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TO THE QUESTION ON GEOMETRIZATION OF ABNORMAL STRUCTURES OF GEOCHEMICAL FIELDS OF HYDROTHERMAL ORE DEPOSITS

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Possibilities of various mathematical methods at geometrization of abnormal geochemical fields of ore deposits are discussed. Peculiarities of application of linear and nonlinear methods of image recognition are considered on the specific example for solution of these problems: discriminant analysis, multiple regression method, artificial neural networks. Conditions of optimum application of the named methods are defined. The opportunity of secondary aureoles mapping data application for identification of the primary abnormal geochemical field structure is shown.

Research of zoning of abnormal geochemical fields is a component of the problem of endogenous zoning, one of the major in the theory of ore deposits. That constant attention turned to this problem by researchers is caused by its value for development of the theory of oreformation and by possibility of practical use of the revealed laws for forecasting of hidden mineralization.

Universality of vertical geochemical zoning of primary aureoles of ore deposits, for the first time noted by N.I. Safronov [1] and most fully proved for sulphidocontaining deposits [2, 3], is lain in the basis of some techniques, and more than 30 years used for the quantitative forecast of mineralization, determination of the level of its erosive section, evaluation of flanks and abyssal horizons of deposits. Meanwhile, it is established that on golden-ore deposits, column and stage distributions of mineralization are usual, the decrease of values of zoning coefficients is often combined with their very complex distribution in the plane of ore bodies, which makes problematic the use of the named factors at rare network of approbation. Besides, many authors in the concept of anomaly, except for aureoles of element addition, include areas of their subtraction, considering these complementary in space positive and negative anomalies as components of uniform hierarchically constructed structures [4–8].

The structural method of research of geochemical fields in the most consecutive view is stated by S.A. Grigorov [9]. By this author in the construction of abnormal structure of geochemical field (ASGF) of ore object of any rank are allocated: nuclear zone concentration of ore elements, surrounding zone of transit (with low concentration of ore elements) and external (face-to-face) zone of concentration. The listed zones, in turn, form a zone of nuclear concentration of the following hierarchical level. Close functional connection between all elements of ASGF defines obligation of presence of all hierarchical levels of the senior rank at presence of the younger. Mineralization occupies in ASGF a certain position, therefore the structural method essentially facilitates grading of numerous anomalies revealed during the process of geochemical survey, and allows allocating most perspective of them even at identity of their efficiency by the basic element.

Correct interpretation of an internal construction of geochemical field, considering spatial overlapping of abnormal structures of various hierarchical levels and an essential element of subjectivity at their geometrization, is the main problem at application of the structural method.

Various groups of methods based on various theoretical preconditions are now used for the research of the structure of abnormal geochemical fields. The majority of authors prefer only one technique; therefore it is expedient to lead the comparative analysis of advantages and disadvantages of the most widespread methods of geometrization of abnormal geochemical fields. They are: 1) *the R-method* of factorial analysis, as representative of methods of variable clusterization; 2) the system «Geoksan», realizing a modernized ideology of cluster-analysis observations 3) methods based on ideas of differential mobility of elements in hydrothermal process (coefficients of zoning); 4) methods of calculation of the intensity of geochemical transformations (energy of ore-formation, rank dispersion, dispersion of the geochemical spectrum, etc.). Application of image recognition methods is necessary in some cases for identification of the abnormal geochemical field construction. Linear methods of regression and discriminant analyses and artificial neural networks can be used as such methods.

The carried out comparative analysis of efficiency of the listed techniques allows to ascertain that sites of maximal mineralization with a various degree of detail are fixed by the majority of the considered methods, however the correct decoding of the structure of abnormal geochemical field and, finally, the forecast of mineralization are possible only at combination of several methods of geometrization, using different ideology [11, 12]. Methods of variable grouping allow restoring the course of hydrothermal process at the level of mineral paragenesises and geometrize the intensity of their display. Clusterization of observations fixes the total result of all mineral-forming processes and allows differentiating an abnormal geochemical field in gradation of intensity, evaluating specificity of the allocated zones through their geochemical spectra. The additional information for delineation ASGF and evaluation of the erosive section of mineralzation gives the parameters of zoning, fixing the tendencies of differentiated distribution of elements in hydrothermal process. Parameters of intensity allow to judge about scales of mineralizaton and give the additional information for decoding of geochemical analyses genesis.

