MULTIVARIATE STATISTICAL ANALYSIS OF GEOCHEMICAL DATA FOR THE GOLD MINERALISATION IN THE OBICHNIK ORE DEPOSIT, BULGARIA (PRELIMINARY DATA)

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ABSTRACT. The geochemical characteristics and association of elements in the Obichnik ore deposit, as well as their spatial distribution, have been investigated in this study. The Obichnik deposit is located in the northern part of the Zvezdel-Pcheloyad ore field, which includes hydrothermal Pb-Zn and Au-Pb-Zn mineral occurrences associated with the Zvezdel volcano. The geochemical dataset obtained during the exploration drilling program of the deposit was used to determine the spatial correlation between the chemical elements and their geochemical associations. A total of 40 elements were included for the statistical data processing of more than 13,000 samples from 74 drillholes. A range of statistical processing methods were employed in a systematic sequence. The proposed methodology includes preliminary data preparation, univariate statistical analysis, and Principal component analysis (PCA) as a variety of factor analysis. The groups of elements with the highest loadings in each factor represent the geochemical associations. The associations that include ([Zn, Cd, Pb] S, Au, Cu) from factor 3 and ([As, Sb] Mo, Ag, K) from factor 4 represents the spatial distribution of the main ore zones. These two associations show similar directions of distribution.

Key words: Obichnik ore deposit, geochemical associations, multivariate statistical analysis.

МНОГОМЕРЕН СТАТИСТИЧЕСКИ АНАЛИЗ НА ГЕОХИМИЧНИ ДАННИ ОТ ЗЛАТНАТА МИНЕРАЛИЗАЦИЯ В НАХОДИЩЕ ОБИЧНИК, БЪЛГАРИЯ (ПРЕДДВАРИТЕЛНИ ДАННИ)

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РЕЗЮМЕ. В настоящата работа са изследвани геохимичните особености и асоциациите от химични елементи в находище Обичник, както и пространственото разпространение на тези асоциации. Находището е разположено в северните части на Звездел-Пчелоядското рудно поле, което включва хидротермални Pb-Zn и Au-Pb-Zn находища свързани с Звезделската вулкано-плутонична структура. Изследваната геохимична база данни е получена в резултат на сондажна програма от проучването на находището, като е използвана за определяне на пространствената корелация между химичните елементи и за извеждане на асоциациите от елементи. Общо 40 елемента бяха включени за статистическа обработка на данните от над 13 000 проби от 74 сондажа. Използвани са редица статистически методи за обработка, организирани в систематична последователност. Предложената методология включва предварителна подготовка на данните, едномерен статистически анализ и метод на главните компоненти (PCA), като разновидност на факторен анализ. Групите от елементи с най-високи факторни тегла във всеки фактор представляват геохимичните асоциации. Асоциациите ([Zn, Cd, Pb], S, Au, Cu) от фактор 3 и ([As, Sb] Mo, Ag, K) от фактор 4 представят пространственото разпределение на основните рудни зони. Тези две асоциации показват сходни посоки на разпространение.

Ключови думи: находище Обичник, геохимични асоциации, многомерни статистически методи.

Introduction

Multivariate statistical analysis encompasses a variety of methods, such as cluster analysis and factor analysis, which can identify geochemical features in ore mineralisation, hydrothermal alterations, and characteristics of the host rock within an ore system. This would assist in the interpretation of ore deposit models and supporting exploration programs of these deposits. Principal component analysis is one of the most popular multivariate statistical techniques. Several case studies focus on the statistical analysis of geochemical data and applying factor analysis to map geochemical associations in an individual ore deposit (Popov 2002, 2016, Marinov et al. 2019, Klimentov et al. 2024).

The Obichnik ore deposit is situated in the northern part of the Zvezdel-Pcheloyad ore field which includes hydrothermal lead-zinc and gold-lead-zinc mineral occurrences associated with the Oligocene Zvezdel volcano-plutonic complex (Georgiev, 2012; Popov & Popov, 2022). The deposit is situated immediately to the north of the village of Obichnik and to the east of the village of Drumche. The Obichnik gold mineralisation is associated mainly with pyrite, sphalerite, galena, chalcopyrite, tennantite-tetrahedrite, and enargite, with gold variably distributed within these sulphides and quartz, sericite, kaolinite, illite/smectite, and adularia (Petrova and Stanchev, 1994).

The ore bodies come in two types - isometric (unclearly tubular) and sub-horizontal stratiform, according to their deposition format and conditions. The ore-forming process in the Obichnik area is in two-stages: gold-bearing quartz-sulphide and carbonate (Dragiev et al., 2010).

