–	–	–	–
S	26.64	25.47	25.20	24.94	26.46	25.48	24.80	25.40	25.26	24.86	25.12	24.55
Se	–	–	–	–	–	–	0.07	–	–	–	–	–
Total	101.39	100.95	99.99	99.38	101.11	99.94	98.79	99.80	100.44	101.26	100.62	99.66
Formula units at calculation on 29 atoms												
Cu^{1+}	9.50	9.25	8.97	9.15	9.47	9.25	9.19	9.27	9.13	9.04	9.32	9.47
Ag	0.41	0.73	0.74	0.80	0.50	0.73	0.78	0.73	0.84	0.88	0.63	0.48
Tl	–	–	–	–	–	0.01	0.01	–	–	–	–	–
Total	9.91	9.98	9.71	9.95	9.97	10.00	9.98	10.00	9.97	9.92	9.95	9.95
Zn	1.54	1.24	1.37	1.29	1.61	1.48	1.33	1.39	1.32	1.38	1.24	0.91
Fe	0.32	0.34	0.32	0.48	0.25	0.17	0.20	0.44	0.48	0.43	0.57	0.81
Cu^{2+}	–	–	–	–	–	–	–	0.02	–	–	–	–
Hg	0.19	0.47	0.56	0.39	0.17	0.31	0.40	0.24	0.28	0.37	0.26	0.30
Cd	–	–	–	–	–	0.01	0.01	–	–	–	–	–
Total	2.05	2.05	2.25	2.16	2.03	1.96	1.94	2.09	2.09	2.18	2.07	2.02
As	2.60	2.45	2.44	2.39	2.32	2.27	2.26	2.04	1.84	1.67	1.37	0.61
Sb	1.41	1.55	1.55	1.62	1.63	1.74	1.78	1.90	2.15	2.35	2.62	3.37
Bi	–	–	–	–	–	–	0.01	–	–	–	0.02	0.02
Te	–	–	–	–	–	–	0.01	–	–	–	–	–
Sn	–	–	–	–	–	0.01	0.02	–	–	–	–	–
Total	4.02	4.00	3.99	4.01	3.95	4.01	4.08	3.94	3.97	4.02	4.01	4.00
S	13.02	12.97	13.05	12.88	13.05	13.03	12.98	12.96	12.97	12.88	12.97	13.03
Se	–	–	–	–	–	–	0.02	–	–	–	–	–
Total	13.02	12.97	13.05	12.88	13.05	13.03	13.00	12.96	12.97	12.88	12.97	13.03
Sb#	35	39	39	40	41	43	44	48	54	58	66	85
Cu#	0	0	0	0	0	0	0	1	0	0	0	0

Note: *Au, Pb, Ni, Co, In, Ge were not detected*

microadmixtures within the bounds of the whole deposit. The earliest of falhores (the first generation) are associated with cubanite, Ni-Co-pyrite, chalcopyrite; fahlores overgrow and substitute chalcopyrite, form vienlets in it. By chemical composition, this is zinc- and iron-bearing tennantite, rarely tetrahedrite, with average relative content of copper (Cu^{2+}/Me^{2+},%) from 0 to 18%, with low contents of Ag (less than 0.4 wt %), Hg, and Tl, poor by Cd, Bi, Sn, Te, Se (Tabl. 1). The later of them are zinc-bearing tennantite and predominating tetrahedrite of the second generation form microveinlets in chalcopyrite and early tennantite. Fahlores of the second generation is rather rich by Ag (1.5-2.6 wt %) and Sn (0.1-0.2 wt %), poor by Hg, Tl, Cd, Bi, Te, Se (Tabl. 2), they have low relative content of copper.

Fahlores of the productive assemblage are remarkably different in the ore bodies IV and I.

Kvartsitovaya Gorka IV. Fahlores form the xenomorphic aggregations up to 20-40 mm, usually 0.05-3 mm in size, in the calcite nests together with antimonite, sulphosalts of Pb-Sb, Pb-Fe-Sb, Pb-Cu-Sb, and Ag-Pb-Sb, mercurous gold.

Fahlores of the first generation are the most widespread and form the largest aggregations; they are associated with antimonite, zinkenite, jamesonite, chalcostibite, the low-silver Hg-gold. They contain relics of chalcopyrite, arsenopyrite, and ferriferous sphalerite. The contacts of crystals of fahlores and antimonite are the inductive surfaces of joint growth. By chemical composition, fahlores correspond to mercury-zinc tennantite and tetrahedrite with a moderate content of Ag (3-6 wt %) (Tabl. 3). Outside zones of crystals are more antimonial.

