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Mineralogical and Geochemical Characteristics and Predicted Reserves of Gold–Base Metal Ore Mineralization in Southern Armenia and Northwestern Iran

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Abstract—This paper reports newly obtained data on the mineralogy, geochemistry, and predicted reserves of the Shaumyan gold–base metal deposit in southern Armenia and the Kharvana occurrence of ore mineralization in northwestern Iran.

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INTRODUCTION

One of the principal goals of exploration geochemistry is the quantitative assessment of geochemical anomalies in the form of quantified predicted reserves of corresponding categories, which are further used to select first-priority targets for more detailed exploration operations and to minimize the exploration costs of sub- and uneconomic mineral deposits and occurrences [1–4]. This assessment is conducted by means of studying the mineralogy and chemistry of the ores and the primary aureoles at thoroughly explored deposits and examining their geochemical zoning with the aim of selecting geochemical criteria for determining the depth of the erosion level and predicting the vertical extent of ore mineralization at analogous mineral deposits and occurrences. As a reference example, this paper presents materials on the exhaustively studied and thoroughly explored Shaumyan gold–base metal deposit in southern Armenia. The metrics of this deposit contains data on the predicted reserves of the similar Kharvana occurrence of gold–base metal ore mineralization in northwestern Iran.

SHAUMYAN GOLD–BASE METAL ORE DEPOSIT

The deposit is restricted to the southeastern flank of the Kafan ore field and is hosted by tuffacceous–sedimentary rocks of a Middle and Late Jurassic age (Fig. 1). The older volcanic–sedimentary Chinarskaya Formation consists of andesite–dacite tuffs, tuff-sandstones, and sandstones (Amiryan, 1984). These rocks occur in contact with quartz andesidacites of the Baratumskaya Formation, which dominate at the Shaumyan deposit, with contours of the field of these rocks practically coinciding with the boundaries of the ore field. The vein rocks are dikes of diabases and gabbro-diabases. The Shaumyan deposit is related to a large Middle Jurassic volcanic edifice. All of its economic orebodies are hosted in subvolcanic quartz andalusite in the central part of the edifice (Zograbyan, 1979). The area of the deposit is broken by shear faults into a series of narrow blocks trending northwest and roughly north. The largest of the faults is the Barabatum–Khaladzh Fault, which was traced for more than 7 km at the surface and in mining workings. Other major faults are the Central, Eastern Shaumyan, Western Shaumyan, and Tezhadin faults, which are accompanied by thick zones of folded and sheared rocks with tectonic clay.

MINERALOGY OF THE GOLD–BASE METAL MINERALIZATION

The gold–base metal ores of the Shaumyan deposit are hosted in thick veins and relatively thin veinlets, often accompanied by zones of stringer–disseminated mineralization. The mineralized veins were traced along their strikes for a few hundred meters and have thicknesses from 0.6 to 3.5 m (in the swells of the largest orebodies). Sulfide minerals are often localized in the marginal parts of large veins, whose central portions are made up of a quartz–carbonate mass. The major ore minerals are pyrite, sphalerite, chalcopyrite, and galena (Fig. 2), and the ores also contain tennantite, tetrahedrite, bornite, enargite, chalcosine, covellite, Pb, Au, Ag, Bi tellurides, and native gold and silver. The predominant gangue minerals are quartz, calcite, Mn-bearing calcite, barite, anhydrite, and gypsum. The hydrothermal ore-forming process occurred at the deposit in several stages (Zar'yan, 1963): (1) quartz–pyrite; (2) pyrite–chalcopyrite (with Bi tellurides); (3) galena–chalcopyrite–sphalerite; and (4) productive, with Pb, Bi, Ag, and Au tellurides. The productive

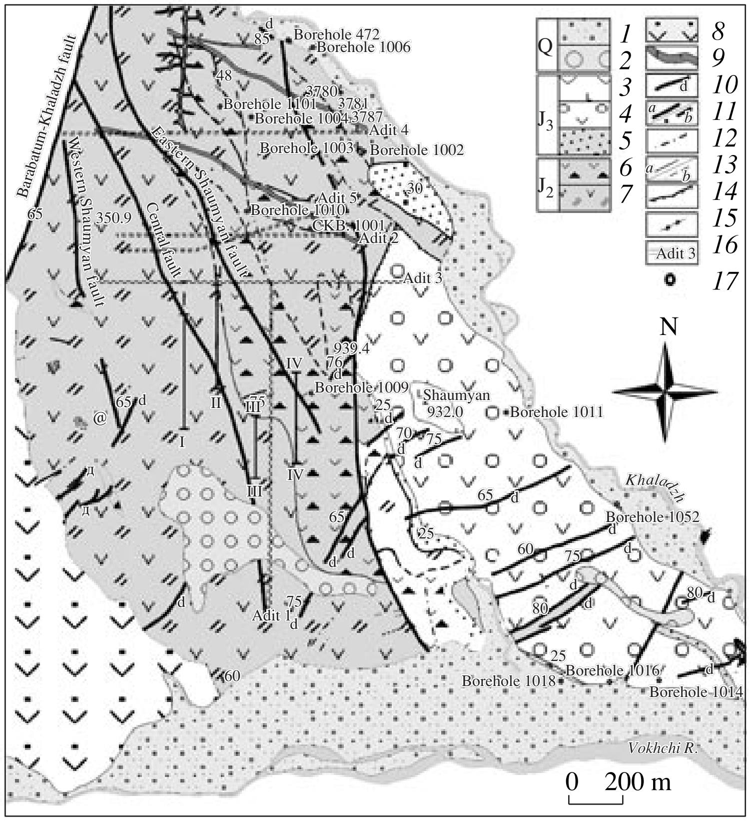

Fig. 1. Geological map of the Shaumyan deposit (modified after Sarkisyan, Zagrobyan, and Achikgesyan, 1968). (*1*) Alluvial and diluvial deposits; (*2*) boulder–shingle deposits of ancient terraces; (*3*) andesite and basaltic andesite lava sheets; (*4*) tuff–conglomerates; (*5*) volcanomictic sandstones and tuff–sandstones; (*6*) volcanic breccias, lava-breccias, tuff-breccias, and tuffs of andesidacite composition (undifferentiated); (*7*) quartz andesitacites (Barabatum Formation); (*8*) volcanic–sedimentary rocks of the Chinarskaya Formation; (*9*) gabbro-diabases; (*10*) diabases and diabase porphyries; (*11*) faults with tectonic clay and slickensides: (*a*) observed, (*b*) inferred; (*12*) small faults; (*13*) rock boundaries: (*a*) observed, (*b*) inferred; (*14*) stratigraphic unconformities; (*15*) veins and veinlets with base-metal ore mineralization; (*16*) underground mining workings; (*17*) exploration boreholes.