Geological settings

The Obichnik deposits is located in the South of Bulgaria (Fig. 1). It is situated in the Morava-Rhodope zone and its East Rhodope tectonic unit, according to the tectonic scheme of Dabovski et al. (2002). It is part of the Alpine-Himalayan belt. During the Late Cretaceous-Eocene times, it experienced subduction-collision events (Marchev et al., 2007). Late Cretaceous-Palaeocene magmatism is represented exclusively by plutons composed of amphibole-biotite granodiorite and biotite- and two-mica granites. In contrast, Late Eocene-Oligocene magmatism is represented by volcano-plutonic suites and intrusives with largely variable in K and Si. Epithermal deposits are associated with the magmatic rocks.

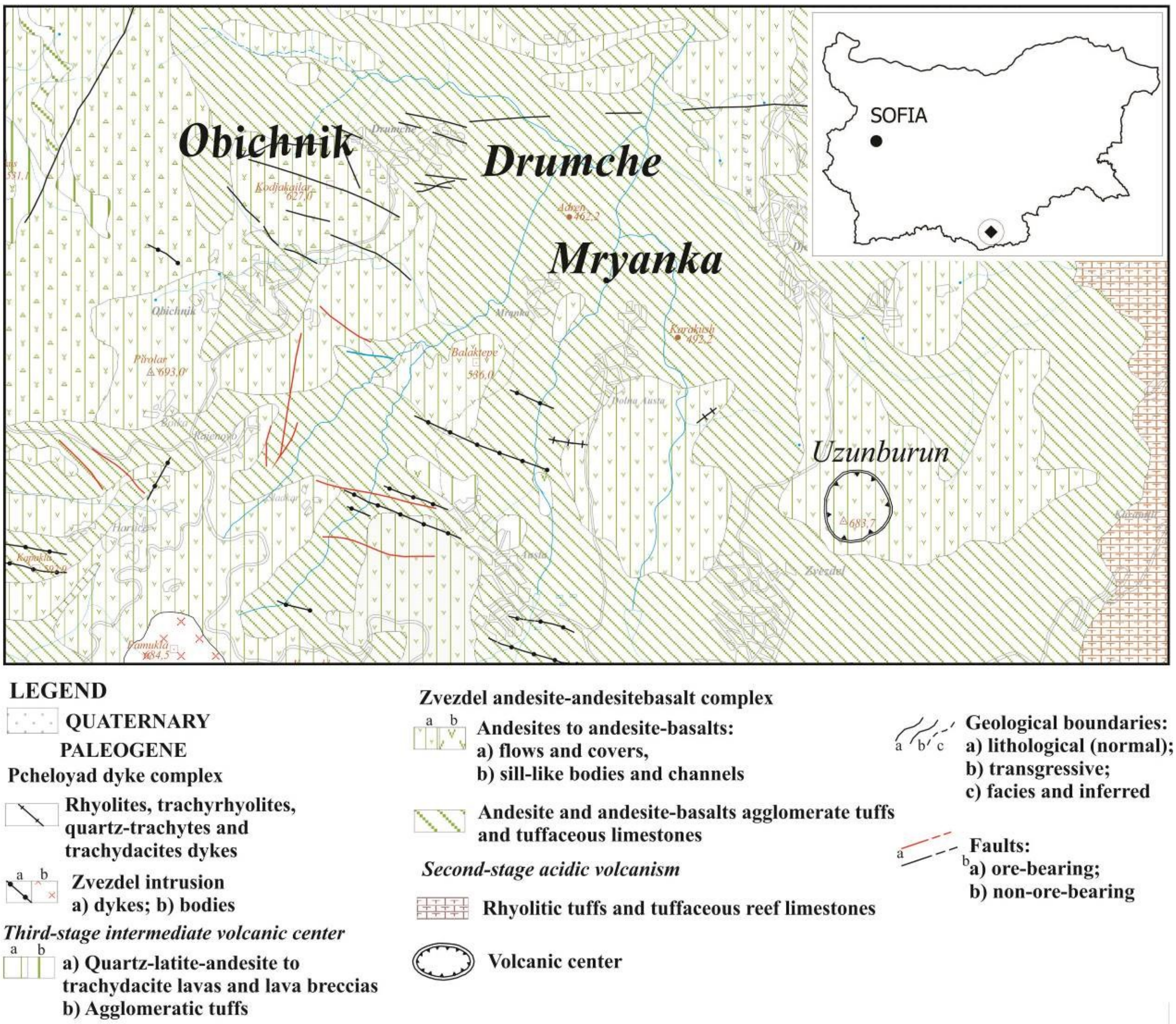

Fig. 1. Geological map in scale 1: 50 000 (after Cekova, V., 1965, Dragiev et al., 2010)

