Applied Geochemistry xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Applied Geochemistry

journal homepage: www.elsevier.com/locate/apgeochem

Geochemical and mineralogical pattern recognition and modeling with a Bayesian approach to hydrothermal gold deposits

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ARTICLE INFO

Available online xxxx

ABSTRACT

The Bayesian approach is an effective method of identifying the probability of mineralogical and geochemical type (MGT) mineralization of trace elements in galena, pyrite and other distributions in ore mineralization. Monomineralic samples have been identified using a computer-based Bayesian method and exploration geochemical techniques of Au deposits for MGT. In order to employ the method, a data bank was used consisting of the results of analysis of more than 12,000 monomineralic samples collected from the main hydrothermal Au deposits in Tajikistan (a territory of CIS). The Bayesian approach applied to geochemical data, such as posterior probabilities and discriminant analysis, provide numerical and graphical means through which the relationships between the trace elements and samples can be studied. The method used here, along with GIS, to find MGT can be used as geochemical indicators of regions with Au mineralization. The results of analyzing 100 monomineralic samples of pyrite from the Au–Ag Shkolnoe deposit (Tajikistan) show a multi-MGT anomaly superposition which is a combination of three MGT: (1) Au–Ag type (85% and more), (2) Au-sulfide-polymetallic type (46%), and (3) Au-sulfide type (40%). Mineralogical and geochemical maps (MGM) can be drawn based on results of MGT anomalies in a GIS environment. These maps can replace traditional metallogenic maps. The advantage of MGM substitutions is that a qualitative tool is replaced by a quantitative one. This helps one to make optimal managerial and more economical decisions.

1. Introduction

Each year there is new information on mineral properties and their MGT conditions. In some cases, this information allows one to determine relationships between characteristics of minerals and their MGT, which reveals typomorphic indications of minerals and mineral associations.

Depending on the relationship between genetic and typomorphic properties of a single mineral or complex, decoding processes of formation of the minerals includes allowing possible evaluation of their geochemical anomaly and estimation of the potential reserves. There are many traditional statistical methods of analysis, e.g., correlation analysis, regression analysis and factor analysis. In this research the main concern was to introduce an applied method to clarify the relationship between the trace element content of minerals and their MGT and geochemical anomaly, which is one of the main goals of mining geochemistry. In this method, the trace element contents of minerals are used to identify their MGT (Kuzmin, 1993). To apply the method, at least three basic components are needed for pattern recognition: (1) an electronic library or a database on trace element content in minerals of Au deposits or MGT, (2) a data bank of a geochemical anomaly area, and (3) a data clustering technique.

Clustering is a mathematical tool that attempts to discover structures or certain patterns in a data set, where the objects inside each cluster show a certain degree of similarity. Combination of these three components and analyzing the correlation between MGT and geochemical anomaly are the main tasks of GIS. For complex visualization and interpretation of the data used in modeling, it is necessary to create an extension to achieve the following primary purposes: (1) management of the trace element databank and the databank on a region's geochemical anomaly; (2) statistical processing of the data for further qualitative and quantitative interpretation (Ziaii and Abedi, 2004; Ziaii et al., 2007a). Having some GIS components described above, research was carried out on the geochemical anomaly in the area of the Shkolnoe Au deposit (Kurama Mountains, north Tajikistan) (Fig. 1). Trace element contents of mineral concentrates from the Au deposits allowed discrimination between the different mineralogical and geochemical types. The comparison of statistical processing has allowed selecting groups of the most frequent elements described by specific features of their distribution in various MGT. Table 1 shows the trace element contents in the mineral samples taken from the available

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0883-2927/$ - see front matter © 2009 Published by Elsevier Ltd.
doi:10.1016/j.apgeochem.2009.02.006

Please cite this article in press as: Ziaii, M., et al. Geochemical and mineralogical pattern recognition and modeling ... Appl. Geochem. (2009), doi:10.1016/j.apgeochem.2009.02.006