Table 4. **Chemical composition (wt %) of zinc- and iron-bearing tetrahedrite of the second generation of productive assemblage in intergrowth with antimonite, famatinite, high-silver mercury-enriched gold, Kvartsitovaya Gorka IV.**

Elements	32	33	34	35	36	37	38	39	40	41
Cu	33.69	32.54	30.75	32.82	32.10	32.32	32.89	33.72	31.06	31.27
Ag	6.44	7.05	9.75	7.26	8.28	8.30	5.07	4.90	7.80	7.83
Tl	–	–	0.02	–	–	–	0.01	0.04	–	–
Zn	5.74	5.67	2.71	5.23	4.38	4.17	3.48	3.65	3.23	3.23
Fe	2.71	2.67	3.91	2.86	3.21	3.20	3.23	2.96	3.52	3.35
Hg	1.22	2.03	0.36	1.61	1.47	1.66	0.12	–	0.06	0.20
Cd	–	–	0.07	–	–	–	–	–	–	–
As	4.97	4.91	3.50	3.09	2.97	2.94	0.89	0.69	0.45	0.44
Sb	21.62	22.23	23.40	22.56	23.53	24.12	27.65	28.81	28.28	28.52
Bi	–	–	0.14	–	–	–	0.27	0.09	–	0.14
Te	–	–	0.04	–	–	–	0.05	0.03	0.04	0.06
Sn	–	–	0.16	–	–	–	0.16	0.11	0.17	0.16
S	25.21	25.19	24.40	24.93	23.89	24.87	24.64	24.69	23.88	23.72
Se	–	–	0.03	–	–	–	0.02	0.03	–	0.03
Total	101.60	102.29	99.23	100.36	99.83	101.58	98.46	99.71	98.50	98.94
Formula units at calculation on 29 atoms										
Cu^{1+}	8.72	8.46	8.30	8.67	8.66	8.54	8.90	9.04	8.54	8.61
Ag	0.98	1.08	1.55	1.13	1.32	1.29	0.81	0.77	1.26	1.27
Tl	–	–	–	–	–	–	–	–	–	–
Total	9.71	9.54	9.85	9.80	9.98	9.83	9.71	9.81	9.81	9.88
Zn	1.44	1.43	0.71	1.34	1.15	1.07	0.91	0.95	0.86	0.86
Fe	0.80	0.79	1.20	0.86	0.99	0.96	0.99	0.90	1.10	1.05
Cu^{2+}	–	–	–	–	–	–	–	–	–	–
Hg	0.10	0.17	0.03	0.13	0.13	0.14	0.01	–	0.01	0.02
Cd	–	–	0.01	–	–	–	–	–	–	–
Total	2.34	2.39	1.95	2.34	2.26	2.17	1.92	1.85	1.97	1.93
As	1.09	1.08	0.80	0.69	0.68	0.66	0.20	0.16	0.11	0.10
Sb	2.92	3.02	3.30	3.11	3.31	3.33	3.91	4.03	4.06	4.10
Bi	–	–	0.01	–	–	–	0.02	0.01	–	0.01
Te	–	–	0.01	–	–	–	0.01	–	0.01	0.01
Sn	–	–	0.02	–	–	–	0.02	0.02	0.02	0.02
Total	4.01	4.10	4.14	3.80	3.99	3.98	4.16	4.21	4.20	4.24
S	12.94	12.98	13.05	13.06	12.77	13.02	13.21	13.11	13.02	12.94
Se	–	–	0.01	–	–	–	–	0.01	–	0.01
Total	12.94	12.98	13.06	13.06	12.77	13.02	13.21	13.12	13.02	12.95
Sb#	73	74	80	82	83	83	95	96	97	98
Cu#	0	0	0	0	0	0	0	0	0	0

Note: *Au, Pb, Ni, Co, In, Ge were not detected*

Fahlores of the second generation, associating with antimonite, famatinite, and the silver-enriched Hg-gold, are represented by the zinc- and iron-enriched high-antimonial tetrahedrite, containing 5-10 wt % of Ag, up to 2 wt % of Hg, poor by Bi (Tabl. 4). Outside zones of the fahlores crystals do not practically contain As.