Direct application of more mediated methods of image recognition for geometrization of ASGF is not usually practiced. However, there is a number of problems where their application is necessary. In particular, such problems are: estimation of the level of the erosive section of shallow dipping ore bodies, identification of facies of metasomatites based on the data geochemical works, prediction of mineral types of ores with use of geochemical data and others. Besides, by means of image recognition methods it is possible to identify zones of ASGF when the quantity of tests is insufficient for delineation of the structure as a whole. A similar situation is usual at drilling of search wells chinks or developments. As a training sample it is necessary to use the results of mapping of the well-studied deposit-standard.

Zoning of abnormal geochemical fields of hydrothermal gold deposits is shown, first of all, in the polar behavior of two groups of elements which we call concentrating and deconcentrating after E.V. Plyuschev [12]. Concentrating elements (mainly chalcophylic) are accumulated together with gold in ore bodies, deconcentrating elements (mainly siderophylic and lithophylic) are characteristic for the near-ore space, in ore bodies their contents is usually lower than the background. The element composition of the named groups, depending on conditions of mineralizaton formation, is defined by methods of clusterization of variables for specific geological-industrial types of deposits. The intensity of addition and subtraction of the revealed by such methods associations of elements geometrizes as the sum of their concentration coefficients relatively to clark. Minimal-abnormal values of these parameters are calculated by the standard technique; therefore contours of the obtained anomalies do not depend on subjective predilections of the executor.

The following stage is the evaluation of orderliness of the revealed abnormal structures. Because rank is expressed through contrast of distinctions in the structure of central and intermediate zones of ASGF, for its quantitative characteristic it is offered to use standard criteria for testing of the hypothesis on equality of two unknown averages. Average concentration coefficients of deconcentrating elements in central and intermediate zones of ASGF are compared among themselves, because behavior of these elements in the named zones is diametrically opposite. Student's criterion is used at the normal law, D.A Rodionov's criterion at the lognormal, and rank criteria is used at the unknown distribution law [13].

The named criteria have various intervals of values, but all of them can be expressed in gradations of confidential probability, therefore for convenience of use the numerical value of the rank coefficient (C_{rk}) is taken equal to the quantile of normal distribution, corresponding to the calculated significance value of criterion. The value C_{rk}=2,0 is taken as the boundary value (which corresponds to the significance value of 0,05) is accepted. Theoretically, the range of values C_{rk} is not limited. In practice, for medium-ore sections of deposits it does not fall outside the limits of 10... 6, and in the process of mineralization pinchout it gradually decreases to an insignificant level.

Fig. 1, *A* shows the structure of ASGF in the section through the Main ore body of Olympiada deposit (Yenisei range). The abnormal structure has a distinct concentric construction with isolation of the central (nuclear), intermediate and frontal zones. Au, As, Sb, W, Ag, Cu are accumulated in the central zone, Ba, Mn, in the intermediate, and Ti, Cr, V in the fronatal. For the cited here section of ASGF the rank coefficient amounts to 16, which testifies to a high concentrating degree of ore elements.

The results of geochemical approbation on the cited section are used as a training sample for methods of image recognition. Their three modifications are applied: 1) artificial neural networks, 2) multiple regress method, and 3) discriminant analysis.

The artificial neural networks, being primitive models of biological systems, can be successfully used for nonlinear multidimensional modeling of geochemical fields. This direction of statistical researches experiences a rapid development in the last years, especially in those areas of science and production, where solution of forecasting, classification or management problems is required. The essence of neural systems consists in the following. In systems with direct signaling, which are usually used at solution of practical problems, all neurons are organized in layers. The input layer serves only for input of values of input variables. Neurons of intermediate layers are intended for processing of input information by calculation of activation values, which on the output will are transformed to activation functions. In commonly used networks with a full communication system, each neuron is connected with all elements of the previous layer. After the whole network is worked-off, the values of elements of the output layer are accepted as output of the network as a whole. Thus, the dependence between the input and output information of the network is established during the training. The training can be controllable («with a teacher») and uncontrollable («without a teacher»).