gold–telluride mineralization is the latest within the framework of stage 3. The postmineral stages were as follows: (5) quartz–carbonate; (6) anhydrite–gypsum. The sphalerite of the Shaumyan deposit contains 0.22–0.34 wt % Fe, 0.03–0.36 wt % Hg, and 0.07–0.47 wt % Cd; and the chalcopyrite contains 0.07 wt % Ag. The concentration of Ag in the galena is notably lower than usual (from trace amounts to 0.11 wt %), and the bulk of Ag of the ores is contained in tellurides (Tables 1, 2). Fahlore aggregates are sharply zoned (Fig. 3), and their composition varies from tennantite to Te–As tetrahedrite, which is a typical mineral of volcanogenic gold ores [5]. The widespread gangue minerals are Mn-calcite (up to 6 wt % MnO) and ripidolite (up to 3 wt % MnO). The ores of the Shaumyan deposit contain Hg, Au, and Ag tellurides: sylvanite, hessite, and coloradoite (Fig. 4).

Coloradoite HgTe is a typomorphic mineral of volcanogenic hydrothermal gold and gold-bearing deposits, ranging from sulfide to lean-sulfide types [5]. Coloradoite from the Shaumyan deposit is rich in Pb. The ores of the deposit contain widespread *sylvanite* $AuAgTe_4$, which is the main concentrator of Au. The sylvanite is enriched in Au and depleted in Ag relative to the stoichiometric proportions and contains a notable concentration of Cu (up to 0.72 wt %), which is characteristic of volcanogenic gold ores [5]. *Hessite* Ag_2Te composes numerous clusters of metasomatic grains in galena or, more rarely, sphalerite, chalcopyrite, and tetrahedrite and occurs in aggregates with altaite. Much of the hessite was produced by the replacement of sylvanite, and hessite seems to be the youngest hypogene mineral of the ores. The hessite is practically devoid of Au but contains notable amounts of Pb (up to 3 wt %) (Table 3). The supergene minerals are native copper, chalcosine, covellite, tennortite, cuprite, malachite, azurite, chrysocolla, jarosite, and limonite.

GEOCHEMISTRY

In order to work out a method for the geochemical exploration and assessment of the reserves of the gold–base metal ore mineralization, we examined the tendencies in the origin of the primary aureoles around thor-

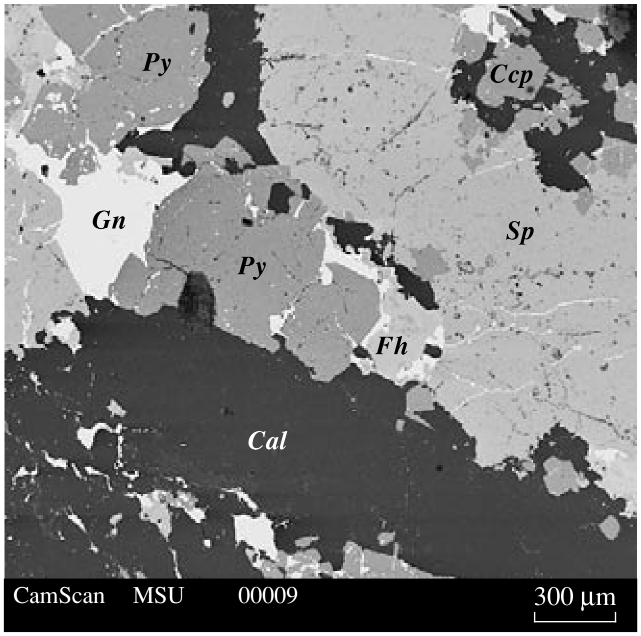

Fig. 2. Aggregates of pyrite (*Py*), sphalerite (*Sp*), chalcopyrite (*Ccp*), Mn-bearing calcite (*Cal*), and younger galena (*Gn*) and fahlores (*Fh*). Shaumyan deposit, level 780 m; BSE image.

oughly explored and prospected orebodies at the deposit. For this purpose we used the results of lithochemical sampling of the ore-hosting rocks and ores in underground mining workings and in the core of boreholes arranged along profiles across the strikes of ore-controlling structures. We also utilized the results of geochemical exploration operations conducted by the Yerevan Geological Survey under the supervision of B.G. Bezirganov (1981). Geochemical exploration has revealed primary geochemical aureoles of Au, Pb, Zn, Ag, Cu, Ba, As, Cd, Sn, Mo, Co, Ni, Cr, and V within zones of intense hydrothermal alterations of the host rocks around gold-bearing orebodies. The largest and geochemically most contrasting aureoles around gold–base metal mineralized zones are typical of Au, Ag, Zn, Cu, Pb, and As. The vertical extension of these aureoles is 60–120 m from the roof of the deep-sitting orebodies. The effective width of the primary aureoles is 100–180 m, as can be clearly seen in underground mining workings. The aureoles of these elements trend for a few hundred meters and some of them merge into zones of fractured and shattered rocks and can be traced from the western to eastern flanks of the deposit. The primary aureoles of ore elements are wider and longer at the surface, a fact explained by the widespread branching of the orebodies and their merging into zones of closely spaced steep veins. Fairly contrasting primary aureoles were also detected in the Late Jurassic rocks, in which these aureoles are the continuations of aureoles around orebodies hosted by Middle Jurassic rocks. In the supergene dissemination field of the Shaumyan deposit, the average concentrations ($K_k = C_{an}/C_b$) of major ore elements are as follows: Au_{25}—Ag_{10}—$Zn_{7.9}$—$Pb_{6.3}$—$Cu_{3.9}$—$Mo_{3.7}$—$Mn_{3.5}$—$Bi_{2.7}$—$Co_{2.5}$—$V_{2.4}$—$Sn_{1.2}$. According to their correlations in the typomorphic