Fahlore of the third generation is the ferriferous high-antimony tetrahedrite enriched by Ag (9-15 wt %), containing up to 2 wt % Hg (Tabl. 5); it are associated with antimonite, andorite, roshchinite, mercury-enriched gold and electrum. Outside zones of the fahlore crystals do not practically contain As.

The positive correlation of the Fe and Ag contents is characteristic for fahlores of the ore body IV.

Kvartsitovaya Gorka I. Size of fahlores of productive assemblage is microscopic. The fahlores of the first generation occur in assemblage with antimonite and the low-silver Hg-gold; they are represented by the zinc- and iron-enriched arsenic tetrahedrite, containing 3-8 wt % of Ag, up to 2 wt % of Hg (Tabl. 6).

In assemblage with the high-silver Hg-gold are fahlores of the second generation, they are enriched by the silver zinc tetrahedrite and argentotetrahedrite, containing up to 31 wt % of Ag and 0.4 wt % Cd (Tabl. 7). The low contents of Hg (0.1-0.3 wt %) are characteristic for these fahlores. Argentotennantite forms outside zones of the fahlores crystals.

In the richest ore columns of the ore body I is the assemblage of fahlores of the third generation with galena and late Hg-gold and Hg-electrum. Intergrowths of these minerals

Table 5. **Chemical composition (wt %) of ferriferous tetrahedrite of the third generation of productive assemblage in intergrowth with andorite, roschinite, high-mercury gold, Kvartsitovaya Gorka IV**

Elements	42	43	44	45	46	47	48	49	50	51	52	53
Cu	29.42	31.77	27.43	28.58	28.52	30.28	27.81	28.55	27.99	28.37	28.39	27.78
Ag	11.32	9.41	13.36	14.51	13.20	11.46	11.81	11.79	14.12	12.55	13.81	13.53
Tl	–	–	–	–	–	–	0.19	0.17	–	0.02	–	–
Zn	2.68	2.67	2.97	3.1	2.49	2.78	2.60	3.46	2.65	2.58	2.72	2.94
Fe	4.39	4.04	3.91	3.25	4.33	3.86	3.68	3.03	3.81	3.62	3.95	3.38
Hg	1.73	0.67	1.85	0.91	1.22	0.74	0.15	0.43	0.58	0.53	0.49	0.79
Cd	–	0.01	–	–	–	0.06	0.05	0.06	–	0.06	–	0.13
As	4.92	4.66	3.12	2.55	2.37	2.09	0.77	0.67	0.64	0.65	0.22	0.07
Sb	20.94	21.15	23.13	24.13	24.41	24.87	27.24	27.66	26.81	27.58	27.78	26.94
Bi	–	–	–	–	–	–	0.08	0.03	–	–	–	–
Te	–	–	–	–	–	–	0.01	0.06	–	0.05	–	–
Sn	–	–	–	–	–	–	0.16	0.11	–	0.15	–	–
S	24.42	24.56	23.87	24.43	24.08	24.17	23.76	23.37	23.76	23.82	23.82	23.39
Se	–	–	–	–	–	–	–	0.05	–	–	–	–
Total	99.82	98.94	99.64	101.46	100.62	100.31	98.30	99.43	100.36	99.98	101.18	98.95
Formula units at calculation on 29 atoms												
Cu^{1+}	7.92	8.50	7.56	7.69	7.77	8.17	7.78	7.96	7.70	7.85	7.77	7.76
Ag	1.80	1.48	2.17	2.31	2.12	1.83	1.95	1.94	2.30	2.04	2.23	2.24
Tl	–	–	–	–	–	–	0.02	0.01	–	–	–	–
Total	9.71	9.98	9.73	10.00	9.88	10.00	9.74	9.91	10.00	9.89	10.00	10.00
Zn	0.70	0.69	0.80	0.81	0.66	0.73	0.71	0.94	0.71	0.69	0.73	0.80
Fe	1.34	1.23	1.23	1.00	1.34	1.19	1.17	0.96	1.20	1.14	1.23	1.08
Cu^{2+}	–	–	–	0.03	–	0.03	–	–	0.03	–	0.02	0.04
Hg	0.15	0.06	0.16	0.08	0.11	0.06	0.01	0.04	0.05	0.05	0.04	0.07
Cd	–	–	–	–	–	0.01	0.01	0.01	–	0.01	–	0.02
Total	2.19	1.98	2.18	1.93	2.11	2.03	1.90	1.95	1.98	1.89	2.02	2.01
As	1.12	1.06	0.73	0.58	0.55	0.48	0.18	0.16	0.15	0.15	0.05	0.02
Sb	2.94	2.95	3.33	3.40	3.47	3.52	3.98	4.03	3.86	3.98	3.98	3.95
Bi	–	–	–	–	–	–	0.01	–	–	–	–	–
Te	–	–	–	–	–	–	–	0.01	–	0.01	–	–
Sn	–	–	–	–	–	–	0.02	0.02	–	0.02	–	–
Total	4.07	4.01	4.06	3.99	4.02	4.00	4.19	4.21	4.01	4.16	4.03	3.97
S	13.03	13.02	13.03	13.09	12.99	12.98	13.17	12.92	13.00	13.06	12.95	13.02
Se	–	–	–	–	–	–	–	0.01	–	–	–	–
Total	13.03	13.02	13.03	13.09	12.99	12.98	13.17	12.93	13.00	13.06	12.95	13.02
Sb#	72	74	82	85	86	88	96	96	96	96	99	100
Cu#	0	0	0	2	0	2	0	0	1	0	1	2