At controllable training it is necessary to prepare a set of training data which represent examples of the input data and the corresponding output. The network in this case learns how to establish connection between the first and the second, and then independently classifies new input data for which output values are unknown. The back-propagation method of is used as the algorithm of controllable training at which all the available data are used for adjusting of weights and threshold values of the network in order to minimize an error of the forecast on the training set. In many software implementations (in particular, in the widely used package ST Neural Networks of the StatSoft Company used in our work) the special algorithm of automatic search of an optimum configuration of the network is included. It is necessary to notice that systems which contain only input and output layers generate linear models and are similar to the linear discriminant function (at solution of classification problems), or procedure of multiple regress (at solution of regression problems).

The result of application of the neural network method (Fig. 1) confirms the presence of a contrast concentric zoning of the investigated ASGF, and testifies to the perspectivity of application of the given method for decoding the structure of abnormal geochemical fields.

The results of linear methods of regressive and discriminant analyses also specify to a contrast zoning of the described structure (Fig. 1, *B, Г*). The statistics, obtained under the training collection with sample from admittedly central, intermediate and frontal zones (coefficient of multiple correlation 0,75; Willks's lambda is less than 0,18; $F(46, 1344)=18,3$), testify to reliable division of the specified zones with a probability higher than 0,9999 (Fig. 2). It is also indicated by high values of Mahalanobis distance between the centre and the allocated cluster (14,2 between the central and intermediate zones; 5,8 between the intermediate and frontal and 15,3 between the central and frontal zones at statistically significant distance 3,0).

The results of training are widespread to the whole massif of samples and are used for identification of the abnormal geochemical field structure in the section through the ore body of the Western site of Olympiada deposit. In spite of the fact that the main ore body is unique by many parameters, the received picture testifies to a high enough quality of recognition and a principal opportunity of applying methods of image recognit-