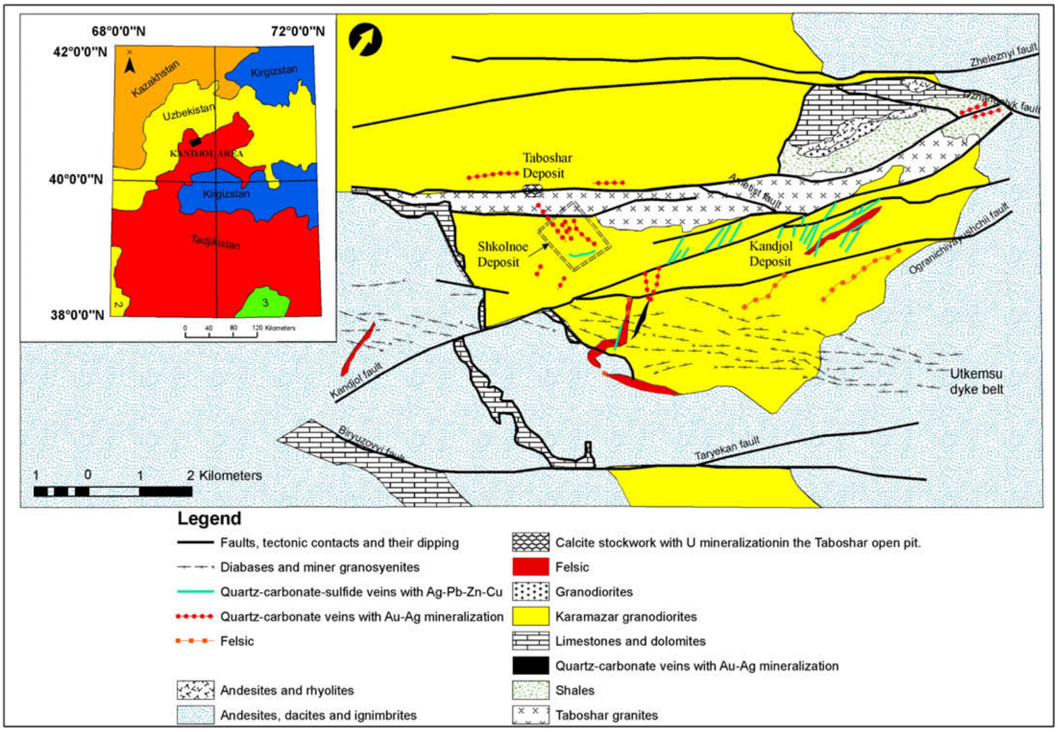

Fig. 1. Geological map of the Kandjol area, Tajikistan: (1) Middle Carboniferous-Lower Permian (diabases and minor granosyenites; felsic), (2) middle Carboniferous (andesites, dacites and ignimbrites; Karamazar granodiorites; Taboshar granites), (3) middle Devonian-Lower Carboniferous (limestones and dolomites), (4) lower–middle Devonian (granodiorites; andesites and rhyolites), (5) Ordovician-Silurian (shales) (after Turlychkin, 1972a,b; Baikov, 1972).

data base. These elements are extracted from the raw data by a statistical anomaly to select the most frequent elements in the minerals.

The development of a classification of Au deposits is a complex problem, primarily because of the 'cosmopolitanism' of this chemical element. Gold may be concentrated as the main or secondary constituent in endogenic and exogenic deposits of an extremely wide ranging genesis, therefore, mineralogical–geochemical investigations are extremely important to trace the behavior of Au in sedimentary, metamorphic, magmatic and post-magmatic processes, as well as to determine the physicochemical conditions of concentration in the ore bodies. This problem can be successfully solved by using a large number of analytical data. Although the results of a vast amount of analyses of Au in rocks and minerals are available in the world literature, the patterns of their dispersal and concentration have not yet been summarized. Mining geologists have collected a unique data base of the geology and trace elements of Au deposits in the CIS but it has not been used in many cases for developing the theory of ore formation.

The classification of Au deposits should obviously be an integral part of the general classification of endogenic deposits. The relationships between deposits of various composition and genesis can only be established thereby and the boundaries of qualitative and quantitative transitions between ore mineral types then determined. Many geologists in the CIS are presently using the classification of Au deposits proposed by Petrovskaya (1973). Petrovskaya's classification is also applied because of the simplicity of its structure. Safonov (1997) proposed a classification of Au deposits which determined the associated mineral types with their distribution, geological-genetic types, and productivity of ore-forming systems which represent the probable sources of ore-forming solutions. Hydrothermal Au deposits were related to ore-forming systems of 16 geological-genetic types.

Based on the classifications of Petrovskaya et al. (1976), Konstantinov (1991) and Safonov (1997) hydrothermal Au deposits were related to ore-forming systems of different kinds and classified MGT. This model is based on data obtained during a study of Au deposit (Ziaii, 1999) in the former USSR where 12,000 monomineralic pyrite, galena, arsenopyrite and sphalerite samples from 100 hydrothermal Au deposits were studied.