Note: *Au, Pb, Ni, Co, In, Ge were not detected*

form small (60-100 microns) metasomatic ingrowths in pyrite. Fahlores are presented by the zinc antimony argentotennantite (to 34 wt % of Ag) and arsenic argentotetrahedrite (to 39 wt % of Ag) (Tabl. 8). Argentotetrahedrite forms the isolated aggregations and margins around crystals of argentotennantite. The stable admixture of Cd (0.10-0.12 wt %), extremely low contents of Hg, and also remarkable relative content of copper are characteristic for late fahlores, that distinguishes them among other fahlores of the productive assemblage.

The late productive mineralization with high-silver fahlores is found at different levels of the ore body I: from surface to a depth of 950 m.

Evolution of chemical composition of fahlores

Fahlores of pre-productive assemblage, tennantite and, in smaller degree, tetrahedrite, are poor by Ag, Hg, Cd and have a moderate content of copper. Fahlores of the productive assemblage are enriched by Ag, often Hg, and with extremely low content of copper. That is an evidence of the low oxidizing potential of ore-bearing solutions.

Fahlores of productive assemblage of the ore body IV are enriched by silver tetrahedrite, rarely tennantite. Fahlores of productive assemblage of the ore body I are tetrahedrite, rarely argentotennantite and argentotetrahedrite. During ore formation from the first to third generation, the concentrations of silver in fahlores increased (Fig. 1b-d).

The largest concentration of mercury was

Table 6. **Chemical composition (wt %) of zinc- and iron-bearing tetrahedrite of the first generation of productive assemblage, Kvartsitovaya Gorka I**

Elements	54	55	56	57	58	59
Cu	35.89	35.21	34.59	34.80	35.24	31.95
Ag	3.96	5.23	4.34	3.54	3.33	8.27
Tl	0.06	–	0.14	–	–	–
Zn	6.75	5.64	6.67	3.52	3.44	6.03
Fe	0.58	2.36	0.89	3.80	3.49	1.13
Hg	1.76	0.49	0.52	1.72	1.73	0.05
Cd	0.04	–	0.06	–	–	–
As	8.33	4.41	2.06	2.04	1.37	0.58
Sb	16.53	22.25	26.11	26.18	27.38	27.36
Bi	0.05	–	0.11	–	–	–
Te	0.05	–	0.06	–	–	–
Sn	0.06	–	0.13	–	–	–
S	25.99	24.67	24.93	24.64	25.18	23.87
Se	0.05	–	0.03	–	–	–
Total	100.08	100.26	100.65	100.24	101.16	99.24
Formula units at calculation on 29 atoms						
Cu^{1+}	9.18	9.19	9.13	9.22	9.26	8.67
Ag	0.60	0.81	0.68	0.56	0.52	1.33
Tl	–	–	0.01	–	–	–
Total	9.78	10.00	9.82	9.78	9.78	10.00
Zn	1.68	1.43	1.71	0.91	0.88	1.60
Fe	0.17	0.70	0.27	1.15	1.04	0.36
Cu^{2+}	–	0.02	–	–	–	0.07
Hg	0.14	0.04	0.04	0.14	0.14	–
Cd	0.01	–	0.01	–	–	–
Total	2.00	2.19	2.03	2.20	2.06	2.03
As	1.81	0.98	0.46	0.46	0.31	0.13
Sb	2.20	3.04	3.60	3.62	3.75	3.91
Bi	–	–	0.01	–	–	–
Te	0.01	–	0.01	–	–	–
Sn	0.01	–	0.02	–	–	–
Total	4.03	4.02	4.10	4.08	4.06	4.04
S	13.18	12.79	13.04	12.94	13.11	12.93
Se	0.01	–	0.01	–	–	–
Total	13.19	12.79	13.05	12.94	13.11	12.93
Sb#	55	76	89	89	92	97
Cu#	0	1	0	0	0	3