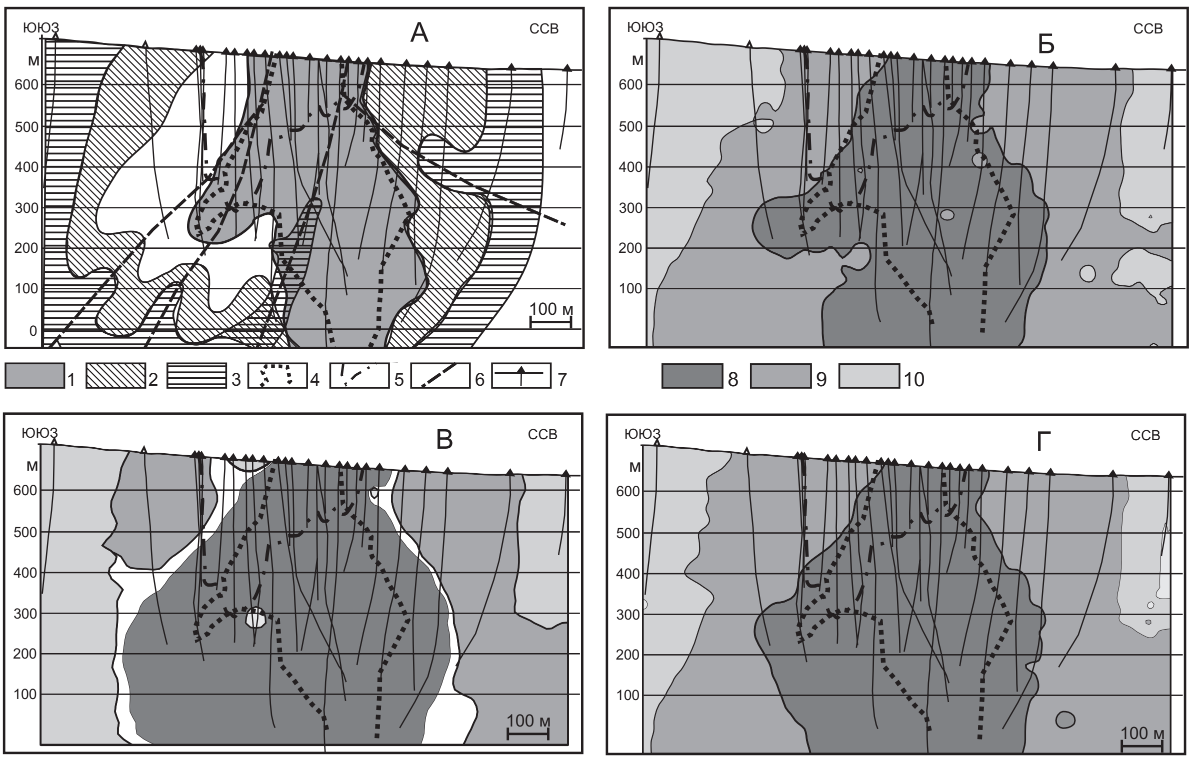

Fig. 1. *The structure of the abnormal geochemical field in the vertical section through Main ore body of Olympiada deposit on the prospecting line 25: A) geochemical associations according to the factorial analysis: 1) Au, As, Sb, Mn, Ag, Cu, W; 2) Ba, Mn; 3) Ti, Cr, V; 4) the ore body contour; 5) linear crust of weathering ; 6) breaks; 7) prospecting wells; Б-Г) the geochemical field structure, restored by methods of image recognition: Б) artificial neural networks; В) multiple regress; Г) discriminant analysis; 8-10) ASGF zones established by image recognition methods: 8) internal; 9) intermediate; 10) external*

ion for geometrization of ASGF (Fig. 3). The structure of the geochemical field, restored by the method of discriminant analysis (Fig. 3) corresponds to the real situation. A close picture is given by the neural network method (Fig. 3). The results of the regression analyses are defined in a lesser degree (Fig. 3).

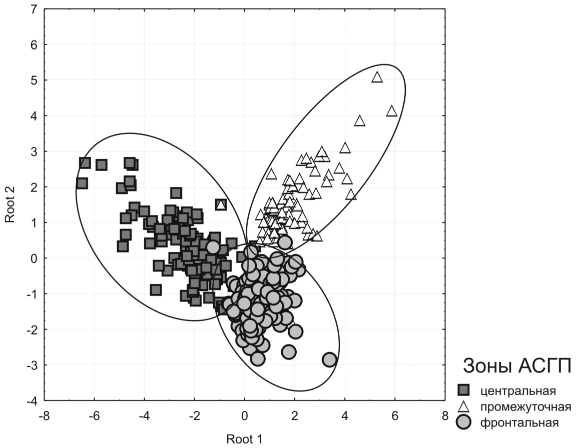

Fig. 2. *Differentiation of ASGF zones of Olympiada deposit based on the results of the discriminant analysis*
Explanation to Fig. 2: центральная – central; промежуточная – intermediate; фронтальная – frontal

Thus, the linear method of discriminantal analysis at decoding of the field structure does not concede to more complex nonlinear methods of artificial neural networks, which was pointed out by us earlier [10]. This conclusion is fair for cases when initial data are presented by homogeneous quantitative data, and the number of variables is not too great. Application of the neural networks method, hence, is expedient in situations when supervision are represented by both quantitative and qualitative data and (or) the number of variables is too great, which complicates application of linear methods.

Objective geometrization of ASGF by primary halos is in most cases possible only for ore bodies and in detailed studied deposits. The density of the approbation network of radical rocks of at prospecting-estimated works, as a rule, is insufficient for correct quantitative estimation of ASGF of rank parameters of deposits and ore fields; therefore, attraction of mapping results of secondary geochemical fields for these purposes is a necessary element of researches. The parity of element concentration in primary and secondary halos is controlled by the whole set of factors, and to predict the total influence of which is practically impossible. Coefficients of residual efficiency are usually calculated on each object during special researches. The data obtained by us specify that

Table. *The structure of multidimensional canonical variables revealed by the discriminant analysis (Olympiad deposit)*

Root	Fe	Ti	Ba	Cr	V	Ni	Co	Cu	Pb	Zn	Sb	As	Ag	Mo
1	–0,32	0,03	0,43	0,24	0,48	0,10	–0,10	0,05	0,39	0,11	–0,53	–0,65	–0,13	0,00
2	0,17	–0,29	0,36	–0,38	0,37	0,27	0,02	–0,03	–0,07	–0,19	0,35	0,25	–0,22	0,07

