GEOCHEMICAL ASSOCIATIONS IN THE SEDEFCHE ORE DEPOSIT, BULGARIA

Stoyan Klimentov, Kalin Ruskov, Kamen Popov, Ivan Marinov

University of Mining and Geology “St. Ivan Rilski”, 1700 Sofia; E-mail: klimentov@gorubso.bg

ABSTRACT. The geochemical associations and spatial distribution of chemical elements in the Sedefche deposit are studied. The ore deposit is located in the easternmost part of the Zvezdel-Pcheloyad ore field. The data obtained during the exploration drilling program conducted in the period 2019-2020 by *Gorubso-Kardzhali JSC* was used to determine the spatial correlation between the chemical elements and their geochemical associations. A total of 28 elements were included for the statistical data processing. The results of the factor analysis reveal that the total variation is decomposed on 7 factor axes. The results of the 3D modelling of the factor scores contributes to clarify the geochemical associations and spatial distribution of groups of elements characterised by a certain similarity. The association of ([Ag, Pb, Sb, Au] Cu, As, Cd) from factor 2 represents the distribution of the main ore elements in the deposit. The other associations that follow the morphology of the ore bodies are represented by factor 1 ([Mn, Be, Co, Zn, Fe] Al, Ni, Tl) and factor 3 ([Hg, Tl, Mo, As] S, Au, K, Sb) and probably describe the distribution of the Quartz-sphalerite-galena, the Quartz-arsenopyrite, and the Sulfosalt parageneses.

Key words: Sedefche ore deposit, geochemical associations, 3D modelling, factor analysis.

ГЕОХИМИЧНИ АСОЦИАЦИИ В НАХОДИЩЕ „СЕДЕФЧЕ“, БЪЛГАРИЯ

Стоян Климентов, Калин Русков, Камен Попов, Иван Маринов
Минно-геоложки университет „Св. Иван Рилски“, 1700 София

РЕЗЮМЕ. Изследвани са геохимичните асоциации и пространственото разпределение на химичните елементи в находище „Седефче“. Находището е разположено в най-източните части на Звездел-Пчелоядското рудно поле. За определяне на пространствената корелация между химичните елементи и техните геохимични асоциации са използвани данни от проучвателното сондиране, извършено в периода 2019-2020 от „Горубсо-Кърджали“ АД. Общо 28 химични елементи са използвани при статистическата обработка на данните. Резултатите от факторния анализ показват, че общата вариация е разложена на 7 факторни оси. Резултатите от 3D моделирането на факторните тегла допринася за определяне на геохимичните асоциации и пространственото разпределение на групите от елементи, характеризиращи се със сходно разпространение. Асоциацията ([Ag, Pb, Sb, Au] Cu, As, Cd) от фактор 2 представя разпространението на основните рудни елементи в находището. Другите асоциации, които следват морфологията на рудните тела, са представени от фактор 1 ([Mn, Be, Co, Zn, Fe] Al, Ni, Tl) и фактор 3 ([Hg, Tl, Mo, As] S, Au, K, Sb) и вероятно отчитат разпространението на кварц-сфалерит-галенит, кварц-арсенопирит и сулфосолната парагенези.

Ключови думи: находище „Седефче", геохимични асоциации, 3D моделиране, факторен анализ.

Introduction

The Sedefche ore deposit is located in the easternmost part of the Zvezdel-Pcheloyad ore field, which is defined by the development of the Zvezdel volcano-plutonic complex (Georgiev, 2012; Popov & Popov, 2022). Specifically, it is situated immediately to the north-northwest of the village of Sedefche. The ore field is part of the Momchilgrad ore sub-region, which coincides spatially with the Momchilgrad depression. The area of the deposit consists of two tectonic complexes, as noted by Georgiev (2012):

The Pre-Tertiary metamorphic complex comprises various metamorphic rocks, including biotite and dual-mica gneiss, amphibolite-biotite gneiss, marble, and kyanite-garnet-biotite schists. Their age is considered to be Pre-Cambrian.

The Tertiary volcanogenic-sedimentary cover is composed of sedimentary, volcano-sedimentary, and volcanic rocks. Limestones and sandy-loam rocks lie above the metamorphic rocks. In some areas, limestone is partially silificated. The volcanic activity during the Oligocene formed acid to intermediate composition lava dykes of rhyolite, dacite, and andesite.