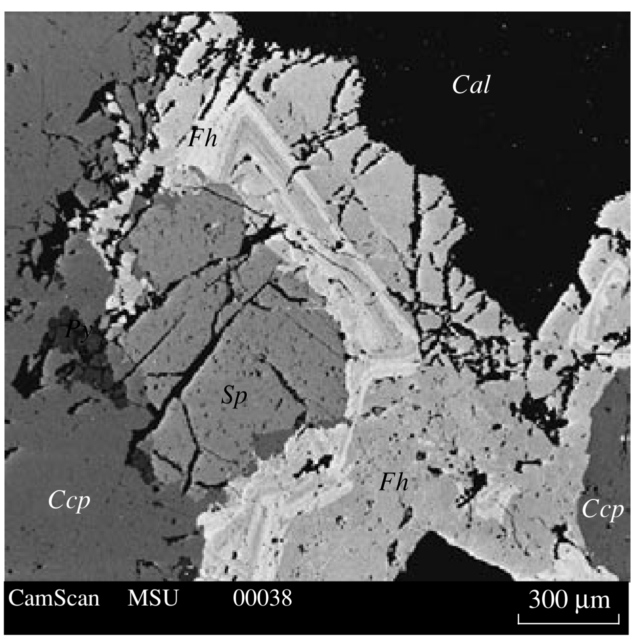

Fig. 3. Zonal grains of fahlores (*Fh*) in aggregates with sphalerite (*Sp*), chalcopyrite (*Ccp*), pyrite (*Py*), and Mn-calcite (*Cal*). Shaumyan deposit, level 780 m; BSE image.

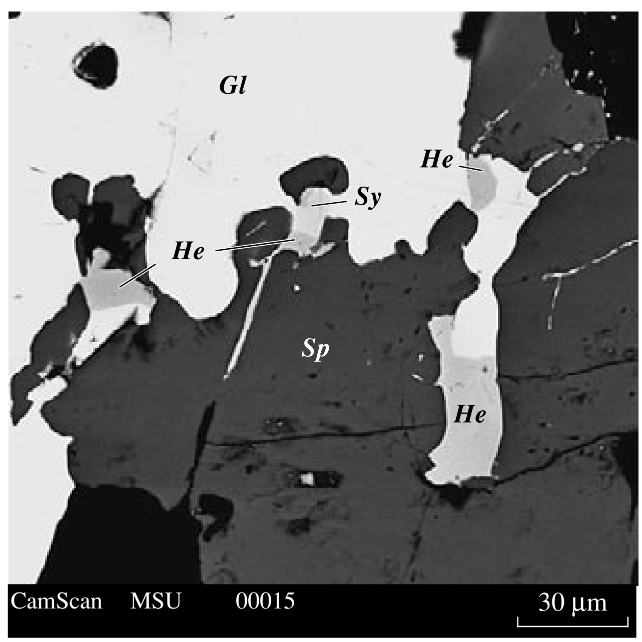

Fig. 4. Metasomatic ingrowths of sylvanite (*Sy*) and hessite (*He*) near the contact with galena (*Gl*) and sphalerite (*Sp*). Shaumyan deposit, level 820 m; BSE image.

Table 1. Chemical composition of (1–3) sphalerite and (4–5) galena from the Shaumyan deposit

Element	Sample			Element	Sample	
	Sh-714	Sh-7596			Sh-714	Sh-7596
	1	2	3		4	5
Zn	66.63	66.97	67.64	Pb	86.74	87.53
Fe	0.22	0.34	0.26	Ag	0.00	0.11
Cd	0.47	0.28	0.07	Bi	0.16	–
Hg	0.36	0.26	0.03	Sb	0.04	–
Cu	0.05	0.09	0.13	Cd	0.01	0.07
Ag	0.00	0.04	0.03	Hg	0.00	0.03
Bi	–	0.27	0.29	Cu	0.08	0.18
S	33.05	33.33	33.38	Fe	0.13	0.02
As	0.00	0.14	0.08	S	13.55	13.69
Sb	0.05	0.01	0.11	Se	–	0.03
Te	0.01	0.02	0.02	As	0.00	0.05
Total	100.84	101.75	102.04	Te	0.12	0.04
Formula units normalized to a total of 2				Total	100.83	101.75
Zn	0.989	0.986	0.992	Formula units normalized to a total of 2		
Fe	0.004	0.006	0.005	Pb	0.989	0.987
Cd	0.004	0.002	–	Ag	–	0.002
Hg	0.002	0.001	–	Bi	0.002	–
Cu	0.001	0.001	0.002	Sb	0.001	–
Ag	–	–	–	Cd	–	0.002
Bi	–	0.001	0.001	Hg	–	–
Total	1.000	0.997	1.000	Cu	0.003	0.006
S	1.000	1.001	0.998	Fe	0.005	0.001
As	–	0.002	0.001	Total	1.000	0.998
Sb	–	–	0.001	S	0.998	0.998
Te	–	–	–	Se	–	0.001
Total	1.000	1.003	1.000	As	–	0.002
				Te	0.002	0.001
				Total	1.000	1.002

Note: Analyses were conducted on a Camebax electron microprobe, analyst I.M. Kulikova.

complex, the elements can be subdivided into three clear-cut groups (Fig. 5).

The first group (group I) comprises the major ore elements of the deposit: Au, Ag, Zn, Cu, Pb, Cd, Sb, Bi, and As. The second group (group II) includes Ba, Sn, and Mo and is characterized by both introduction and removal aureoles at the deposit. The removed elements are Co, Ni, Mn, and V (group III). They form clearly pronounced anomaly fields in the western flank of the deposit. The analysis of the distribution of ore elements in the ores and primary aureoles of the deposit indicates that the strongest correlations with gold in the primary aureoles and ores of the deposit are typical of silver ($r = +0.85$), which is predetermined by the preferable occurrence of the latter element in sylvanite, copper ($r = +0.67$), zinc ($r = +0.37$), and lead ($r = +0.31$).