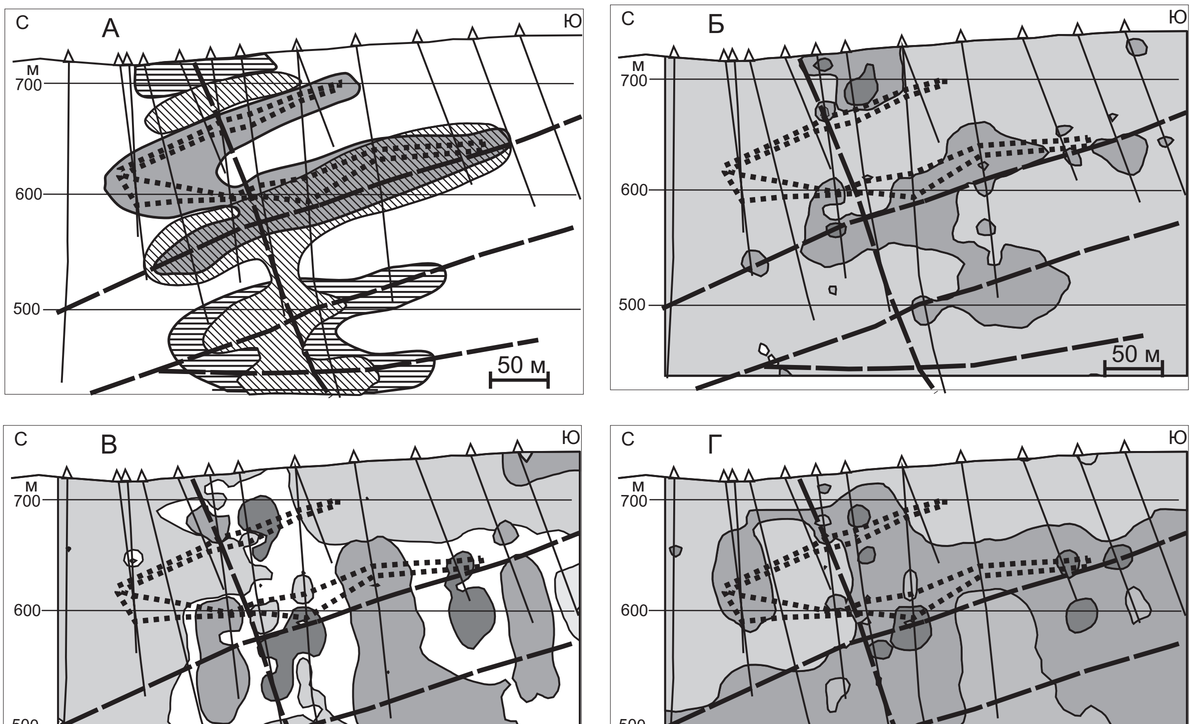

Fig. 3. *The structure of an abnormal geochemical field in the vertical section through the ore body of Western site of Olympiada deposit by the prospecting line 8: symbols are on Fig. 1*