In this paper, the following Bayesian classifiers are described and applied to a detailed-scale Au deposit in the Kandjol ore field.

Table 1
The most informative trace elements analyzed in monomineralic samples of ore minerals.

Monomineral	Trace elements
Pyrite	As, Pb, Co, Cu, Zn, Ni, Ag
Galena	Sb, Mn, Au, As, Zn
Arsenopyrite	Au, Ag, Pb, Zn, Cu, Sb, Co, Ni
Sphalerite	Cu, Pb, Cd, Sb, Mn, Co, Sn, Ga, Ag, Au

2. Study area

The Shkolnoe deposit is located in the Kandjol ore field at the southwestern end of the Kurama Mountains, north of Tien-Shan, in northern Tajikistan (Fig. 1) (Moralev, 1994). The main part of the Kandjol ore field is built up by the granitoids of the large Karamazar pluton which comprises the Middle Carboniferous Taboshar granites and Karamazar granodiorites (Baikov, 1972).

The Kandjol ore field comprises Paleozoic magmatic rocks and minor sedimentary rocks (Fig. 1). Three types of epithermal and hydrothermal mineralization have been recognized in the area: Au–Ag, Ag-base metals, and U. The Au–Ag mineralization occurs in quartz–carbonate veins in the Shkolnoe deposit and Karaulkhana prospect. The Ag–Pb–Zn–Cu is found in the quartz–carbonate–sulfide veins of the Kandjol deposit (Turlychkin,

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1972a,b). The Shkolnoe deposit is located in the west sector of the Kandjol ore field (Fig. 1). A number of the WNW-trending quartz–calcite veins, 0.2–5 m thick and 100–2000 m long, are hosted by the Middle Carboniferous Karamazar granodiorites (Turlychkin, 1972a). The numerous NNE-trending pre-mineralization faults arrange the veins into blocks with different morphology and distribution of metals (Moralev and Shatagin, 1999).

The host granodiorites, as well as adjacent volcanics, were altered to albite–chlorite rocks. A sericites–calcite–chlorite–quartz–pyrite alteration envelope (up to 50 m) occurs around the quartz–carbonate veins. Five stages of mineralization have been recognized in the veins (Moralev, 1993; Moralev and Shatagin, 1999):

1. Stage I consists of green and white quartz with gray calcite.
2. Stage II comprises three assemblages A–B–C. The earliest assemblage (A) comprises the rhythmical intercalation of quartz and adularia bands with some of them enriched in sulfides, Ag-rich tetrahedrite, Ag sulfosalts and electrum. The intermediate assemblage (B) displays tabular gray calcite replaced pseudomorphically by fine-grained quartz with a tabular structure. The latest coarse-grained white calcite occurs between quartz tablets. There is also minor disseminated ore mineralization in this assemblage. The latest assemblage (C) comprises massive quartz plus gray and white calcite, enriched in co-precipitated sulfides, Ag-rich tetrahedrite, freibergite, Ag–Sb sulfosalts, naumannite and electrum with minor dyscrasite, allargentum, acanthite and native silver.
3. Stage III consists of gray quartz and blue-gray calcite.
4. Stage IV comprises quartz + Fe–Mn carbonates + calcite + chlorite veinlets with abundant sulfides and, rare Ag–tetrahedrite, Pb–Sb and Ag–Pb–Sb sulfosalts, and niccolite.
5. Stage V is represented by barite + galena veinlets with some quartz, calcite, and minor pyrite, chalcopyrite, and Ag–tetrahedrite.

The Rb–Sr and K–Ar systems of gangue minerals from the Au–Ag mineralization of the Shkolnoe deposit conserve at least three events in its history: the Au–Ag mineralization and two subsequent thermal pulses.

Within the Shkolnoe deposit the minimum duration of the hydrothermal and thermal activity from stage II Au–Ag ore to the IV stage Ag–Pb–Zn–Cu mineralization can be estimated as approximately 30 Ma, based on the difference between the Rb–Sr and the K–Ar isotopic age determinations (Moralev and Shatagin, 1999).

3. Methodology

The different patterns of trace elements in pyrite, sphalerite and galena are coincident with the classification of Au deposit types and are probably a direct consequence of different mineralizing processes. In this regard, Prokhorov (1970), Kuzmin (1993), Grigorian (1992) and Ziaii (1999, 2007) reported differences in trace element contents in gold ores from different mining districts in the CIS. The Bayesian method is used to identify the MGT consists of the calculation of conditional posterior probabilities and decision-making based on comparison of obtained magnitudes. If the number of MGT in set ‘A’ is equal to ‘m’, then each object is characterized by indications.