GEOCHEMICAL ZONING AT THE DEPOSIT

The vertical zoning of the primary aureoles of major ore and associated elements at the Shaumyan deposit was examined along three profiles: I–I, II–II, and III—III. The character of the distribution of elements in ore-hosting rocks accentuates zoning, which is expressed as the occurrence of the highest concentrations of certain elements at the upper levels of mineralization and in the

Table 2. Chemical composition (wt %) of (9–14) sylvanite and (15–17) hessite from the Shaumyan deposit

Element	9	10	11	12	13	14	15	16	17
Au	25.73	25.45	25.30	25.41	25.27	25.82	0.00	0.00	0.00
Ag	12.58	12.82	12.57	12.67	12.46	11.70	61.63	62.53	60.04
Cu	0.00	0.03	0.03	0.07	0.22	0.72	0.28	0.33	0.00
Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.06	0.08
Pb	0.00	0.00	0.00	0.00	0.00	0.00	0.88	0.31	2.89
Bi	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.07	0.13
Te	62.05	62.77	62.50	62.55	62.38	63.46	36.81	37.71	36.28
Sb	0.24	0.38	0.17	0.41	0.44	0.31	0.12	0.22	0.17
Se	0.00	0.00	0.04	0.00	0.14	0.00	0.00	0.00	0.00
S	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.06	0.07
Total	100.60	101.46	100.61	101.11	100.91	102.01	99.94	101.26	99.66
	Formula units								
Au	1.04_5	1.04	1.04_5	1.04	1.03_5	1.04_5	–	–	–
Ag	0.95_5	0.96	0.95	0.95	0.93_5	0.86_5	1.97	1.96_5	1.95
Cu	–	0.00_5	0.00_5	0.01	0.03	0.09	0.01_5	0.02	–
Fe	–	–	–	–	–	–	–	0.00_5	0.00_5
Pb	–	–	–	–	–	–	0.01_5	0.00_5	0.05
Te	3.98	3.97	3.99	3.97	3.95_5	3.98	0.98	0.99	0.98_5
Sb	0.02	0.02_5	0.01	0.03	0.03	0.02	–	0.00_5	0.00_5
Se	–	–	–	–	0.01_5	–	–	–	–
S	–	–	–	–	–	–	0.02	0.00_5	0.00_5
Total	6	6	6	6	6	6	3	3	3

Note: Analyses were conducted on a Camebax electron microprobe, analyst I.M. Kulikova; neither Hg or As were detected.

overlying rocks and the highest concentrations of other elements at the middle and lower levels of ore mineralization and in the underlying rocks. The broadest and most contrasting aureoles in the upper parts of the vertical sections are typical, in addition to Au, also of Pb, Zn, Ag, and As. The effective widths of the primary aureoles notably diminish with depth, and their intensities simultaneously decrease. Primary aureoles of a similar position and size are characteristic of Ba and Cd. Aureoles most widely spread in the lower parts of the profiles are the broad and contrasting aureoles of Co, Mo, and V, whereas the aureoles of Ni and Sn are narrower. The fairly contrasting primary aureoles of Cu, Cd, and Cr can be traced throughout the whole orebodies. The method of zoning coefficients [4, 6] applied to the three profiles across the deposit allowed us to establish the following partial sequences of the zonal precipitation of elements (Bezirganov, 1981): profile I–I (upsection): Mo—V—Sn—Co—Cd—Cr—Ni—Cu—Ag—Zn—Pb—As—Ba; profile II–II: Sn—Ni—Mo—Co—Cr—V—Cu—Cd—Zn—Ag—Ba—As—Pb; profile III–III: V—Ni—Sn—Mo—Co—Cd—Cr—Cu—Zn—As—Ag—Pb—Ba. The close similarities between the partial zoning patterns allowed us to deduce a generalized zoning sequence for the Shaumyan deposit (upsection): Sn—Mo—V—Ni—Co—Cr—Cd—Cu—(Au)—Zn—Ag—As—Pb—Ba. The position of Au in the zoning sequence was determined based on a limited number of samples. Using the Nyu-2 computer program [1–3], we determined the sequence of the zonal precipitation of elements in profile I–I by the centers of gravity of the plots of elemental pair ratios in the typomorphic complex: Mo—V—Ni—Co—Sn—Cu—Cr—Cd—Ag—Ba—Zn—Pb—As, which is close enough to the generalized sequence (the rank correlation coefficient between them is $r = +0.88$ at $r_{5\%} = 0.55$). The most important indicator elements of the zoning that were used to evaluate the depth of the erosion level of the geochemical anomalies were elements maximally distant from one another in the zoning sequence. The indicator elements in the upper mineralized zone and overlying rocks of the Shaumyan

Table 3. Chemical composition (wt %) of (1–4) Pb-bearing coloradoite from the Kharvana deposit and (5–8) altaite from the Shaumyan deposit

Element	1	2	3	4	5	6	7	8
Hg	56.56	56.41	57.09	55.39	0.28	0.00	0.09	0.00
Pb	3.70	4.31	4.45	6.68	60.71	60.54	60.30	61.36
Cd	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.21
Cu	0.02	0.02	0.09	0.00	0.00	0.05	0.01	0.05
Fe	0.03	0.10	0.00	0.09	0.00	0.00	0.00	0.00
Ag	0.06	0.06	0.02	0.00	0.75	0.50	0.25	0.00
Te	38.48	38.96	38.82	39.07	38.06	37.73	37.34	37.43
Sb	0.21	0.38	0.25	0.43	0.20	0.23	0.25	0.70
Bi	0.00	0.00	0.00	0.08	0.14	0.23	0.00	0.12
As	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00
S	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00
Total	98.96	100.24	100.72	101.76	100.24	99.36	98.24	99.87
	Formula units normalized to a total of 2							
Hg	0.93	0.92	0.93	0.89	0.00_5	–	–	–
Pb	0.06	0.07	0.07	0.10	0.97_5	0.97_5	0.99	0.99
Fe	–	–	–	0.01	–	–	–	–
Cd	–	–	–	–	–	–	–	0.00_5
Bi	–	–	–	–	0.00_5	0.00_5	–	–
Te	1.00	1.00	0.99	0.99	0.99	0.99	0.99_5	0.98
Sb	0.01	0.01	0.01	0.01	0.00_5	0.00_5	0.00_5	0.02
S	–	–	–	–	–	0.00_5	–	–

