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Factor analysis of the geochemical associations in Milin Kamak ore deposit, Bulgaria

Факторен анализ на геохимичните асоциации в находище Милин Камък, България

Ivan Marinov, Kamen Popov, Kalin Ruskov, Daniela Nikolova
Иван Маринов, Камен Попов, Калин Русков, Даниела Николова

University of Mining and Geology "St. Ivan Rilski", 1700, Sofia; E-mails: imarrinov@gmail.com; kpopov@mgu.bg; rouskov@mgu.bg; danny.nikolova@abv.bg

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Introduction. The Milin Kamak deposit is located in the area of Western Srednogorie, municipality of Breznik. The intensive exploration activities carried out between 2004–2018, including surface and underground exploration works, prove the economic importance of the deposit. There has been confirmed intermediate sulfidation epithermal gold-silver deposit with associated components of Pb, Zn and Cu (Sabeva et al., 2012). The ore zones are localized in 8 veins, developed among lapilli tuffs and basalt dykes, affected by argillic and sericitic alteration. The main objective of this study is to determine spatial distributions of the elements and 3D modelling of geochemical association.

Materials and methods. To determine the spatial correlation and geochemical associations, the data obtained during the exploration drilling program conducted in the period 2016–2018 and provided by Trace Resources Ltd was used. A total of 36615 samples from 393 drill holes and 11 trenches were analyzed for the study of the primary geochemical haloes of the Milin Kamak deposit. The drilling samples were analyzed by ICP analysis for 33 elements. Some of the analyzed elements that are not part of the ore-forming processes and are below the detection limit of the analysis are excluded. A total of 22 elements were included for the statistical data processing (Ag, Bi, Cu, Sb, Cd, Zn, Pb, As, Au, Mn, Mo, Ba, Be, Cr, Ni, W, Co, Fe, Ti, V, Ca, Mg).

The methodology to determine geochemical associations and developed by Popov (2002, 2016) is used to evaluate the spatial correlation of the elements and the 3D modelling. The statistical processing includes as follows: preliminary data preparation and univariate statistical analysis; correlation and cluster analysis; factor analysis and 3D modelling of the geochemical association. Principal component analysis with varimax normalized rotation method was applied to evaluate the factors. To evaluate the spatial distribution of established geochemical associations, the data was processed with Leapfrog 3D modelling software. Radial Basis Function (RBF) was used to interpolate the scattered data with varying sample density.

Results and discussion. The results of the factor analysis for 22 elements are presented in Table 1, where the factors are distributed into 6 axes. Based on the factor analysis, the scores for each sample in the given factor can be calculated (Popov, 2002, 2016). This approach makes it possible to perform further modelling concerning the factor scores that represent the spatial relationship between elements (Fig. 1). Six groups of factors with similar spatial distribution were obtained in the Milin Kamak deposit as a result of the applied methods. The association of ([As] Au) Mn with a negative correlation with Ca, Mg from factor 6 represents the main ore body and coincides with the positions with the highest Au contents. The distribution of the factor is along the entire ore zone 1 as well as zone 2. The geochemical anomalies are worse represented in other ore zones. Along zone 1, factor scores are most manifested in the eastern parts and hypsometrically in the upper levels above elevation 720. From a mineralogical point of view, the group most likely represents the finely dispersed invisible Au inclusion in pyrite presumable quartz-polymetallic stages (Sabeva et al., 2012; Nikolova, 2019). The

Table 1. Factor analysis for determination of the geochemical association. Highest factor loadings of elements are marked in bold and intermediate values are in bold-italic