Geological surveys outlined two ore bodies in the deposit: the Northern (central) and the Southern ore body (fig. 1). The Northern (central) ore body is located several hundred meters north of the village of Sedefche and is developed as an elongated strip (400 x 60 m) in an area of intensely hydrothermally altered pyroclastic rocks and andesites, trending in a N-NE direction (Dragiev, 2006). The basement includes marble, amphibolite, alternating chlorite, chlorite-amphibole and quartz-mica schists, and calc schist. Paleogene rocks built carbonaceous-sedimentary-tuffaceous series of Upper Eocene age (organogenic limestone and intermediate tuff, tuffites, and tuff-breccias). The Oligocene tension dyke complex is presented by gabbro-monzonite, andesite-basalt bodies, and rhyolite bodies and dykes covered by Quaternary eluvial-deluvial sediments (Boyanov, 1961).

The "South" ore body is located west of the village of Sedefche and has an elongated N-S shape. The mineralisation is developed within the silica cap overlying limestones and clay-sandy sediments.

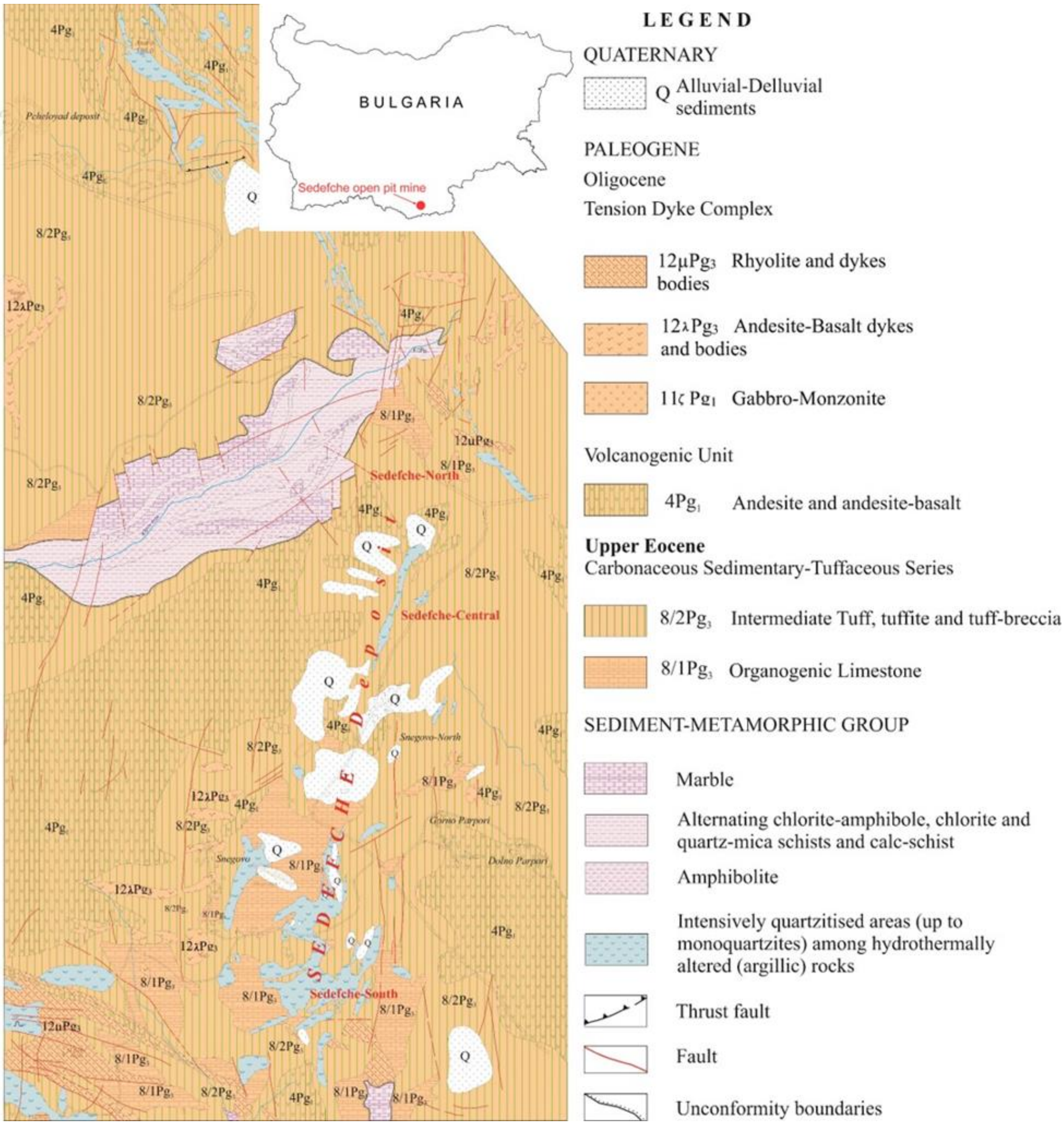


Figure 1 Geological map in scale 1: 50 000 (Cekova, V., 1965)