Note: Analyses were conducted on a Camebax electron microprobe, analyst I.M. Kulikova; Au, Zn, and Se were not detected.

deposit are Ba, Pb, Zn, Ag, and As; and such elements in the lower mineralized zone and underlying rocks are Sn, Co, No, Mo, and V. The zonal distribution of these elements is pronounced more clearly in the distribution of the multiplicative coefficient $K_z = \frac{\text{Pb.Zn.Ag.As}}{\text{Sn.Co.Mo.V}}$, which is fairly contrasting ($R = K_{max}/K_{min} \approx 7 \times 10^4$). The numerical values of the chosen multiplicative coefficient definitely delineate the primary geochemical aureoles at the surface of the deposit and at its exploration levels. The geochemical fields of this coefficient at the surface ($K_z \geq 10 \times 10^5$) coincide with the contours of the gold–base metal ore mineralization and the projections of deep orebodies. At exploration levels, these fields contour known orebodies in the examined sections and unexposed orebodies occurring at deeper levels (up to 200 m).

We examined the geochemical zoning of the Shaumyan deposit in profile I–I, using the Nyu-2 computer program [1–3]. The input data to be processed were the above-background linear productivities (M, m %) of the elements of the typomorphic complex, which were calculated in discrete sections of the mineralized zone. The program was designed, first and foremost, for the identification of the sequences of the zonal precipitation of chemical elements and the selection of geochemical indicators of zoning as geochemical criteria to be used for the subsequent evaluation of the erosion level and the prediction of ore reserves contained at various depths in genetically similar orebodies. The

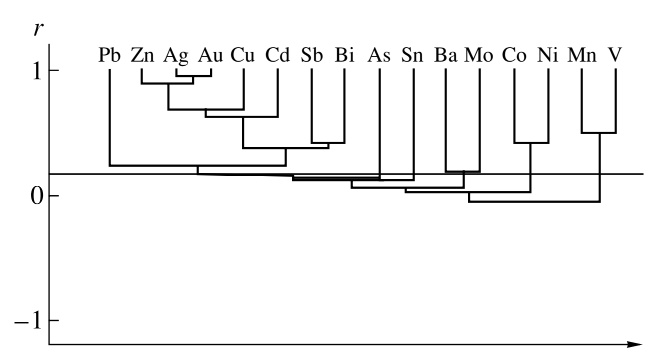

Fig. 5. Correlation dendrogram for the concentrations of chemical elements (n = 1113). Shaumyan deposit, level 780 m.

identification of the sequences of the zonal precipitation of chemical elements by the Nyu-2 program is conducted by analyzing the plots of the paired ratios of contents (productivities) of elements at the discrete levels of individual orebodies. If the plots have a complicated, uneven configuration, the criterion of a decrease or increase in a geochemical indicator of the first-order zoning 1 along a specified direction is assumed to be the position of the "centers of gravity" of these plots in the metrics of the sampled levels. The complete (square) matrix of the gravity centers of all plots is calculated for the paired ratios (both monotonous and nonmonotonous), which are then averaged (disregarding the diagonal of the matrix). According to the calculated average values, the elements are ranked updip to the mineralized zone and thus determine the deposition zonal sequence of these elements at a given orebody. The measure of similarities between the partial sequences of zoning in two orebodies is the value of the rank correlation coefficient. If a significant positive correlation is revealed, a generalized zonal sequence can be derived for the ore mineralization.

The other principal task of studying zoning at mineral deposits is determining geochemical indicators, which are dimensionless ratios of the average above-background concentrations (or productivities) of two or more chemical elements, which systematically vary within the contour of a given orebody. Indicators of zoning were traditionally applied to characterize the lateral and vertical variability of ore mineralization in the form of pair ratios of the concentrations of elements: Pb/Zn (base-metal deposits), Ag/Au (gold deposits), Cu/Mo (porphyry copper deposits), and others. Depending on the number of chemical elements written in the numerators and denominators of the geochemical zoning coefficients, the indicators differ in order: first-order indicators (ν = one chemical element/one chemical element), second-order indicators (ν = two chemical elements/two chemical element), third-order indicators (ν = three chemical elements/three chemical elements), and indicators of higher orders. Geochemical indicators of zoning are able to unambiguously characterize the erosion level if these indicators unidirectionally (monotonously) vary within a mineralized zone, including the orebody itself and its primary aureole. Neither the absolute concentration of any given element nor the ratios of the concentrations (productivities) of elements (which can assume equal numerically values in different sections of a single mineralized zone) can characterize the zoning of ore mineralization. The latter situation arises if a decrease (or an increase) in the value of ν along a specified direction gives way to its increase (decrease), and these unsystematic variations occur more than once. The plot of the geochemical zoning indicator can be of polygonal character with the transition from level to level, but the sign of its gradient should not change, and thus, the problem can be formulated as the analysis of various relations between the elements of the typomorphic complex with the aim of selecting monotonously varying zoning indicators.

The presence of a zonal succession of the precipitation of elements makes it possible to predict a decreasing or increasing character of the ν_z plots for given pairs of elements but does not characterize their monotonousness. Searches for monotonously varying zoning indicators start with an analysis of the plots of pair ratios of two elements. These first-order indicators ν_z may include no monotonously varying ones, their number can be small, and their resolution $R = \nu_{max}/\nu_{min}$ can be insufficient. In this situation, the researcher is forced to apply indicators of second, third, and higher orders, whose numbers progressively increase and are manyfold greater than the number of pair ratios of elements. The algorithm of the Nyu-2 program enables the researcher to analyze all first- through third-order indicators (and, if needed, also fourth-order indicators) with the aim of selecting only coefficients monotonously varying over the specified interval of ore mineralization. The coefficients are thereby characterized (increasing or decreasing and their resolution $R = \nu_{max}/\nu_{min}$).