Elements	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Ag	0.129538	–0.034905	–0.014001	***0.460687***	0.008553	0.120547
As	0.042227	0.050795	0.062438	***0.296357***	0.028852	**0.709866**
Au	–0.111833	–0.022826	0.020344	***0.256040***	0.083714	**0.547751**
Ba	–0.125752	0.020482	0.055676	***0.209070***	**–0.615572**	–0.054150
Be	0.105433	0.036271	0.168534	***–0.261221***	**–0.722406**	0.136835
Bi	0.161150	0.034319	0.038025	**0.620976**	0.058981	0.099131
Ca	–0.176895	***–0.478813***	0.113403	–0.123995	***0.260469***	***–0.479001***
Cd	**0.919101**	–0.018240	0.013075	***0.209265***	0.031119	0.103896
Co	–0.023048	**0.650070**	***0.317638***	–0.043445	0.179290	0.055518
Cr	0.003650	–0.034024	**0.907819**	0.068698	–0.148048	0.000789
Cu	0.059131	0.028717	0.046833	**0.777120**	–0.095395	0.100236
Fe	0.104801	**0.661194**	0.024511	***0.293580***	***0.293082***	***0.222901***
Mg	–0.174965	0.134517	0.136188	–0.066101	***0.313753***	**–0.622256**
Mn	0.116927	–0.043619	0.015330	0.031830	0.042296	**0.497457**
Mo	0.064661	–0.013296	0.076506	–0.059073	0.106736	0.146235
Ni	0.010439	–0.027687	**0.937645**	0.032096	–0.001681	–0.004474
Pb	**0.838153**	–0.027846	0.003228	***0.319745***	0.029539	0.075001
Sb	0.238737	–0.040914	–0.000828	**0.736246**	–0.072103	0.099695
Ti	–0.072426	**0.801004**	–0.176495	–0.122495	–0.157082	–0.217914
V	–0.078108	**0.865131**	–0.099284	–0.072003	–0.134671	–0.176053
W	0.090085	0.027573	0.089191	–0.019597	0.110057	0.070748
Zn	**0.915405**	–0.012106	0.018586	***0.202217***	0.057566	0.124182
Expl.Var	2.640530	2.512934	1.931445	2.334715	1.305999	1.923549
Prp.Totl	0.120024	0.114224	0.087793	0.106123	0.059364	0.087434

association of factor 1 [Cd, Zn, Pb] is mainly developed in the most western part of zone 1 and zone 2. In the other parts of zone 1, as well as in the other zones, factor anomalies are poorly manifested. The distribution of this geochemical association is usually where factor 1 associations are the least prevalent. From a mineralogical point of view, the group clearly marks the distribution of minerals from the quartz-galena-sphalerite association. The ([Cu, Sb] Bi) Ag association explained by factor 4 has a similar spatial distribution with the factor 6 anomalies along ore zones 1 and 2. In the other zones, geochemical anomalies are not so well represented. This factor is more manifested in the central parts of zone 1 and is deeper than this of factor 6. The geochemical association clearly marks the distribution of minerals represented by the quartz-sulfosalt-pyrite-galena-sphalerite association. The 3D modelling of other geochemical associations, ([V, Ti] Fe, Co) by factor 2, [Ni, Cr] by factor 3 and [Be, Ba] by factor 5, shows no clear spatial attachment to any zone. They are probably not related to hydrothermal processes and are everywhere among lapilli tuffs and dykes.

Conclusion. The results of the multivariate factor analysis and 3D modelling of the factor scores make it possible to clarify the geochemical associations and spatial distribution of groups of elements characterized by a certain similarity. The association of ([As] Au) Mn from factor 6 is marked by spreading of quartz-polymetallic stages and represents the ore zones 1 and 2. The association of factor 1 [Cd, Zn, Pb] probably follows the distribution of quartz-galena-sphalerite association while factor 4 ([Cu, Sb] Bi) Ag clear marks quartz-sulfosalt-pyrite-galena-sphalerite association. The 3D modelling of the similarity in the spatial distribution of the elements clearly shows that the elements in factors 1, 4 and 6 are related to hydrothermal ore-forming processes and represent the ore bodies. A certain spatial zoning is also observed: [Cd, Zn, Pb] association is mainly located in the western parts of the ore zone 1, away from the geochemical associations ([Cu, Sb] Bi) and ([As] Au) Mn, and the latter two associations overlap spatially to some extent.