The ore bodies in the Sedefche deposit have a layer-like, pseudo-conformable shape (Georgiev, 2012). The Sedefche deposit is a typical representative of the low-sulfidation epithermal gold-silver deposit type. There are two broad styles of mineralisation:

Base-metal/low gold-bearing mineralisation containing abundant sulphides (pyrite and marcasite) and gold-silver bearing silica replacement bodies are present, which are partially stratabound and controlled by steep N-S structures that overprint the volcanism.

The first style of mineralisation is closely related to the Zvezdel-Pcheloyad alkalic intrusive complex, which also hosts the Pcheloyad lead zinc deposit. The second style of mineralisation is later and may be related to the younger resurgent rhyolite complex located south of the Sedefche deposit. The gold-bearing mineralisation contains abundant sulphosalts, with much of the gold being refractory.

Lyutov (2019) describes six mineral parageneses, including Quartz-arsenopyrite, Quartz-pyrite, Quartz-sphalerite-galena, Marcasite, Sulfosalts, and Calcite paragenesis.

Materials and methods

The data obtained during the exploration drilling program conducted in the period 2019-2020 by *Gorubso* JSC were used to determine the spatial correlation between the chemical elements and their geochemical associations. A total of 4668 core samples from 84 drill holes were analysed to study the primary geochemical haloes of the Sedefche deposit. The chemical content of the drilling samples was determined by ICP analysis for 33 chemical elements.

A total of 28 elements were included for the statistical data processing (Au, Ag, Pb, Zn, Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Mo, Na, Ni, P, S, Sb, Sr, Ti, Tl, V). Some of the analysed elements which are not typical of the ore-forming processes or their contents are below the detection limit of the analysis are excluded from further statistical processing.

The methodology used to evaluate the spatial correlation of elements and the 3D modelling of the factor loadings involves factor analysis (Popov 2002, 2016). The statistical processing methods utilised in this study include preliminary data preparation and univariate statistical analysis, correlation and regression analyses, multivariate statistical analyses such as cluster and factor analysis, and 3D modelling of the resulting geochemical association. A principal component analysis with varimax rotation was performed to evaluate the factors, and statistical processing was conducted using the *Jamovi* software. The results were then processed with the *Leapfrog* 3D modelling software utilising Radial Basis Function (RBF) interpolation to visualise the spatial distribution of invoked geochemical associations.

Results and discussion

The results of the factor analysis for the 28 elements are shown in Table 1, where the total variation is decomposed on 7 factor axes.

Table 1. Factor analysis for determination of the geochemical associations. Only the factor loadings larger than ±0.3 are shown.

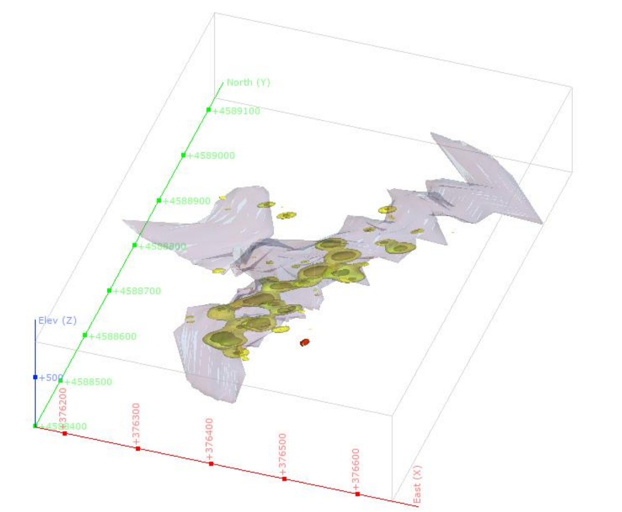
	F1	F2	F3	F4	F5	F6	F7	Uniqueness
Au		**0.539**	0.319					0.598
Ag		**0.881**						0.214
Pb		**0.841**						0.278
Zn	**0.692**							0.355
Al	0.422			0.463			0.366	0.405
As		0.436	**0.508**					0.483
Ba					-0.313	0.301		0.633
Be	**0.818**							0.286
Ca				**-0.783**				0.275
Cd		0.390						0.710
Co	**0.769**							0.313
Cr					**0.793**			0.277
Cu		0.500						0.738
Fe	**0.680**							0.392
Hg			**0.775**					0.392
K			0.353	0.330		0.420		0.508
Mg				**-0.684**				0.498
Mn	**0.854**							0.214
Mo			**0.672**					0.482
Na						**0.758**		0.387
Ni	0.406				**0.811**			0.172
P				0.330			**0.749**	0.293
S			0.418	0.386		-0.339		0.424
Sb		**0.768**	0.301					0.316
Sr							**0.803**	0.258
Ti					0.390	**0.634**		0.430
Tl	0.370		**0.714**					0.337
V				0.482		0.427	0.394	0.402