The outcome of the processing of geochemical data with the Nyu-2 program is the selection of a set (six to ten) of zoning coefficients (most often, of the first or second orders) that monotonously vary with depth. The selected coefficients should have large enough amplitude R in the conditional metrics of the mineralized zone 0.0–0.1 [1–3] and should vary relatively evenly within this range. The sets of chemical elements in the numerator and denominator in selected ν should correspond to the succession of zonal precipitation established for the elements, and the sets of elements should maximally differ from one another. Their numerical values in a z (depth)–$\log\nu$ plot are used to assess (tax) a deposit or mineralized zone penetrated by single exploration workings in the metrics of the examined reference deposits. The results of the assessments are expressed in the form $z = \bar{z} \pm s/\sqrt{n}$, where $\bar{z} = \frac{1}{n}\sum_{i=1}^{n} z_i$ is the average estimate of the assessed (taxed) level (in levels, meters); s is the standard deviation of discrete assessments z_i, which is determined from the amplitude $R = (z_{max} - z_{min})$, and a tabulated coefficient β, which depends on the amount of the data [7, Appendix VI]; and n is the number of various ν selected for the assessment. The confidence levels for the assessment of the average value $\bar{z}$ characterize the reliability of the estimates and are utilized as criteria of the genetic closeness between the assessed ore mineralization and that of the reference deposit. The results of the assessment are considered satisfactory at $\pm s/\sqrt{n} \le 0.5$ for a "level" or ±40–50 m in linear units. At large confidence limits, it is expedient to revise the selection of the reference deposit.

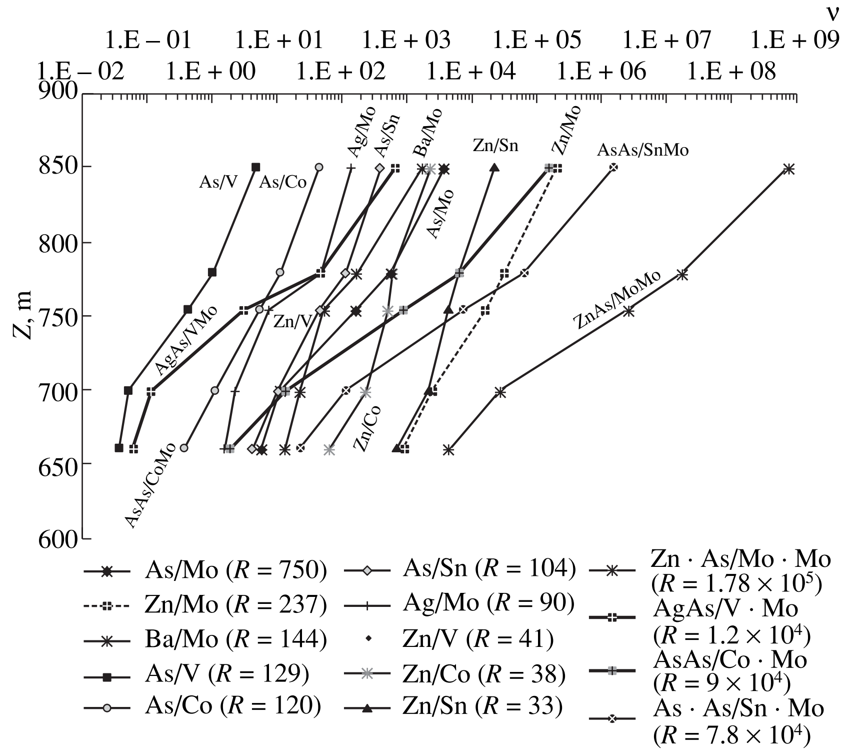

Fig. 6. Variations of the geochemical indicators of zoning with depth. Shaumyan gold–base metal deposit.

The processing (by the Nyu-2 computer program) of the data of the lithochemical sampling of the Shaumyan deposit allowed us to reveal 366 monotonously varying geochemical indicators of first- and second-order zoning, with 14 of these indicators selected as maximally contrasting. Figure 6 demonstrates variations in these indicators with depth. The selected geochemical indicators and the fourth-order multiplicative coefficient of zoning (described above) can be applied as reliable geochemical criteria for the assessment of the ore potential of the lithochemical anomalies during exploration for deep-seated ore mineralization of a given type and for the evaluation of the erosion level of mineralized zones, as well as for the prediction (on this basis) of the vertical variations in the reserves and the assessment of the reserves of the selected ore-forming metals.

KHARVANA OCCURRENCE OF GOLD–BASE METAL ORE MINERALIZATION

The Kharvana mining district in northwestern Iran is located 30 km southeast of the village of Kharvana at a distance of 100 km from the Shaumyan deposit. Gold mineralization was discovered within the field of Cretaceous–Oligocene flyschoid rocks cut and metamorphosed by intrusions and dikes of granodiorite porphyries, diorite porphyries, and andesites of the Eocene–Miocene age (Mehrparto, 1997). Structurally, Kharvana gold mineralization is hosted by the same tectono–metallogenic zone that also includes the Shaumyan gold–base metal deposit in southern Armenia.

The *mineralogy* of the Kharvana occurrence of gold–base metal mineralization is similar to that of the Shaumyan deposit. The orebodies at both Kharvana and Shaumyan are surrounded by zones of argillisites (up to secondary quartzites) and propylites. The major ore minerals are pyrite, chalcopyrite, galena, sphalerite, fahlores (which are strongly zoned from tennantite to Te–As tetrahedrite), and Pb, Hg, Ag, and Au–Ag tellurides. The gangue minerals are quartz, adularia, Mn-bearing calcite, and ripidolite. The chemical compositions of the major ore minerals are fairly close to those of analogous minerals from the Shaumyan deposit. The Kharvana ores include a late productive gold–telluride association of ore minerals. Our samples were devoid of selenides and had low concentrations of Se in the sulfides and tellurides, perhaps, because of the significant depth of the erosion level. We were the first to describe coloradoite, sylvanite, and hessite at Kharvana. Coloradoite aggregates in the Kharvana ores are larger (up to 1 mm, Fig. 7), enriched in Pb (3.7–6.7 wt %), and shows a negative correlation between Pb and Hg concentrations (Table 3). In contrast to the Shaumyan ores, in which gold is contained mostly in sylvanite, the Kharavna ores contain native gold. The latter occurs in close association with coloradoite (Fig. 8) and, conceivably because of this, does not contain mercury.