The most important Intermediate Sulphidation epithermal deposits (Chala, Madjarovo, and Zvezdel-Pcheloyad) are hosted in the shoshonotic and high K-Ca alkaline magmatic rocks of the Borovitsa, Madjarovo, and Zvezdel paleovolcanoes (Marchev et al., 2007). Occasional occurrences of Cu-Mo porphyry mineralisation have been identified in close spatial proximity. Intermediate rocks predominate in all three volcanic areas, with felsic varieties being voluminous in Borovitsa and subordinate in Madjarovo and Zvezdel.

The primary rocks comprising the Obichnik area are volcanics with andesitic composition, along with their pyroclastics, such as diverse breccia and tuffs, as well as diorite dykes (Fig. 1). Metasomatic and supergene alterations are observed in the area.

The Obichnik deposit can be considered as epithermal adularia-sericite type Au mineralisation with quartz-sulphidic gold-bearing and carbonate phases in the hypogenic stage (Kunov, Mandova, 1997). The mineralisation occurs within quartz-sericite-pyrite altered epiclastic breccias within an east-west trending zone of hydrothermal alteration (Abbott, 2021).

Ore mineralisation is associated with several types of alteration. The following are distinguished: propylitic, argillic (locally occurring), and quartz-adularia-sericite, which is the most distinct and to which the gold mineralisation is associated.

Materials and methods

The data obtained during the exploration drilling program of the deposit were used to determine the spatial correlation between the chemical elements and their geochemical associations. A total of 13 462 core samples from 74 drill holes were analysed to study the primary geochemical haloes of the Obichnik deposit area. The chemical content of the drilling samples was determined for gold by fire assay and by Inductively Coupled Mass Spectrometry (ICPMS) analysis for 40 chemical elements.

A total of 29 elements were included for the preliminary statistical data processing (Au, Ag, Pb, Zn, Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, La, Mg, Mn, Mo, Na, Ni, P, S, Sb, Sc, Sr, Ti, V). Those of the analysed elements which are not typical of the ore-forming processes, or their contents are below the detection limit of the analysis or have constant values, are excluded from further statistical processing.

A range of statistical processing methods were employed in a systematic sequence (Popov 2002, 2016, Marinov et al. 2019, Klimentov et al. 2023) in this study. The methodology used for assessing the spatial correlation of elements and creating 3D models of factor loadings includes preliminary data preparation, univariate statistical analysis, as well as correlation and regression analyses. This part of the methodology enables the identification and rectification of errors in the data. The next step encompasses multivariate statistical techniques such as cluster and factor analysis. Sophisticated 3D modelling techniques were applied to visualise the resulting geochemical associations. Principal component analysis (PCA), as a variety of factor analysis, represents a statistical procedure that allows the information content in a large dataset to be summarised by means of a smaller set of factors, which can be more easily visualised and analysed.

Principal component analysis with varimax rotation was executed to calculate the factors. The statistical processing was conducted using the *Jamovi* software, ensuring robust analysis. Subsequently, the outcomes underwent further refinement using the *Leapfrog* 3D modelling software. This involved employing the Radial Basis Function (RBF) as an interpolant to effectively visualise the spatial distribution of the identified geochemical associations.

The Cluster analysis method represents another data exploration tool for dividing a multivariate dataset into “natural” clusters (groups). Hierarchical approach is used and the distance between two clusters is defined to be the average distance between data points in the first cluster and data points in the second cluster.

Table 1. *Results of Principal Component Analysis (PCA). Only the factor loadings larger than ±0.3 are shown.*

Component Loadings

	Component							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**Uniqueness**
Fe	**0.82**							0.266
Co	**0.78**							0.342
Mn	**0.779**							0.289
Sc	0.655				0.538			0.223
P	0.446						0.445	0.53
Ca		**0.834**						0.257
Sr		**0.734**						0.386
Mg		**0.726**						0.273
Be		0.672						0.41
Zn			**0.884**					0.186
Cd			**0.845**					0.271
Pb			**0.810**					0.313
Au			0.501					0.688
Cu			0.485					0.609
S			0.398					0.576
As				**0.813**				0.315
Sb				**0.79**				0.342
Mo				0.654				0.521
Ag				0.392				0.815
K		0.304		0.352				0.647
Ti					0.622			0.596
V	0.614				0.621			0.159
Al		0.473			0.618			0.344
Na		0.39			0.593			0.437
Cr						**0.832**		0.242
Ni	0.374					**0.722**		0.266
La						-0.308		0.654
Ba							0.626	0.55
Hg							-0.336	0.796

Note. 'Varimax' rotation was used

Results and discussion

The results of the factor analysis using principal component analysis for 29 elements are shown in Table 1, where the total variation is decomposed on 7 factor axes.