Note. 'varimax' rotation was used

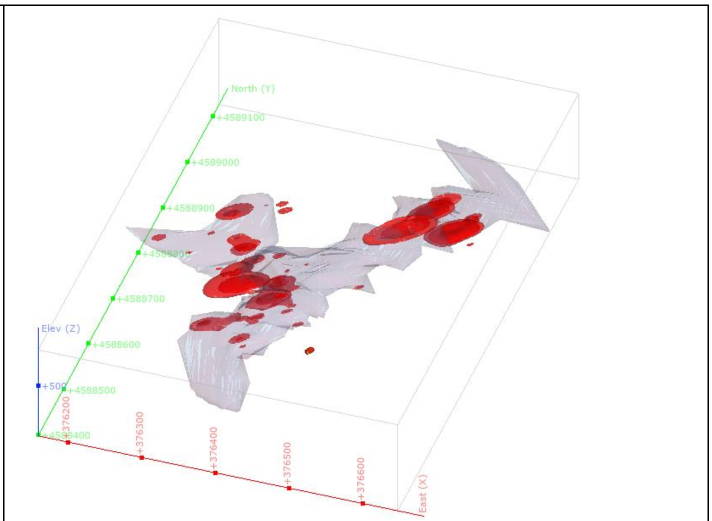
The groups of elements with the highest loadings in each factor represent the geochemical associations. Thus, the obtained geochemical associations of elements with similar spatial distribution presented by each factor are as follows:

Factor 1: ([Mn, Be, Co, Zn, Fe] Al, Ni, Tl)
Factor 2: ([Ag, Pb, Sb, Au] Cu, As, Cd)
Factor 3: ([Hg, Tl, Mo, As] S, Au, K, Sb)
Factor 4: -([Ca, Mg]) (Al, V, K, S, P)
Factor 5: ([Ni, Cr] Ti) -(Ba)
Factor 6: ([Na, Ti] V, K, Ba) -(S)
Factor 7: ([Sr, P] V, Al)

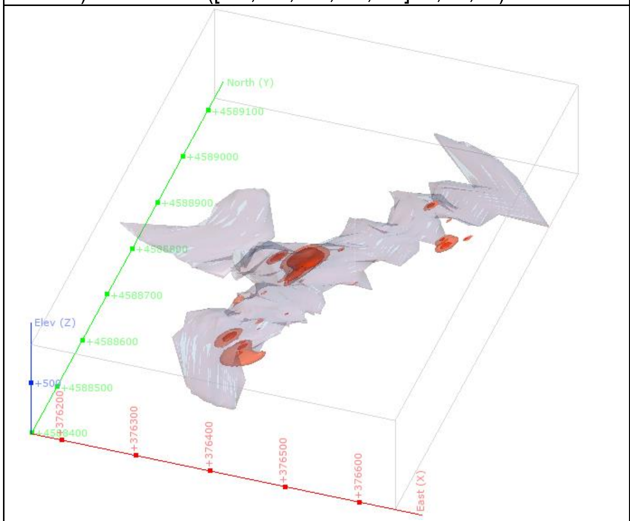
Based on the factor analysis, the scores for each sample in the given factor can be calculated (Popov, 2002, 2016). This approach allows to perform further 3D modelling considering that the factor scores represent the spatial relationship between elements (Fig. 1).