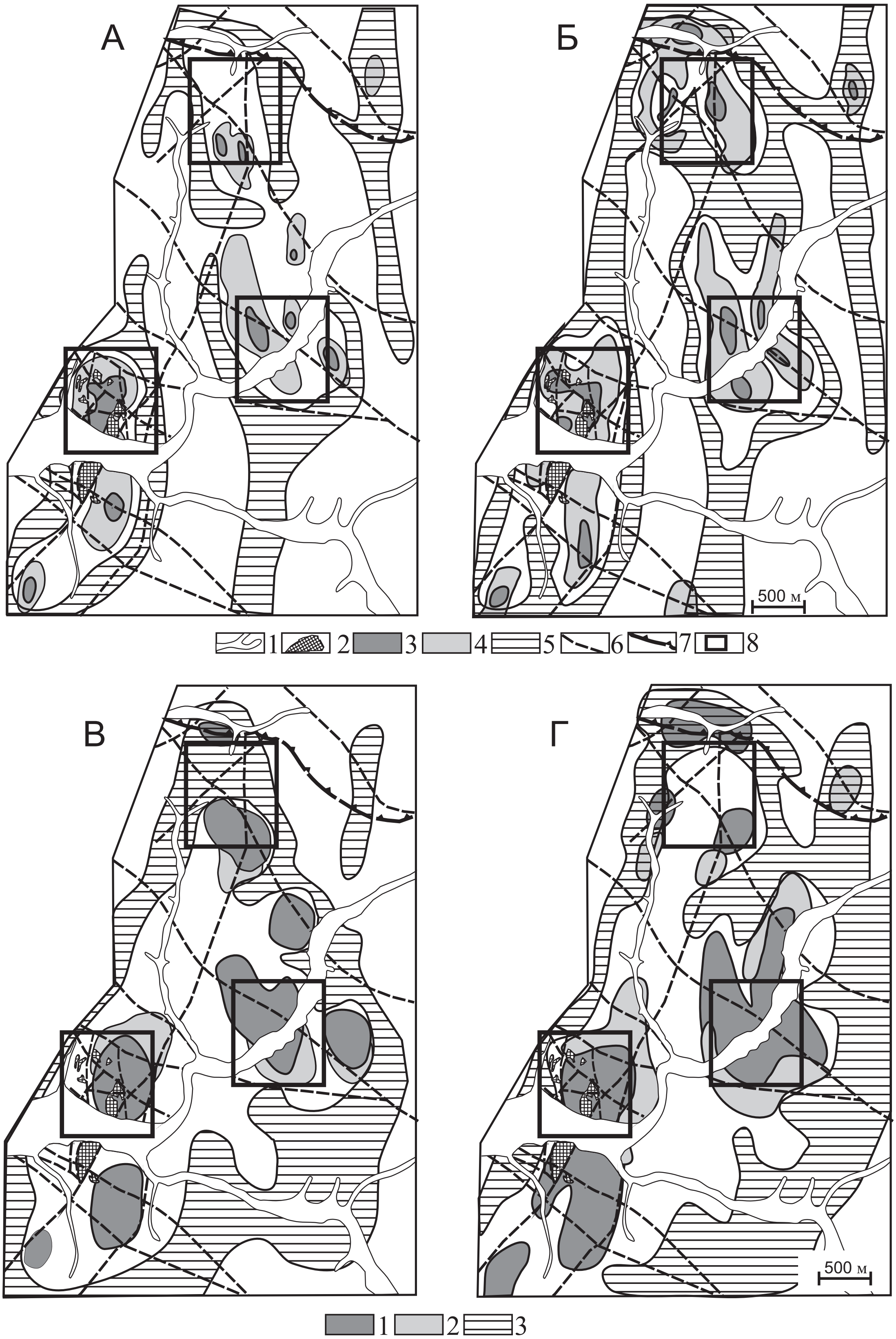

Fig. 4. *The structure of primary and secondary abnormal geochemical fields of Mayskiy-Lebedskiy ore field (made by the author on materials of JSC «Tetsi-T»): А) distribution of geochemical associations in the secondary geochemical field; Б) the same in the primary geochemical field: 1) alluvial deposits; 2) skarns; associations: 3) Au, Ag, Cu, Bi, As, Pb, Zn; 4) Cr, Ni, V; 5) Ti, Zr, Ba; 6) explosive infringements; 7) Talon overstep; 8) golden-ore rank sites of deposits; В) positive anomalies of relative concentration coefficients in the secondary geochemical field: 1) Co:Ni; 2) Ag:Au; 3) Pb:Zn;) Г) the same in the primary geochemical field*

ASGF, revealed in primary fields, generally maintain the morphology in secondary accumulations (Fig. 4).

Quantitative parameters of ASGF in the certain degree are deformed, but can be adjusted according to residual efficiency coefficients calculated for each parameter [14].

Conclusion

1. Opportunities of various mathematical methods at geometrization of abnormal geochemical fields of ore deposits are analyzed. It is established that methods of variable grouping allow geometrizing the intensity of mineral paragenesis, and clusterixation of observation captures the total result of all mineral-forming processes and allows differentiating the abnormal geochemical field in gradations of intensity, evaluating the specificity of the allocated zones through their geochemical spectra.
2. It Is established that a linear method of discriminant analysis at decoding of the geochemical field structure, in conditions of uniformity of initial quantitative data, does not concede to more complex in application nonlinear methods of artificial neural networks. Therefore, neural networks are recommended to be applied in situations when supervision are represented as both quantitative and qualitative data, and (or) the quantity of variables is so great that it complicates the application of linear methods.
3. The revealed in primary halos abnormal structures of geochemical fields as a whole maintain the morphology and efficiency in secondary accumulations. It allows considering the legitimate application of mapping data of secondary halos for identification of the structure of the primary abnormal geochemical field (in view of corresponding correction coefficients).

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