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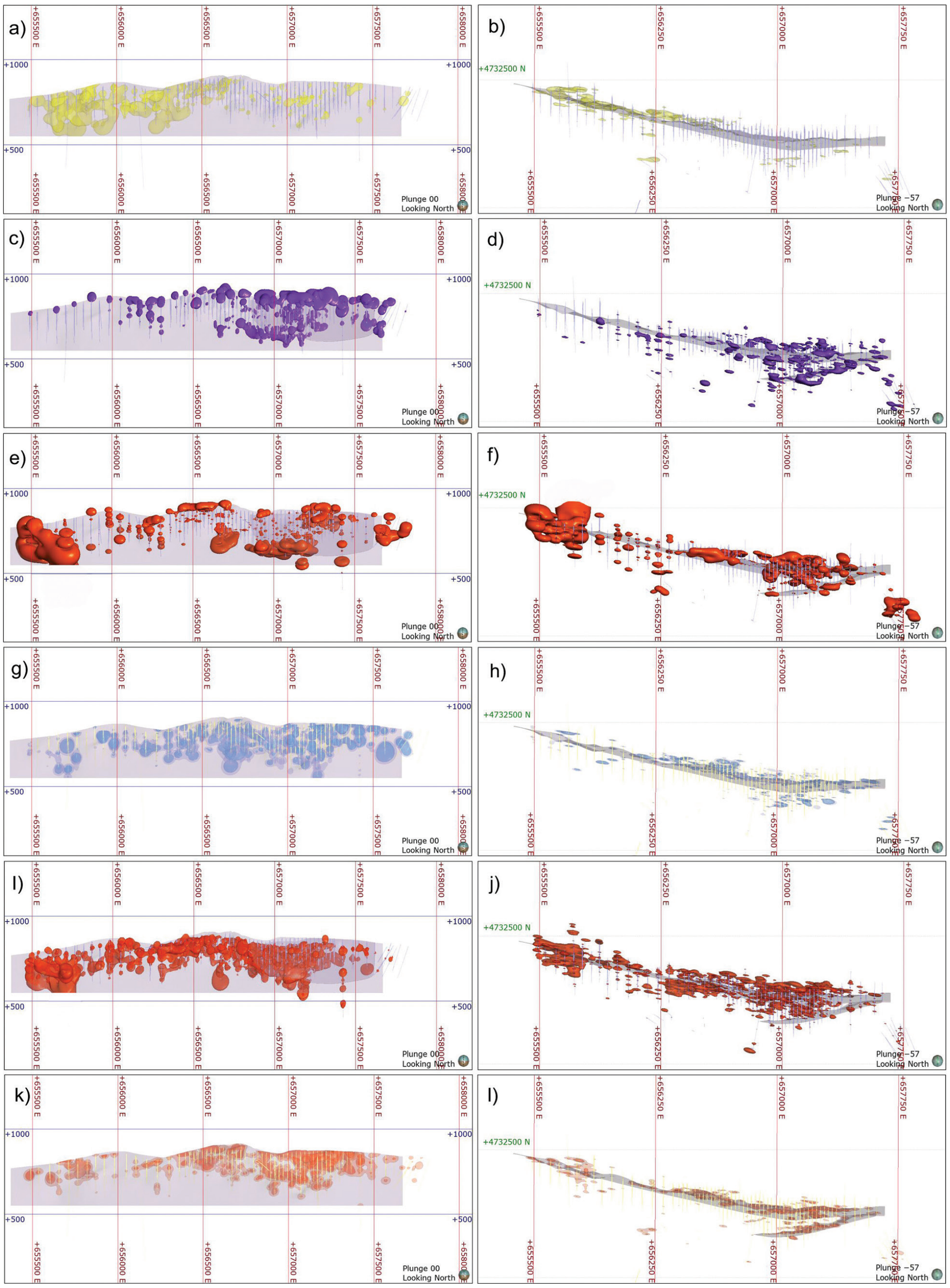

Fig. 1. Distribution of the geochemical associations: *a*, cross section and *b*, plane view of [Cd, Zn, Pb] association (Factor 1); *c*, cross section and *d*, plane view of ([V, Ti] Fe, Co)–Ca association (Factor 2); *e*, cross section and *f*, plane view of: ([Ni, Cr]+Co association (Factor 3); *g*, cross section and *h*, plane view of ([Cu, Sb] Bi)+Ag, Pb±As, Fe, Au, Ba, Zn association (Factor 4); *i*, cross section and *j*, plane view of -[Be, Ba], positive±Mg, Fe, Ca association (Factor 5); *k*, cross section and *l*, plane view of ([As] Au) Mn±Fe–([Mg] Ca)±Fe association (Factor 6)

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