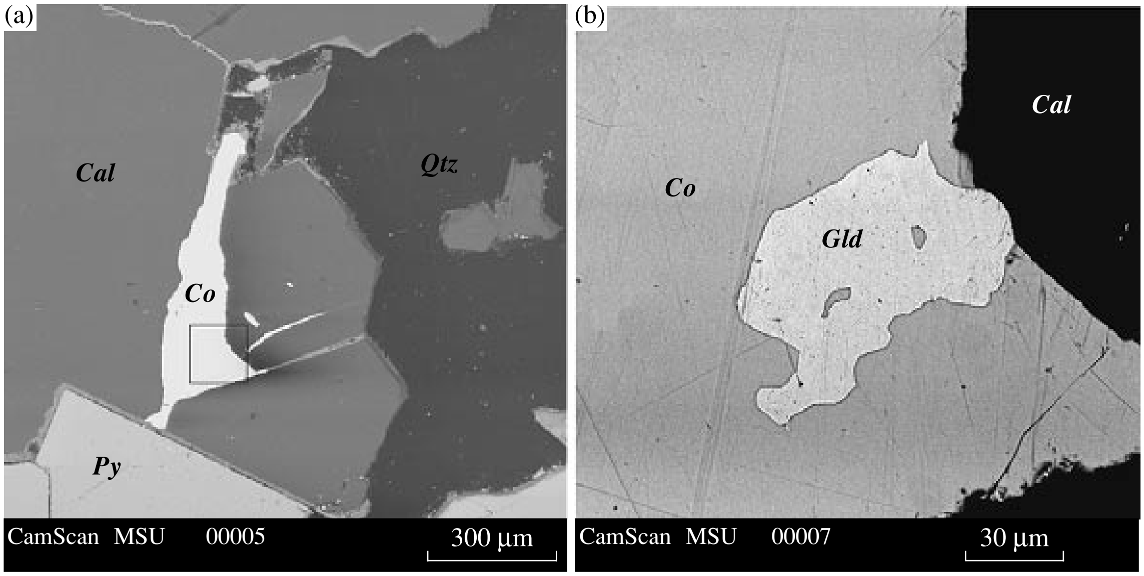

Fig. 7. (a) Metasomatic ingrowths of coloradoite (*Co*) with native gold in Mn-bearing calcite (*Cal*) near contact with pyrite (*Py*) and quartz (*Qtz*). (b) Enlarged fragment of the image in Fig. 7a: aggregates of coloradoite and native gold (*Gld*). Kharvana occurrence of ore mineralization, BSE image.

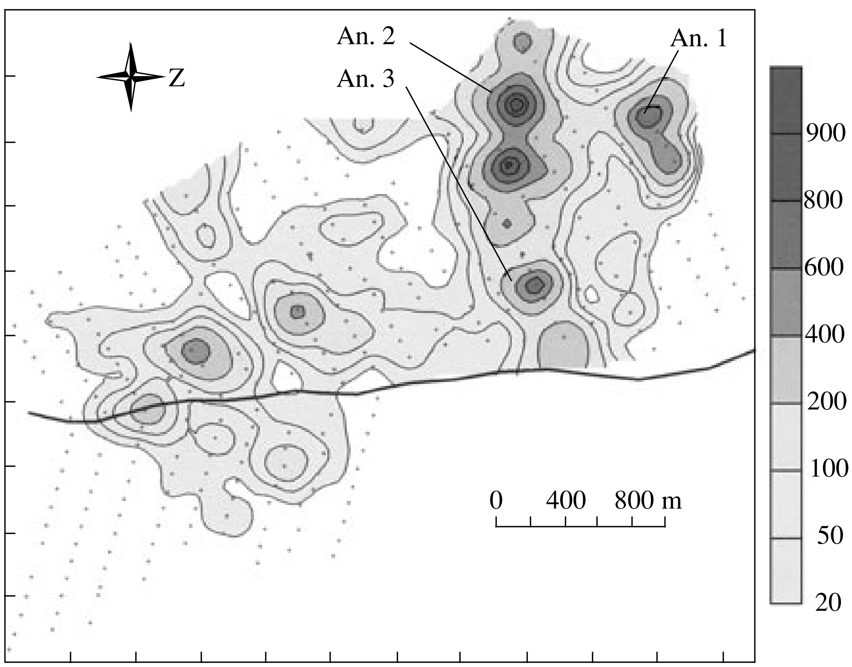

Fig. 8. Schematic map of gold distribution at the Kharvana occurrence of ore mineralization.

Gold grains at most hydrothermal deposits are compositionally zonal (practically always show normal zoning, with the inner parts of gold particles being richer in gold and having a higher fineness, and their outer zones being higher in silver and having a lower fineness [5]). The Kharvana gold typically has reversed zoning: the outer rims of large gold grains and small gold particles are enriched in Au and have a fineness of 953–970, and their cores are 937–945 fine (Table 4). The probable reason for this character of gold distribution is an increase in the chemical potential of Te in the solutions during the crystallization of native gold, with progressively greater amounts of silver accommodated in hessite.

Table 4. Chemical composition (wt %) of native gold (in aggregates with coloradoite) from the Kharvana deposit

No.	Au	Ag	Cu	Hg	Total	Fineness, ‰
18	93.46	5.55	0.05	0.00	99.06	943
19	94.47	5.45	0.06	0.00	99.98	945
20	95.39	4.75	0.00	0.00	100.14	953
21	96.30	4.42	0.00	0.00	100.72	956
22	93.97	6.33	0.03	0.00	100.33	937
23	95.28	6.20	0.02	0.00	101.50	939
24	93.85	5.87	0.06	0.00	99.78	941
25	96.21	4.39	0.00	0.00	100.60	956
26	97.75	2.97	0.08	0.00	100.80	970
27	97.59	3.04	0.00	0.00	100.63	970

Note: (18–21) Medium-sized gold grain (18—core, 19, 20—intermediate zones, 21—margin). (22–25) Medium-sized gold grain (22—core, 23, 24—intermediate zones, 25—margin). (26–27) Small gold grain (26—core, 27—margin). Analyses were conducted on a Camebax electron microprobe, analyst I.M. Kulikova.