Suppose:

$$x_1 = x_1^0,\ x_2 = x_2^0, \ldots, x_n = x_n^0, \quad K_n = \{x_1^0, x_2^0, x_3^0, \ldots, x_n^0\}$$

The probability of realization an event K_n will be determined using Bayes’ formula:

$$P(A_i|K_n) = \frac{P(A_i)\cdot f_i(x_1^0, x_2^0, \ldots, x_n^0)}{\sum_{i=1}^{m} P(A_i)\cdot f_i(x_1^0, x_2^0, \ldots, x_n^0)},$$

where i is class of MGT.

The value of

$$P(A_i)\cdot f_i(x_1^0, x_2^0, \ldots, x_n^0)$$

is dependent with the probability compound:

$$P(A_i)\cdot f_i(x_1^0, x_2^0, \ldots, x_n^0) = \prod_{i=1}^{n} P(A_i) f_i(x_i).$$

The main method applied in this research is based on the prior probability of the Bayesian approach. Algorithms of Bayesian approach are programmed in Visual Basic for trace element contents in pyrite, galena, sphalerite and arsenopyrite. The trained classifier applies Bayes’ rule to compute the posterior probabilities of all states of the class variable given the particular instances of attributes in the feature vector, and predicts the class label that takes the highest posterior probability. Bayesian classifiers can be efficiently used in mineral potential mapping of an area, because they involve predictive classification of each spatial unit having a unique combination of predictor patterns as mineralized or barren (Grigorian et al., 1999; Ziaii, 1999; Ziaii et al., 2007c).

4. Geochemistry of ore minerals

4.1. Sampling, sample preparation and analysis

To characterize the MGT of the Shkolnoe deposit, more than 100 samples were collected using a chip channel sampling method. The samples were taken from the wall rock and stages I, II and IV mineral assemblages on the mining levels 1300, 1265, 1255, 1207, 1120, 1115 and 986 m above sea level (Fig. 2). Using a binocular microscope the size-fraction was selected in which the pyrite and galena were concentrated. Polished sections were made from these samples.

Other samples, in which the size-fraction is small, were crushed, homogenized, and divided into two parts. Ore minerals were analyzed for the elements shown in Table 1. Ore mineral concentrates were examined and refined by handpicking under a binocular microscope to obtain 10 g of high purity concentrate. Finally, the concentrates were powdered in an agate mortar. All samples were analyzed by LSEC (Laser Spectroscopy Emission) at the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry (IGEM), Moscow (Moralev, 1993).

4.2. Trace elements in pyrite and galena concentrates

Trace element contents of pyrite and galena concentrates from the Shkolnoe deposit have allowed discrimination between the different mineralogical and geochemical types. Based on Fig. 2, one can conclude that with increasing depth, the types Au–Ag and Au–sulfide-polymetallic decrease while the type Au–sulfide increases. This figure clearly shows the multi-MGT anomaly with depth of mineralization.

The comparison of statistical processing between pyrite and galena (Table 2) has allowed the selection of groups of the most important MGT types. Based on the Shkolnoe experiments it can also be stated that galena shows better behavior in the model than pyrite. The above relations can be easily expanded for multi-MGT anomalies. Geochemical and mineralogical pattern recognition and modeling using a Bayesian approach of trace elements in galena can therefore be applied to any Au classification problem. This can be explained by noting that pyrite has more stages than galena.