The goal of PCA analysis is to extract the important information from the data and to express this information as a set of summary indices called factors. Varimax rotation procedure is used for additional adjustments of the factor axes. The purpose of this rotation is taking the factor pattern plot and rotating the axes in such a way that the points fall close to the axes. 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: ([Fe, Co, Mn] Sc, P, V, Ni)
Factor 2: ([Ca, Sr, Mg] Be, K, Al, Na)
Factor 3: ([Zn, Cd, Pb] S, Au, Cu)
Factor 4: ([As, Sb] Mo, Ag, K)
Factor 5: (Sc, Ti, V, Al, Na)
Factor 6: ([Cr, Ni] -La)
Factor 7: ((P, Ba)-Hg)

The results of the hierarchical cluster analysis are shown in Figure 2. The distinct groups are similar to those of the factor analysis, with elements from factors 6 and 7 exhibiting weaker correlations and being attached to other groups.

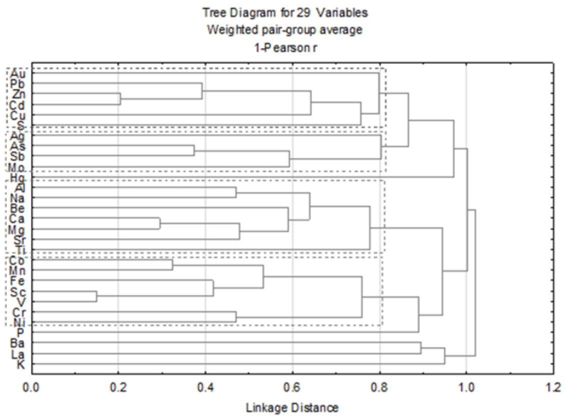

Fig. 2. Hierarchical cluster dendrogram

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 or to plot PCA loadings of the first two principal components comparing geochemical associations considering that the factor scores represent the spatial relationship between elements (Fig. 3).

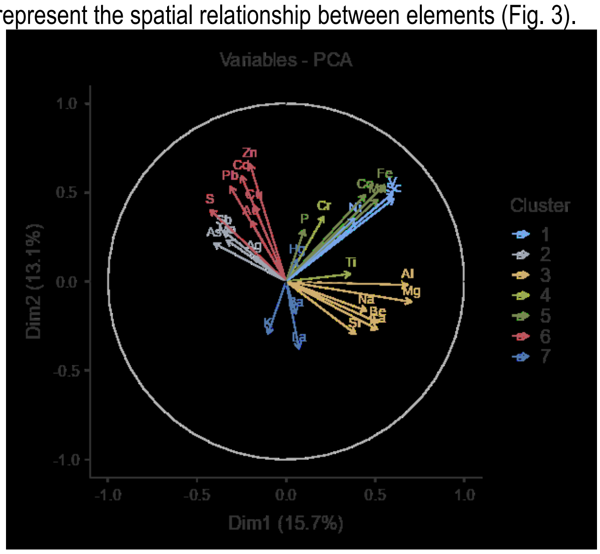

Fig. 3. PCA loading plot of the first two principal components comparing geochemical associations

The first factor represents the association of Fe, Co and Mn, as well as Sc, P, V and Ni but with lower loadings (less than 0.7). The elements comprising this factor may be associated with the carbonate stage of mineral formation, which involves various iron and manganese minerals (Dragiev et al., 2010).

The second factor considers the behavior of the group of elements with the core of Ca, Sr and Mg which have a high correlation with each other. The elements Be, K, Al, and Na also join this group but with lower weights.

The third factor represents the distribution of the main ore elements in the Obichnik deposit, which are joined in an association of Zn, Cd and Pb, as well as S, Au and Cu with lower loadings. The spatial distribution of this factor overlaps the main ore zone and probably follows the Quartz-sulphide stage of mineral formation (Dragiev et al., 2010). This is supported by the microscopic observations made so far, where gold is found in close association with galena, pyrite, sphalerite, and chalcopyrite (Fig. 4).