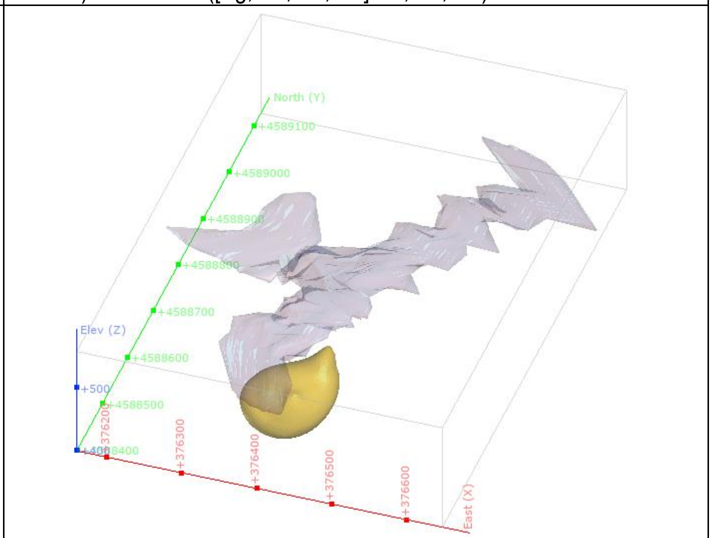
A) Factor 1: ([Mn, Be, Co, Zn, Fe] Al, Ni, Tl)



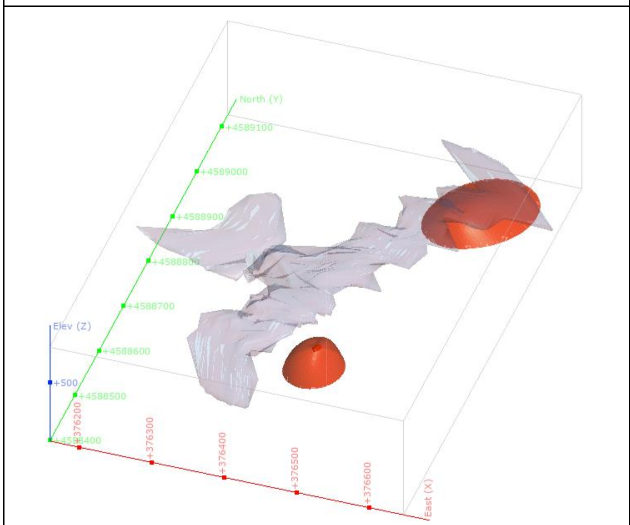
B) Factor 2: ([Ag, Pb, Sb, Au] Cu, As, Cd)



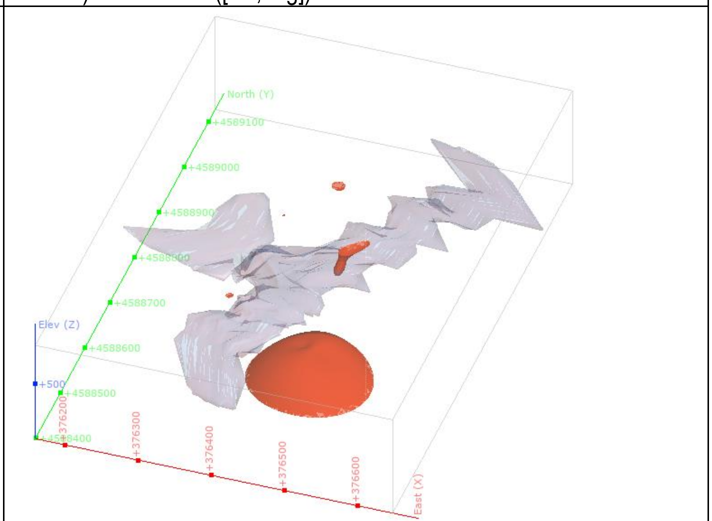
C) Factor 3: ([Hg, Tl, Mo, As] S, Au, K, Sb)