Note: *Au, Pb, Ni, Co, In, Ge were not detected*

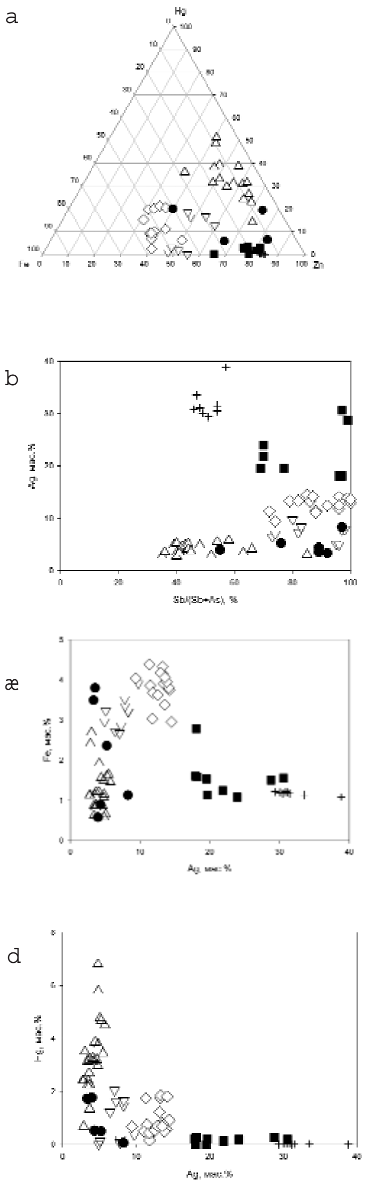

Fig. 1. *Chemical composition of fahlores of productive assemblage of the ore body I (1– first, n – second, and + – third generations) and ore body IV (△ – first, ▽ – second, and ◇ – third generations) of the Kvartsitovye Gorki deposit*

detected in fahlores of productive assemblage of the less deep ore body IV. During ore formation from the first to second and third generation, the concentration of mercury in fahlores decreased (Fig. 1a, d). Mercury was redistributed in native gold.

The relative content of antimony in fahlores of productive assemblage of the ore body IV increased from the first to third generation. This is a standard trend of evolution of the fahlores chemical composition (Charlat, Levy, 1974; Mozgova, Tsepin, 1983; Spiridonov, 1987; Chvileva *et al.*, 1988; etc.). The relative content of antimony in fahlores of productive assemblage of the ore body I from the first and second to third generation considerably decreased, just here argentotennantite occurs.

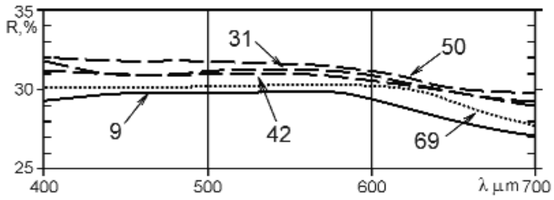

Fig. 2. *Reflectance spectra of tennantite (N. 9), tetrahedrite (N. 31, 42, 50), and argentotennantite (N. 69) of the Kvartsitovye Gorki deposit*

Table 7. **Chemical composition (wt %) of zinc-bearing tetrahedrite (an. 60-66) and argentotetrahedrite (an. 67-68) of the second generation of productive assemblage, Kvartsitovaya Gorka I**