GEOCHEMISTRY AND PREDICTED RESERVES

In order to study the geochemical characteristics of the gold–base metal ore mineralization at Kharvana and assess its reserves, a lithochemical survey was conducted over an area of 16 km^2 within secondary dissemination aureoles and on a grid of 200×50 m within primary aureoles, with subsequent more detailed surveying on a grid of $100 \times 20(5)$ m. The samples thus collected were semiquantitatively analyzed by emission spectral techniques for 22 elements at the certified laboratory of the Testing and Methodical Expedition in Aleksandrov. The chemical spectral analyses for gold were also conducted at this laboratory (with a detection limit of 5×10^{-7}%). Based on the results of the analyses, eight anomalous zones were recognized within the study area, with anomalies 1, 2 and 3 (Fig. 8) being the most interesting according to their areas with gold ore mineralization and the gold concentrations. The average gold concentrations were as follows: 232×10^{-7}% for anomaly 1, $11.4 \times\times 10^{-7}$% for anomaly 2, and 166×10^{-7}% for anomaly 3. The maximum contents for all of the anomalies were 1.5 ppm Au. The principal accompanying elements of Au were Cu, Ag, Zn, Pb, and Mo. The correlations between the concentrations of elements determined at the Kharvana occurrence are fairly close to those at the Shaumyan deposit (Fig. 9). The main ore elements (group I) are here, along with Au, also Ag, Pb, Zn, As, and Cd. In contrast to the Shaumyan ores, the Kharvana ores show weaker correlations between these elements and Au, perhaps, because the latter occurs predominantly in a native metal form. The elements of group II (Sb, Cu, Mo, Ni, Co, and V) form both introduction and removal aureoles. The elements of removal aureoles are Mn, Bi, and Ba (group III), whose anomaly fields are spatially restricted to the peripheral parts of the gold–base metal ore mineralization. The close geochemical similarities between the ores, primary aureoles, and secondary dissemination aureoles of the two compared deposits are also evident from the estimate of the correlation coefficients between the correlation matrices calculated for 15 elements at these two deposits; the numerical value of this coefficient is $r_{\text{S-K}} = +0.73$ at $r_{5\%} = 0.19$. The similarities between the modal and geochemical compositions of the two compared gold–base metal deposits allowed us to evaluate the erosion level of the Kharvana deposit and to assay its predicted reserves using the geochemical criteria proposed during the study of geochemical characteristics and zoning of the thoroughly explored Shaumyan reference gold–base metal deposit. We used six first-order indicators to assay (tax) the erosion level of the Kharvana occurrence. This estimate indicates that Kharvana was eroded to depths below the mineralized zone (Table 5). These values were 594 ± 41 m (a.s.l.) for

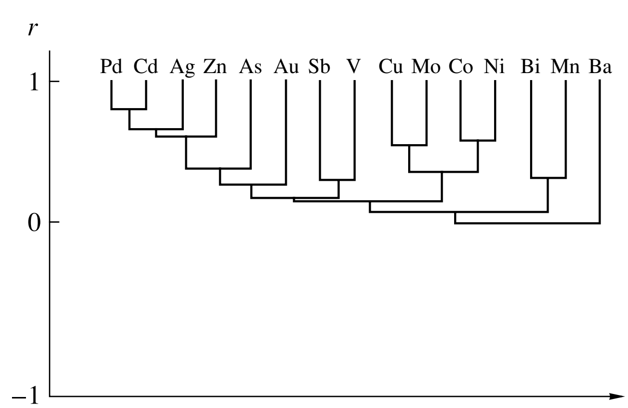

Fig. 9. Correlation dendrogram for the concentrations of chemical elements (n = 683). Kharvana occurrence of ore mineralization, surface.

Table 5. Erosion level depth evaluated for the Kharvana occurrence of ore mineralization based on six geochemical indicators in the metrics of the Shaumyan deposit

Anomaly 1										
Form of ν	V/Zn	Co/Ag	Co/Zn	Ag/Mo	Zn/Mo	Ba/Mo	z_{av}, m	$R = z_{max} - z_{min}$, m	*s*, m	$\pm s/\sqrt{n}$
Numerical value of ν	0.8	60.2	0.2	0.1	41.5	164.5				
z, m	583	548	517	585	558	773	594	257	101	41
Anomalies 2 and 3										
Form of ν	V/Zn	Co/Ag	Co/Zn	Ag/Mo	Zn/Mo	Ba/Mo				
Numerical value of ν	0.6	25.2	0.2	0.3	42.9	108.5				
z, m	600	603	523	614	559	758	610	236	93	38

anomaly 1 and 610 ± 38 m for anomalies 2 and 3. With regard for the evaluated erosion level depth, Kharvana can be attributed to a subeconomic type, and it is hardly expedient to conduct further exploration operations at it. The geochemical assessment of the Kharvana occurrence was confirmed by the materials of exploration drilling: horizontal Borehole 3 drilled through anomaly 1 did not penetrate economic gold mineralization.

PRINCIPAL CONCLUSIONS

(1) Our data obtained on the mineralogy of ores from the Shaumyan gold–base metal deposit in southern Armenia and the Kharvana occurrence of gold mineralization in northwestern Iran revealed close similarities: similar mineral associations and the chemistry of major ore and gangue minerals. These data confirm the earlier conclusion, drawn based on geological evidence, that both objects affiliate with a single tectonometallogenic zone. We were the first to discover Pb-bearing coloradoite at the Shaumyan deposit. A late productive gold–telluride stage of ore mineralization was identified at both objects. The Shaumyan ores contain gold concentrated mostly in sylvinite, whereas gold at the Kharvana occurrence is present mostly in a native form.

(2) We examined the morphology and geochemistry of the primary aureoles and ores of the Shaumyan deposit, revealed characteristic geochemical associations at discrete levels of ore mineralization, and determined the partial and general [Sn—V—Ni—Co—Cr—Cd—Cu—(Au)—Zn—Ag—As—Pb—Ba] sequences of the zonal precipitation of elements. We established contrasting geochemical indicators of first and second orders, which can be utilized as geochemical criteria for evaluating the erosion level and assaying the vertical distribution of the reserves of ore occurrences belonging to analogous types.

(3) We revealed close similarities between the geochemistry of ores and primary aureoles of the Shaumyan deposit and Kharvana occurrence, and this allowed us to determine a deep (below the mineralized zone) erosion level of the Kharvana occurrence in the metrics of the Shaumyan deposit. With regard for these data, the Kharvana occurrence is classified as subeconomic. Our geochemical conclusions were confirmed by the materials of exploration drilling.

ACKNOWLEDGMENTS

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