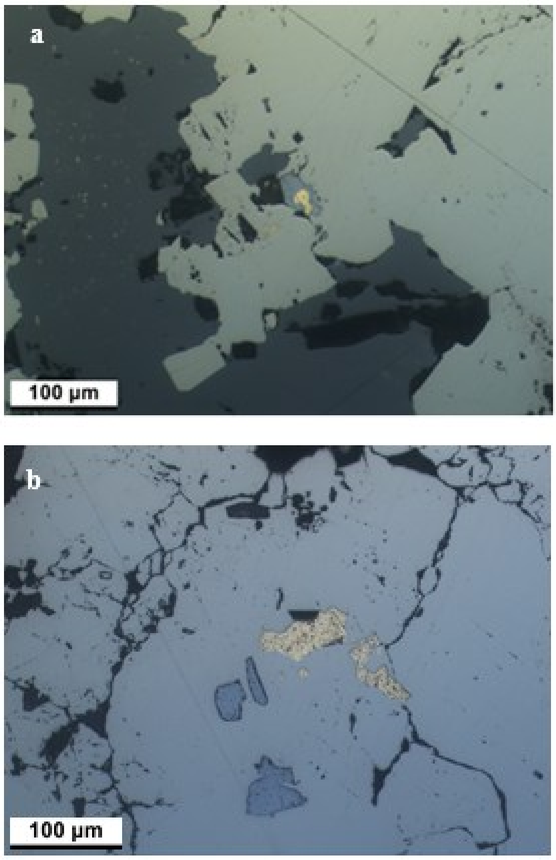

Fig. 4. Photomicrograph in reflected light, parallel Nickols. (a) Gold grain (bright yellow) located in galena and three smaller Au grains among pyrite.
(b) Gold grains included in pyrite. To the left of them galena crystals (light grey).

The fourth factor represents the association of As and Sb which show high correlation with each other and elements Mo, Ag and K joined with lower weights. This factor can also be associated with the quartz-sulphide stage and the spread of tennantite-tetrahedrite. Additional mineralogical studies are needed to explain this connection.

The fifth factor groups Sc, Ti, V, Al and Na and shows some weak relation to them with no factor loading more than 0.7.

The sixth factor describes the association between Cr and Ni and negative correlation with La.

The seventh factor shows a weak correlation between P and Ba and some negative correlation with Hg.

Figure 3 displays the score plot of the first two principal components. These scores are called Dim1 and Dim2. The score plot is a map of 29 elements. The chemical elements close to each other have similar spatial distribution profiles, whereas those far from each other are dissimilar. From the figure, it can be seen that the elements involved in factors 3 ([Zn, Cd, Pb] S, Au, Cu) and factor 4 ([As, Sb] Mo, Ag, K) exhibit similar spatial behaviour. Other two factors with similar behaviour are factor 1 ([Fe,Co, Mn] Sc, P, V, Ni) and factor 6 ([Cr, Ni] -La). Also, it can be noticed that the elements participating in factor 2 ([Ca, Sr, Mg] Be, K, Al, Na) have an opposite direction of propagation compared to those participating in factors 3 and 4.

Incorporating mineralogical data can be crucial for further understanding of the geochemical associations. Observation of the polished preparations with a microscope identified the most common ore minerals and their relationships. Pyrite was the most abundant, followed by sphalerite, galena, and chalcopyrite. In addition, hematite, which is both primary and the result of secondary alteration of primary ore minerals, is observed in nearly all specimens. Specific areas have been targeted for investigation by X-ray spectral microanalysis to resolve the chemistry and type of minerals. Detailed microscopic studies and sample descriptions will be the subject of a separate article.

Conclusion

The results of the multivariate statistical analysis of geochemical data in the Obichnik ore deposit and graphical plots of the factor scores allow to map the geochemical associations of these elements characterised by a certain similarity. The association of ([Zn, Cd, Pb] S, Au, Cu) from factor 3 and ([As, Sb] Mo, Ag, K) from factor 4 represents the spatial distribution of the main ore occurrences.

The results in this study show that geochemical clusters, defining primary lithology, alteration, and ore assemblage that share comparable geochemistry, can be discriminated by different statistical methods, like the joining or tree clustering method, and factor analysis, like PCA. The observed good correlation between the results from these two methods is proof of the robustness of the approach.

Acknowledgements. The authors express their gratitude to Seequent Limited for providing them with an academic license of Leapfrog Geo software and to Gorubso Kardzhali JSC and Velocity Minerals Ltd for providing the database. The analyses were partially financed by scientific research project #GPF-251 of the University of Mining and Geology “St. Ivan Rilski”.

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