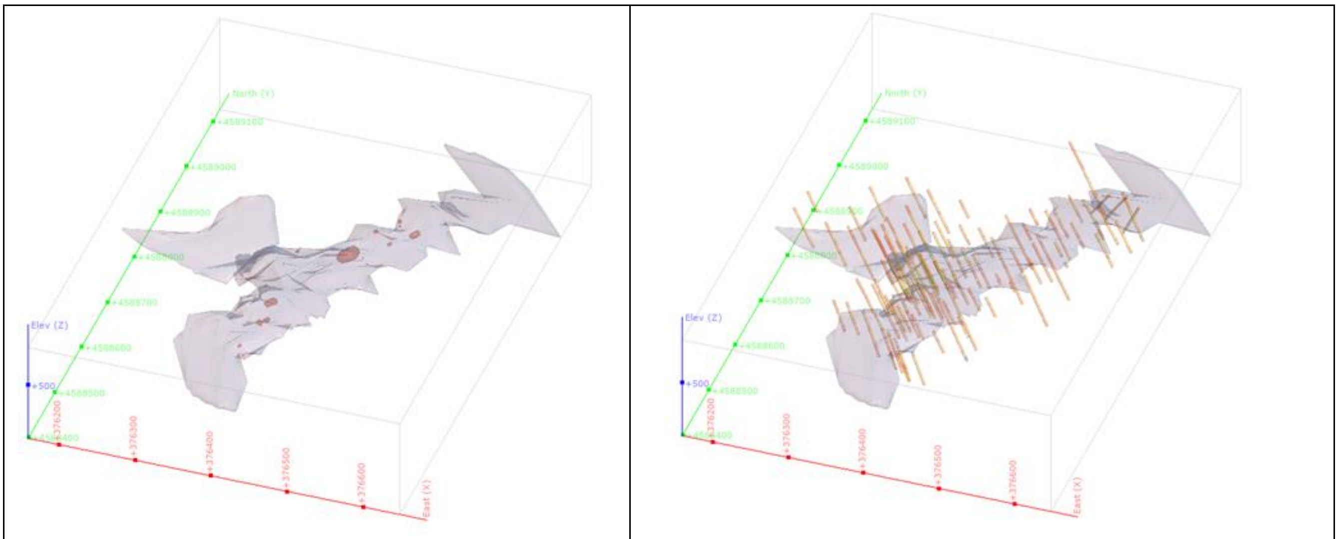
D) Factor 4: -([Ca, Mg])



E) Factor 5: ([Ni, Cr] Ti)



F) Factor 6: ([Na, Ti] V, K, Ba



G) Factor 7: ([Sr, P] V, Al)

H) Drill holes used for modeling

Fig. 2 Spatial distributions of the geochemical associations. The isosurfaces are constructed at the threshold values for each factor - the arithmetic mean + standard deviation.

The first factor considers the behaviour of the group of elements Mn, Be, Co, Zn, and Fe. The lower weights of Al, Ni, and Tl mark their tendency to connect to this group. This factor follows the spatial distribution of the main ore zone and the Quartz – pyrite mineral paragenesis.

The second factor represents the distribution of the main ore elements in the Sedefche deposit, which are joined in an association of Ag, Pb, Au, and Sb, as well as Cu, As, and Cd with lower loadings. This factor coincides with the spatial distribution of all ore zones and probably follows the Quartz-sphalerite-galena and the Quartz-arsenopyrite mineral parageneses.

The third factor describes the association with the core of Hg, Tl, Mo, and As, which have a high correlation with each other. The elements Au, K, S, and Sb also join here with lower weights. The development of this group of elements also falls within the limits of the main ore body and the main ore paragenesis, as their distribution is much more fragmented than that of factor 2.

The fourth factor represents the association of Ca and Mg but with negative values. The elements Al, K, P, S, and V have a relatively weak correlation to this factor, which marks their inversely proportional dependence on Ca and Mg.

The fifth factor groups Cr and Ni, as Ti also shows some weak relation to them.

The sixth factor describes the association of B, K, Na, Ti, and V, with S showing some negative correlation here.

The seventh factor has a high correlation with P and Sr and a lower correlation with Al and V.

The results of three-dimensional modelling of the distribution of geochemical associations clearly emphasise the existing zonation in the deposit.

Conclusion

The results of the 3D modelling of the factor scores contribute to clarifying the geochemical associations and spatial distribution of groups of elements characterised by a certain similarity. The association of ([Ag, Pb, Sb, Au] Cu, As, Cd) from factor 2 represents the distribution of the main ore elements in the deposit. The other factors that follow the morphology of the ore bodies are factor 1 and factor 3, and probably follow the distribution of Quartz-sphalerite-galena, Quartz-arsenopyrite, and Sulfosalt parageneses.

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