Elements	60	61	62	63	64	65	66	67	68
Cu	24.51	21.15	22.72	24.40	23.45	23.97	23.15	14.83	16.35
Ag	19.52	23.93	21.87	19.65	18.18	17.93	18.06	30.57	28.79
Tl	–	–	–	–	0.09	0.18	0.12	–	0.10
Zn	5.62	5.67	5.67	5.86	5.24	5.51	5.25	5.37	5.74
Fe	1.53	1.08	1.25	1.13	1.59	1.60	2.78	1.56	1.50
Hg	–	0.18	0.12	0.20	0.27	0.22	–	0.18	0.26
Cd	–	0.41	0.25	0.24	0.25	0.18	0.18	0.31	0.24
As	5.31	4.94	4.94	3.85	0.61	0.60	0.61	0.41	0.24
Sb	19.05	18.93	19.18	20.72	26.93	26.59	27.30	25.66	26.07
Bi	–	–	–	–	0.12	0.07	0.06	0.13	0.15
Te	–	–	–	–	–	0.11	0.06	0.05	0.06
Sn	–	–	–	–	0.15	0.16	0.14	0.11	0.13
S	23.45	23.12	23.50	23.53	23.25	23.61	23.17	22.52	22.19
Se	0.08	–	0.02	0.01	0.02	–	0.02	–	0.03
Total	99.07	99.41	99.52	99.59	100.11	100.74	100.89	101.69	101.85
Formula units at calculation on 29 atoms									
Cu^{1+}	6.80	6.00	6.37	6.77	6.66	6.73	6.52	4.36	4.80
Ag	3.20	4.00	3.61	3.23	3.04	2.96	2.99	5.30	4.98
Tl	–	–	–	–	0.01	0.02	0.01	–	0.01
Total	10.00	10.00	9.98	10.00	9.71	9.71	9.52	9.66	9.79
Zn	1.52	1.56	1.54	1.59	1.45	1.50	1.44	1.54	1.64
Fe	0.49	0.34	0.40	0.36	0.51	0.51	0.88	0.53	0.50
Cu^{2+}	0.02	0.01	–	0.04	–	–	–	–	–
Hg	–	0.02	0.01	0.02	0.02	0.02	–	0.02	0.02
Cd	–	0.07	0.04	0.04	0.04	0.03	0.03	0.05	0.04
Total	2.03	2.00	1.99	2.05	2.02	2.06	2.35	2.12	2.20
As	1.25	1.19	1.17	0.91	0.15	0.14	0.14	0.10	0.07
Sb	2.77	2.80	2.81	3.02	3.99	3.90	4.02	3.94	3.99
Bi	–	–	–	–	0.01	0.01	–	0.01	0.01
Te	–	–	–	–	–	0.02	0.01	0.01	0.01
Sn	–	–	–	–	0.02	0.02	0.02	0.02	0.02
Total	4.02	3.99	3.98	3.93	4.17	4.09	4.19	4.08	4.10
S	12.93	13.01	13.05	13.02	13.09	13.14	12.92	13.13	12.90
Se	0.02	–	–	–	–	–	0.01	–	0.01
Total	12.95	13.01	13.05	13.02	13.09	13.14	12.93	13.13	12.91
Sb#	69	70	70	77	96	96	97	97	99
Cu#	1	0	0	2	0	0	0	0	0

Note: *Au, Pb, Ni, Co, In, Ge were not detected*

Possibly, such trend of evolution of fahlores is characteristic for such relatively developed to the depth deposits as Kvartsitovaya Gorka I.

Physical properties of fahlores

The reflectance spectra of tennantites, containing antimony and practically non-containing Ag and Hg, are characterized by the presence of a gentle maximum in the yellow-green range and the significant decrease of peaks in the red range (Fig. 2, sample an. 9), this is a reason of a greenish tint of the mineral in reflected light. The reflectance spectra of mercurous tennantite, independently from its relative content of antimony, are distinguished by a noticeable maximum in a yellow range, a sag in green and a decrease of reflection in the red range. Such peculiarities of the reflectance spectrum are shown already in fahlores with 3-4 wt % of Hg (sample an. 31). The reflectance spectrum of argentotennantite is different, in the blue and yellow-green ranges, it has a straight profile, analogous to tetrahedrite enriched by silver, in a red range, reflection of argentotennantite strongly decreases (sample an. 69), a blue tint of mineral is caused by that. In tetrahedrites, with increase of the silver content up to 30%, reflection significantly increases, a form of spectrum changes slightly (samples an. 42 and 50).