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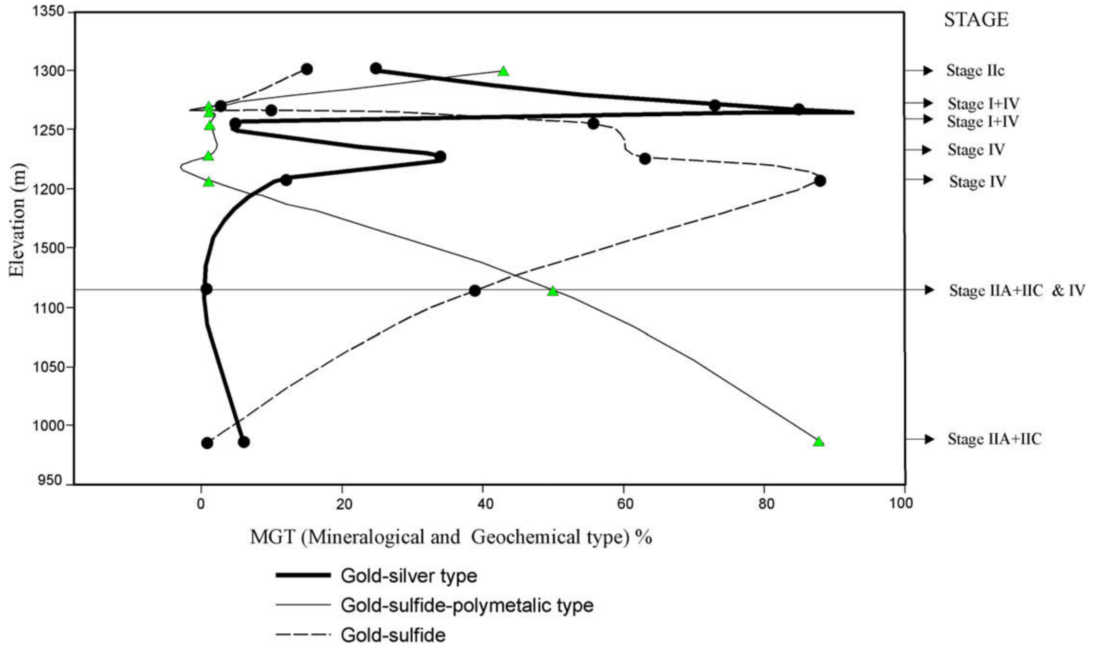

Fig. 2. A multi-MGT anomaly which is a combination of three MGT types: (1) Au–Ag type; (2) Au–sulfide-polymetallic type (▲); (3) Au–sulfide type (●).

Table 2
The results of geochemical and mineralogical pattern recognition and modeling with a Bayesian approach for pyrite and galena in the Shkolnoe deposit.

Mineral	Location of samples and stage		No. of samples	Probability of MGT (%)[a]		
				Au + Ag	Q + S	Au + S + Q
Pyrite	Stage II (A)	Ore body	7	**94**	0.09	0.06
	Primary halo	Upper	4	0.10	*96.5*	1
		Lower	7	0.40	*52.9*	0.3
Galena	Stage II (A)	Ore body	4	**99.1**	0.83	0.00
	Primary halo	Upper	18	**99.4**	0.26	0.16
		Lower	5	**99.9**	0.02	0.02

Bold: The result is true.
Italic: The result is false.
[a] Gold–silver type (Au + Ag), quartz–sulfide type (Q + S), gold–sulfide–quartz (Au + S + Q).

5. The applications of Bayesian approach in gold deposits of Iran

This method was also used to evaluate some of the most important Au deposits of Iran such as Kharvana (NW Iran), Mute (North Isfahan), East of Iran and Gandi (North Iran, Semnan province) ore deposits and the results were as follows:

1. Kharvana ore deposits were classified as Au–sulfide type (Ziaii and Abedi, 2004).
2. Mute Au fields were identified as Au–quartz type (Ziaii et al., 2007b).
3. Gandi ore deposits were classified as Au–polymetallic and quartz–sulfide type (Ziaii et al., 2007a).
4. Garm-e-tamam-Deh, Kanif (East of Iran) were identified as Au with VhMS deposits (Ziaii et al., 2007c).

6. Conclusions

In this paper, a model is proposed to identify galena as the only mineral that can be selected from both ores and non-ores. This method provides an efficient modeling tool for metallogenic mapping. Further, in this study an environment has been provided that optimizes modeling for recognizing ore samples rather than non-ore samples; and identifies multi-formation or multi-MGT types of mineralization zone.

For future work, the authors will focus on extending the methodology, which provides the conditions to reduce the investment risk in Au deposits and monitors mining pollutants throughout the process of mining. Automation of Au mining at the mine scale will also be focused on.

Acknowledgments

The research was funded by the School of Mining, Petroleum and Geophysics at the Shahrood University of Technology. The authors thank the laboratory staff of IGEM for their geochemical analysis work and to G.V. Moralev for providing us with the data sets.

The authors are grateful to N.P. Laverov, Yu.G. Safonov, S.V. Grigorian, and A. Osipenko for their useful suggestions which helped us to improve the mining geochemistry and introducing a new branch of it. Helpful comments by reviewers (Brian Hitchon, Kevin Walsh and one anonymous reviewer) led to substantial improvements of the manuscript.

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Appendix

The software package used in this article can be accessed on line at: http://www.drh.ir/demo/geo/.

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