The unit cell parameters of the studied fahlores increase from tennantite (10.294(2) Å, sample an. 9) to tetrahedrite (10.401(2) Å, sample an. 31); diffractometer DRON-4.5; Co anticathode; inner standard α-quartz; the unit cell parameters were calculated by method of the least squares. During entry of the silver large cation in fahlores, the unit cell parameter increases to 10.417(1) Å (8% of Ag, sample an. 36), 10.452(2) Å (11% of Ag, sample an. 42), and 10.518(2) Å (14% Ag, sample an. 50) in tetrahedrite and to 10.583(2) Å (argentotennantite,

Table 8. **Chemical composition (wt %) of zinc-bearing argentotennantite (an. 69-72) and argentotetrahedrite (an. 73--75) of the third generation of productive assemblage, Kvartsitovaya Gorka I.**

Elements	69	70	71	72	73	74	75
Cu	17.21	15.60	16.76	17.11	17.78	17.78	11.64
Ag	30.87	33.54	31.13	30.07	30.48	31.48	38.86
Zn	5.93	5.44	5.81	5.98	6.23	6.23	5.81
Fe	1.21	1.13	1.19	1.19	1.17	1.17	1.08
Hg	0.02	0.02	–	0.02	0.02	0.01	–
Cd	0.11	0.10	0.10	0.12	0.12	0.12	0.12
As	9.02	8.80	8.72	8.52	7.66	7.66	6.89
Sb	12.64	12.59	12.98	13.34	14.74	14.74	14.83
S	22.87	22.66	22.82	22.90	23.08	23.08	21.92
Se	–	–	–	0.02	0.02	0.01	–
Total	99.88	99.88	99.51	99.27	101.30	102.28	101.15
Formula units at calculation on 29 atoms							
Cu^{1+}	4.84	4.32	4.76	4.88	4.95	4.81	3.26
Ag	5.16	5.68	5.24	5.06	5.05	5.19	6.74
Total	10.00	10.00	10.00	9.94	10.00	10.00	10.00
Zn	1.64	1.52	1.61	1.65	1.70	1.69	1.66
Fe	0.39	0.37	0.39	0.39	0.38	0.37	0.36
Cu^{2+}	0.04	0.16	0.02	–	0.05	0.16	0.17
Hg	–	–	–	–	–	–	–
Cd	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	2.09	2.07	2.04	2.06	2.15	2.24	2.21
As	2.17	2.14	2.11	2.06	1.83	1.82	1.72
Sb	1.87	1.89	1.94	1.99	2.16	2.15	2.28
Total	4.04	4.03	4.05	4.05	3.99	3.97	4.00
S	12.86	12.90	12.91	12.95	12.86	12.79	12.79
Se	–	–	–	–	–	–	–
Total	12.86	12.90	12.91	12.95	12.86	12.79	12.79
Sb#	46	47	48	49	54	54	57
Cu#	2	8	1	0	2	7	8

Note: *Au, Pb, Ni, Co, In, Ge were not detected*

sample an. 69) in tennantite.

The micro-indentation hardness of fahlores decreases in a series from tennantite to tetrahedrite, from 365 (sample an. 9) to 330, 318, and 308 kgs/mm^2 (samples an. 7, 18, and 31). It is maximal in the high-silver fahlores: 307 and 302 kgs/mm^2 (argentotennantite, samples an. 69 and 70).

Conclusions

The Kvartsitovye Gorki deposit is the less deep one from plutonogene gold deposits; it is original by composition and evolution of chemical composition of fahlores. The studied fahlores are stoichiometric by chemical composition, their crystals are often zoned by chemical composition, a smooth change of chemical composition from zone to zone is characteristic. Fahlores are poor by Bi, Te, Se, Tl, Cd, Sn; contents of Au, Pb, Ni, Co, Ge, and In are below detection limits.

Fahlores of productive assemblage are the most diverse. Earlier fahlores are enriched by mercury, especially in the less deep ore body IV (to 7 wt %). In fahlores of late generations of productive assemblage, the contents of mercury are lower in tens times. Evolution of fahlores of productive assemblage of the industrial ore bodies I and IV is different: in the ore body IV, from early to late generations, the contents of silver and relative content of antimony increase; in the deep-penetrating ore body I, from early to late generations the relative content of antimony decreases and the contents of silver increase. Just among the late generation of fahlores in the ore body I, argentotennantite occur.

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